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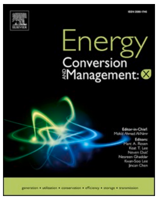

The road to zero emission shipbuilding Industry: A systematic and transdisciplinary approach to modern multi-energy shipyards

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ABSTRACT

The International Maritime Organisation focuses on decarbonising the operational phase of a ship's life cycle. However, shipbuilding contributes to a significant amount of greenhouse gas emissions and air pollutants and has negative impacts on society. Holistic and transdisciplinary studies of the shipbuilding energy sector are lacking and a holistic approach is needed to discuss the potential of measures and tools to improve the shipbuilding industry with zero emissions. This study is an interdisciplinary approach to provide trends, recommendations and policies for decarbonisation of the shipping industry from a life cycle perspective. Taking into account a holistic and transdisciplinary approach, the energy sector in shipbuilding is categorised into an energy supply system, an energy economic system and an energy ecosystem, and the main disciplines for improving energy efficiency and promoting "zero emissions" for shipyards are identified, measures and tools within each discipline are proposed, and their mitigation potential and key issues for improving energy efficiency and reducing air emissions from shipyard activities are discussed. The case study highlights the economic, environmental and sustainability benefits of implementing the proposed modern energy system in an Italian shipyard. Although there is no silver bullet to eliminate air emissions in the shipbuilding industry due to the complexity, the different reduction potentials, the costs and the relationship and interaction between measures and tools, the implementation of the energy management framework can accelerate the transition to a zero-emission shipbuilding industry.

Introduction

Maritime transport plays an important role in improving the well-being of society and the sustainability aspects of cities. Shipping contributes to carrying 80 % of international trade and is considered as one of the most energy-efficient modes of transportation [1] in terms of mass of cargo carried per distance. However, by contributing to 4 % of energy consumption in all transport sectors [2] the industry is responsible for 2.89 % of global Greenhouse Gas (GHG) emissions and is projected to reach 50 % more than the 2018 level by 2050 [3]. In addition, the industry accounts for 5–10 % and 17–31 % of global SOx and NOx emissions respectively [3]. Given that 50 % of these emissions occur in coastal areas and can be up to 400 km from the source of the emissions (ships), air emissions can have serious negative socio-economic impacts on the population living near the coasts [2].

International Maritime Organisation (IMO) as a regulator body for

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Abbreviations: BESS, Battery Energy Storage System; BECCS, Bio Energy with CCS; CAPA, Corrective And Preventive Action; CCSU, Carbon Capture Storage and Utilisation; CE, Circular Economy; CHP, Combined Heat and Power; CI, Carbon Intensity; CO, Carbon Oxide; CO_2, Carbon Monoxide; EEDI, Energy Efficiency Design Index; EEXI, Energy Efficiency Existing Ship Index; EnMF, Energy Management Framework; EnMS, Energy Management System; ESEEMP, Enhanced Ship Energy Efficiency Management Plan; FRCPSP, Resource-Constrained Project Scheduling Problem with flexible resource profile; FAHP, Fuzzy Analytic Hierarchy Process; FTOPSIS, Fuzzy Technique for Order of Preference by Similarity to Ideal Solution; GHG, Greenhouse Gas; GrSCM, Green Supply Chain Management; IMO, International Maritime Organisation; *I*4.0, Industry 4.0; JIT, Just In Time; LCA, Life Cycle Assessment; LCOE, Levelised Cost of Energy; LCOE, Levelized Cost of Energy; LNG, Liquid Natural Gas; MBM, Market-Based Measures; MRCMPSP, Multi-Mode Resource-Constrained Multi-Project Scheduling Problem; MRCPSP, Multi-Mode Resource-Constrained Project Scheduling Problem; NPV, Net Present Value; NPC, Net Present Cost (NPC); NOx, Nitrogen Oxide; OECD, Organisation for Economic Co-operation and Development; PPA, Power Purchase Agreement; RCMPSP, Resource-Constrained Multi-Project Scheduling Problem; RCPSP, Resource-Constrained Project Scheduling Problem; RE, Renewable Energy; RCA, Root Cause Analysis; SMART, Specific, Measurable, Achievable, Realistic, Time; SMG, Smart Grid; SMSS, Small Medium Sized Shipyards; SO_x, Sulfur Oxide.

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international shipping, consider a multidimensional approach to minimize the contribution of the shipping industry to global GHG emissions. IMO implements technical measures such as Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI), and operational measures such as the Enhanced Ship Energy Efficiency Management Plan (ESEEMP) to achieve its goal. Additionally, economic measures such as Market-Based Measures (MBM) are another criterion that may be considered by IMO soon for mitigation of emissions from international shipping [4].

In 2018, IMO adopted its initial strategy to mitigate GHG emissions from ships. The IMO aims to reduce the carbon intensity (CI) at least 40 % by 2030, and 70 % by 2050, compared to 2008; and to reduce the total annual GHG emissions by at least 50 % by 2050 compared to 2008, and pursuing efforts towards phasing them out as soon as possible [4]. To achieve the IMO's strategy targets, IMO adopted a planning tool in meeting the timelines. The IMO's initial strategy refers to a range of candidate short-, mid-long term measures to meet the targets. Short-term measures will be finalized and agreed upon between 2018 and 2023; mid-term measures, between 2023 and 2030; and long-term measures, beyond 2030 [5].

Ports play a key role in global logistics supply and serve as critical assets for states [6]. However, they have a negative impact on the environment and society [7]. The most direct air emissions from shipping occur in ports. As an example, it is 4–5 % for a container ship [6] and about 230 million people from 100 ports are directly affected by these types of air emissions, resulting in 3700 premature deaths in California [8] and burdening the 50 largest ports of the Organisation for Economic Co-operation and Development (OECD) with additional costs of 12 billion euros [9].

Ports have been identified as one of the key players in the IMO GHG strategy to accelerate the reduction of GHG emissions from industry, which can have a positive impact on the sustainability of cities [6]. Port development through infrastructure and supply chain optimisation has been identified as one of the potential short-term measures in the IMO's initial strategy for reducing GHG emissions from shipping [10]. In Resolution MEPC 323(74), the IMO urged countries to pay greater attention to the potential for reducing GHG emissions from ship and port interfaces. The resolution encouraged States to promote and facilitate the reduction of GHG emissions from ships in ports by providing shore-side electricity (preferably from renewable sources), safe and efficient bunkering of alternative and non-carbon emitting fuels, developing incentive schemes for sustainable and carbon-free shipping, and developing optimisation of port visits. Improving energy efficiency and reducing carbon emissions in ports can help improve urban sustainability [11].

Taking the above into consideration, the main focus of IMO is to reduce GHG from the operational phase of ships. However, other ships' life cycle phases, which are construction, maintenance, and dismantling are ignored. Although the major energy-consuming stage during ships' life cycle is the operation phase [12], due to fuel transition of new ordered vessels toward renewable power system, electricity, zero carbon fuel and cleaner fuel such as Liquefied Natural Gas (LNG) the contribution of the shipbuilding industry may be greater than the operational phase [13] and can even reach to more than 50 % of the cradle-to-grave CO_2 footprint in some cases [14]. For example, a hybrid ferry using electricity from the Norwegian grid has higher air emissions during the construction cycle than during the operational cycle [15]. In addition, the Yara Birkeland, the world's first zero-emission self-propelled container ship that can reduce CO_2 emissions by 1,000 tonnes and replace 40,000 trips by diesel trucks per year [16], has more air emissions during the construction phase than during the operational phase.

Shipbuilding is an energy-intensive industry and produces a significant amount of GHG emissions and air pollutants [17]. Air pollution can affect around 400 km of the surrounding area [2] and, as shipyards like ports are located in urban and coastal areas, the air emissions produced can affect human health in the cities and towns at risk. Based on Chatzinikolaou and Ventikos, [18], CO_2 emission in the construction phase contributes to 4 % of ships' life cycle emission, and this contribution reaches 29 % of ships' life-cycle emission for CO. With consideration of the construction phase contribution to emission within the ship life cycle emission, there is not any international regulation to monitor, control, and mitigate the emissions within the phase [13]. If it is aimed to meet the zero-emission shipping industry, a broader, holistic, systematic, and "cradle to grave" approach [19] with consideration of the lifespan of the ship from the design stage to scrapping must be taken into consideration [20].

There is a lack of studies on the reduction of carbon emissions and improvement of energy efficiency and the implementation of a sustainable concept in shipyard processes [21]. Not many shipyards have a holistic and systematic approach to optimising their energy networks, taking into account the interaction between each element. Since not many shipyards implement energy efficiency measures, this study has taken into account the energy management framework proposed by the authors in "Energy-related clean and green framework for shipbuilding community towards zero-emissions: A strategic analysis from concept to case study" [13] to optimize energy networks by considering their interactions in reviewing studies on improving energy efficiency, reducing air emissions and sustainability concepts in shipyards.

The novelty of the paper is classified into three categories: categorizing the shipbuilding energy sector by considering a holistic, systematic and interdisciplinary approach to the energy supply chain system, the energy economic system and the energy ecosystem and identifying the key disciplines for improving energy efficiency and promoting "zero emissions" for shipyards, and proposing measures and tools within each discipline and discussing their mitigation potential and key issues for improving energy efficiency and reducing air emissions from shipyard operations. In addition, the study presents the socio-economic and environmental benefits of the implementation of the proposed energy management framework in an Italian shipyard to prove the validity of the framework.

The study is structured in seven main sections, section 2 contains a literature review on energy efficiency improvement, air emissions reduction and sustainability concepts in shipyards and section 3 explains the methodology of the study, i.e. systematic literature review, semi-structured literature review, multi criteria decision making, and economic modelling. Section 4 describes and discusses the specificities of the energy sector in shipyards. The section identifies the boundaries and defines the systems within the shipyard energy sector. In addition, the section explains the need for systematic and transdisciplinary approaches in the shipyard energy cluster and identifies the disciplines that need to be considered in order to address the issue of reducing air emissions in shipbuilding. Section 5, which deals with results and discussion, summarises the potential measures and approaches classified in each discipline to reduce greenhouse gas emissions and air pollutants from shipbuilding. In addition, section 6 presents the potential of using hybrid electrification systems in shipyards. The example shows the techno-economic and environmental results of the use of a hybrid energy system in an Italian shipyard. Finally, conclusions are presented in section 7.

Literature review

The life cycles of ships include design, construction, operation and scrapping. The IMO, as an international regulatory body, seeks to reduce and control air emissions from the operational phase of shipping. The Organization has considered a multidimensional approach (technical and operational) to control and reduce air emissions from shipping and by introducing the first GHG emissions strategy, it sets out its priority for carbon reduction in the industry. The initial strategy aims to reduce total GHG emissions by 50 % by 2050 and improve carbon intensity by 70 % by 2050 compared to 2008 [4]. Although the majority of air emissions from shipping occur in the operational phase, due to ships switching to cleaner and carbon-free fuels, using renewable energy and other technologies to improve energy efficiency and reduce carbon emissions in the operational phase, the contribution of the construction phase to air emissions is predicted to increase [13,22]. It is therefore important to be proactive and to have a true zero emissions shipping industry, a broader vision and life cycle perspective must be taken into account.

Although the shipbuilding industry is an important driver of economic growth [23], it has significant oil, land, water and air pollution impacts. However, there are no international regulations to reduce, control and monitor these pollutants from shipyards. In addition, less attention is paid to investigating the sustainability aspects of shipyards both in academic disciplines and in industry [20]. According to Tantan and Camgöz-akdağ (2020) [21], there are only 27 papers focusing on the sustainability concept of shipyards.

Sanderson and Woo (2008) [24] explained the challenges of the choice of supply strategy in the UK marine shipbuilding industry. The paper emphasised that dichotomy is not effective in an industry such as shipbuilding, as projects require many different, largely functional, products to be put together in a unique or innovative configuration. Some studies investigated the layout design of shipyards to improve energy efficiency and lean strategies in the shipbuilding industry [25–28]. Lee (2013) [29] investigated sustainable development in small and medium-sized shipyards (SMSS) in Korea. The study suggested that non-competitive SMSS switched to another criterion, such as suppliers of sub-parts, repairs or maintenance. In addition, the author stressed the importance of government financial support to SMSS to overcome the economic barriers.

Lean-oriented occupational health and safety systems have been discussed in Babur et al. [30]. In the study, an OHS system was proposed through axiomatic design principles and implemented in shipbuilding industry. Green Supply Chain Management (GrSCM) and its importance for shipbuilding industry has been investigated by Caniëls et al. [31]. In the study, GrSCM readiness, competitive advantage and social responsibility were highlighted as the main drivers for implementing GrSCM. In addition, the implementation of Industry 4.0 (*I*4.0) can improve the green supply chain and lead to an improvement in the sustainability of the shipyard [32] and Lam (2015) [33] found green engines and machinery as the most important design requirement for green design of ships and highlighted the importance of a sustainable supply chain for shipping by focusing on customer requirements and also Jasmi and Fernando [34] highlighted that top management's commitment to green supply chain, appropriate regulations and safety has a positive impact on shipyard's sustainability.

The definition of green shipping and green ships and related regulations were discussed in Lee and Nam, [35]. The study identified six main barriers and four solutions were proposed I) establishment of a cooperation network for shipping and shipbuilding industry II) information sharing and joint cost reduction for shipping and shipbuilding industry III) shipbuilding industry investment in research and development of green ships, and IV) support for LNG powered ships to improve green shipping in South Korea and Zhou et al. [36] identified dust pollution, noise pollution and CO as the main sources of pollution in the shipyard environment.

India, Bangladesh, Pakistan, Turkey and China accounted for 96.64 % of the global ship recycling market in 2016 [37]. Yan et al., [38] presented the status of the Chinese and international ship recycling industry and discusses the hazardous shipbreaking materials and the impacts on the environment and humans. The study highlights that Chinese shipbreaking yards have greener technology in comparison with other South Asian countries, but the service price is higher than other South Asian competitors. Neşer et al. [39] investigated the "green recycling" capacity of one of the Turkish shipyards and Kusumaningdyah et al. [40] provided modelling of trade-offs in the shipbreaking industry to promote sustainability aspects in Turkish shipbreaking yards. The study observed trade-offs between losses and benefits in the shipbreaking industry with respect to economic, environmental and social issues. Hossain et al. [41] investigated the impact of shipbreaking activities on the coastal environment in Bangladesh. The study identified poor management practices and inadequate plans as the main causes of the shipbreaking industry's negative impact on the environment and suggested effective environmental management measures to mitigate the industry's negative environmental impacts. The sustainability of ship recycling in Brazil was investigated by Ocampo and Pereira, [37]. The study found that Brazilian shipyards are an environmentally and technically qualified industry, with an unused capacity of ± 900,000 tonnes per year and with a capacity of 340 vessels with an estimated market value of US$587 million over the next 25 years, there is a great potential for Brazilian shipyards to contribute to the global market.

Inadequate energy management was highlighted in Bangladeshi shipyards [13] a) and economic barriers were identified as the main barrier to improving energy efficiency and reducing air emissions from Iranian shipyards [42]. Vakili et al. (2022b) [43] analysed the application of smart grids in a shipyard and shows the socio-economic and environmental benefits of the technology for the studied shipyard and the Turkish shipyard by considering the replacement of the old equipment and using digitized technology strived to improve energy efficiency and reduce air emissions from their operations [20].

Hadžić et al. [44] investigated the use of renewable energy sources in shipyards and Neumann et al. [45] analysed the potential for the use of wave power from the sea in Portuguese shipyards. Castro-Santos et al. (2016 and 2020) [46,47] investigated the potential of using offshore wind power platforms in shipyards and Vakili et al. (2022b) [13] investigated the potential of using photovoltaic energy in an Italian shipyard. The use of data for maintenance and repair activities in shipyards and the implementation of *I*4.0 has been discussed by Mayo et al. [48] and Cil et al. (2013) [49]. In addition, the role of the material supply chain in improving energy efficiency was investigated by Praharis et al. (2020) [50] and Liesen et al. [51] examined the improvement of energy efficiency in naval shipyards, and the importance of the power grid and the use of flywheels in saving energy and improving energy efficiency in shipyards was discussed by Jeong et al. [52]. Given the extensive literature review the authors identified the following research gap in zero emission shipping industry:

- There is a lack of academic studies and discussion to improve the concept of "zero emission shipping" from a life cycle perspective.
- There are no holistic and interdisciplinary academic studies and discussion on the shipbuilding energy sector.
- There is a need for a holistic approach to discuss the potential of measures and tools to improve the zero emission shipbuilding industry.
- There is a paucity of studies demonstrating the socio-economic and environmental benefits of energy efficiency measures in shipyards.

Methods

To answer the research questions:

- What measures and tools can improve energy efficiency and reduce air emissions in shipyards? and
- How can measures and tools in five main areas improve energy efficiency and reduce air emissions in shipyards?

The authors used mixed research design (quantitative and qualitative) for several reasons. Firstly, considering mix methodology is a methodology triangulation, which increases the validity and credibility of the findings and the results of the study [53]. Secondly, the authors were aware that there is a lack of researchers on improved energy efficiency, reduced energy consumption and improved sustainability concepts in shipyards and that there are not many comprehensive and interdisciplinary qualitative studies in this area. The researcher therefore wanted to contribute to filling this gap at national and international level. Moreover, the authors chose a qualitative approach to provide an in-depth view of the potential of the measures and tools and the importance of systematic and transdisciplinary approaches to improve energy efficiency and reduce carbon emissions in shipbuilding.

Referring to the research questions, in order to collect and analyse the data, evaluate the validity and examine the accuracy of the evidence in the related topic, the authors decided to choose the best literature review methods among the methods, which are systematic literature review, semi-structured review and integrative review [54,55]. In order to achieve the best results with respect to the research questions, systematic literature review and semi-structured literature review methods were selected for research questions one and two, respectively.

Finally, the quantitative analysis was used for the case study. The Multi-Criteria Decision Making (MCDM) methodology was used to identify the yard's priorities in terms of reducing air emissions from its operations, and based on the identified priorities, a techno-economic analysis was carried out to identify the feasibility of using micro grids at the studied yard.

Systematic literature review

To identify measures and tools to improve energy efficiency and reduce air emissions in shipyards, a systematic literature review was conducted. The methodology was used to identify all empirical evidence, data and analyse them to answer the research question [56]. The method is useful to minimize bias and increase the reliability and replicability of the research and also provides reliable results for conclusions and decision making [57].

As Fig. 1 shows, the systematic literature review was conducted in six steps as follows:

Research question.

The research question in this section was "What measures and tools can improve energy efficiency and reduce air emissions in shipyards?".

Research protocol.

In view of the research question, a research protocol was developed. Table 1 shows the research protocol. Criterion one was to include protocols that considered high quality peer reviewed articles and books, conference papers, and industrial and technical reports. The second criterion was the exclusion protocol. Duplicated articles, low quality articles and industrial reports and those that could not answer the research question properly were excluded.

Table 1
Inclusion and exclusion criteria.

Criterion one (Inclusion)	Criterion two (Exclusion)
Peer-reviewed articles and high quality books, conference proceedings, industrial and technical reports.	Duplicate articles, low-quality articles, industrial reports and articles that could not answer the research question properly were excluded.

Literature search.

The authors have listed literature on and in practice for shipbuilding, as well as literature on other similar industries, such as ports, ships, marine manufacturing facilities, organisations and other energy-intensive industries associated with carbon reduction, environmental sustainability and energy efficiency. As highlighted in the "*research protocol*", the review focused mainly on academic peer-reviewed literature. Due to the fact that some criteria were not examined in the academic literature, grey literature was also included, such as conference papers, book chapters, international, regional and local reports, technical reports and project reports.

The online search for the keywords "shipyard", "green shipyards", "clean shipyard", "sustainable shipyard", "ship building", " environmental sustainability", "energy intensive", "energy efficiency", "energy barriers", " energy conservation", "energy policy", "energy management", "energy system", "renewable energy", "sustainable shipping", "sustainable ports", "port industry", "environmental performance", "reduction of air emission", "socio-technical", "interdisciplinary", "transdisciplinary" and " life cycle assessment in shipping" were found through searching in "Scopus" (abstract and citation database), "Science Direct" (repositories database), "Google Scholar" (search engines database), "Research Gate" (repositories database), "EBSCO" (repositories database) databases with respect to criterion one (Table 1). A total of 746 articles were selected in this section.

Studies per protocol.

As shown in Table 2, three filtering steps were applied to the selected articles from the "*literature search*" section. In the first filtering step, duplicates and unrelated literature were ignored. In this step, 223 literature articles were excluded. In the second filtering step, abstracts and conclusions were reviewed by the authors and criterion 1 was applied to the selected articles and 287 articles were excluded. Finally, in the third filtering step, 236 full articles were read and by applying criterion 2, 14 literatures were excluded. In addition, 16 articles were

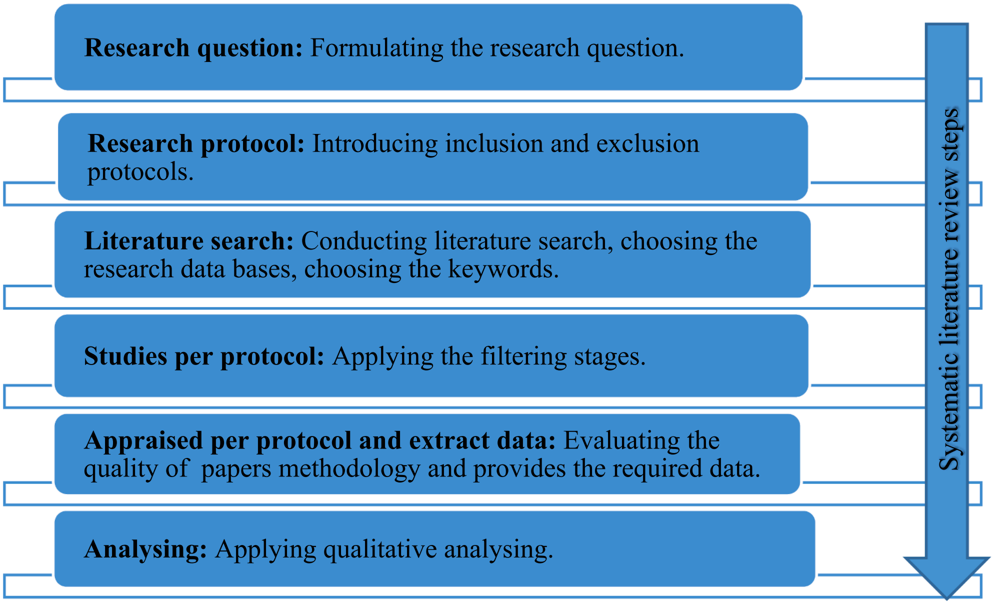


Fig. 1. The systematic literature review process.

Table 2
Filtering steps.

Filtering one	Filtering two	Filtering three
Excluding duplicates and other none related studies.	Abstract and conclusion scan, and application of criterion 1.	Full paper reading and application of criterion 2.

added to the list by applying the forward and backward snowballing method.

Appraised per protocol and extract data.

At this stage, the authors evaluated the methodological quality of the selected full articles to validate their reliability, replicability and validity to ensure that they met the protocol and topic criteria, and to confirm that the "*extracted data*" provide adequate information to answer the formulated "*research question*".

Analysing.

In this stage qualitative analysis was conducted on the extracted data and 19 number of the selected literature was excluded and 219 literatures with respect to limitation and strength of literature was interoperated to answer the "*research question*".

Semi-structured literature review

This method of literature review is useful for topics such as energy efficiency measures that have been discussed in different disciplines with different conceptualizations [58]. The semi-structured literature review considers discussions over time and presents the evolution of the conceptualization of the topic in different disciplines [59]. The method is usually performed qualitatively and is helpful to discover themes, theoretical and conceptual perspectives or common issues within a specific discipline [55]. In this study, this method is used to determine the characteristics of the energy sector at shipyards and to identify the integration and potential of measures and tools across disciplines to improve energy efficiency and reduce carbon emissions.

Online search for the measures and tools identified in each discipline in the previous section, i.e. systematic literature review, was conducted. Key words within each discipline are listed in Table 3. The authors attempted to find out through a semi-structured literature review how the identified measures and tools contributed to the reduction of air emissions from different industries, especially heavy industries such as steel manufacturing, cement, ports, mining, oil and gas, and how they can be used to reduce air emissions from the shipbuilding industry.

Table 3
Decarbonisation measures in each discipline.

Disciplines	Measures and tools
Human factor	• Training Corporate social responsibility Education Capacity building Awareness raising Research and development
Technology	• Industry 4.0 Smart grid and MicrogridRenewable energy (wind, solar, geothermal, bio energy, ocean energy) Carbon Capture Storage and Utilization (CCSU) Alternative and clean fuel (LNG, methanol, hydrogen, ammonia)Alternative power system (electrification, hybrid energy)
Operation	• Resource management Project management Lean approach Optimisation of shipyard design Equipment
Policy and regulation	• Life cycleEnvironmental management system (ISO 14001)Energy management system (ISO 50001) Circular economy Cyber security
Economic	• Economic indicators Economic analysis

Multi criteria decision making

The proposed framework is cross-sectoral and relies on fuzzy logic using different actors and supports decision makers to make an optimal decision in a complex situation [60]. The Multi Criteria Decision Making (MCDM) methodology has been used to identify the best measures and tools among the proposed options. As for the questionnaire designed to identify the priorities of the decision makers in the studied shipyard, the Fuzzy Analytic Hierarchy Process (FAHP) and the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) methods were used. The mentioned two methods are widely applied in various clusters [6,61] and are popular for creating frameworks in the energy sector [62]. The use of these methods helps managers to compare different options with respect to various criteria and rank them according to their preferences.

Economic model

After completing the first phase of the case study, i.e. identifying the yard's priorities for reducing air emissions from its operations, the techno-economic model used to evaluate the implementation of the micro grid at the studied yard. Four economic indicators considered to carry out the economic analysis. Net Present Cost (NPC), Net Present Value (NPV), Levelized Cost of Energy (LCOE) and initial capital cost [63,64].

Characteristics of energy sector in shipyards

This section presents a systematic approach to energy systems in the shipbuilding industry and discusses the need for an interdisciplinary approach to improve energy efficiency and reduce air emissions from shipyards. In addition, the disciplines for improving energy efficiency in shipyards are presented and the energy sector in shipbuilding is categorised.

Systematic perspectives on energy system in shipbuilding industry

Energy system in shipbuilding industry is a complex system and to solve a question in the subject of systems thinking, it is important to understand the variations, causes, effects and integration of elements within the system (Berry et al., 2018). Furthermore, in science and technology studies, energy is categorized within the sociotechnical system [65]. This means that in the socio-technical system, the technology and the surrounding environment have links and interconnections and to solve energy issues within a system, one must not only consider the technological solution but also the surrounding environments such as politics, regulation, operations, the human factor, economics, environmental issues, individuals and geopolitics [13,66].

In addition, innovation is crucial to solving the energy problem. Innovation is achieved through collaboration between different researchers with different disciplinary knowledge [67]. For different knowledge to interact, different researchers and scientists from different disciplines should have a relationship with each other. The extension of the relationship between a company's researchers with different disciplines with other disciplines is a competitive advantage for companies. It can lead to secure external resources, overall cost reductions and improves productivity and (energy) efficiency [68]. However, in order to form and improve the relationship and create new knowledge and innovation process, the boundaries of disciplines need to be broken and appropriate tools considered [69], which is called transdisciplinary approach (will be discussed in section 4.2).

In order to synthesize a complex system such as the energy system, it must be managed according to a systems approach [70]. The systems approach helps the researcher to manage complex systems by promoting interactions and relationships between the system's components within predefined boundaries. Since the systems approach is a bottom-up approach and considers the system as a whole, the researcher can consider the dynamic interactions between each component of the system [71] and can be applied at multiple levels (messo - masso - macro) simultaneously [13].

In order to reduce greenhouse gas emissions in the shipbuilding industry, the energy system within the shipyard must be identified, studied and managed and in order to solve any problems within the energy system, not only technical solutions but also the environment such as policy, regulation, operation, the human factor, economics, environmental issues, individuals must be considered [66]. Decision makers in shipyards to introduce energy management systems in shipyards need to develop a systematic approach. This means that they must identify the elements within the energy system and work out boundaries and linkages.

Is a systematic approach regarding energy system in shipyard sufficient?

System thinking in the energy sector of shipyards means, identifying and creating borders among the elements that are crucial and effective regarding the energy within the shipyards and understanding how different parts of the sector affect each other and the whole system [72]. Additionally, the energy sector within the shipyards requires that multiple skill sets to create a holistic view of the system and explain its behaviour.

Although the systematic approach has many advantages, it cannot answer all questions and fulfil the requirements within the shipyards' energy system. The main characteristic of a systematic approach is identifying the integration and interrelation of different disciplines in a large, complex, and global energy system [73]. However, identifying the integration and interaction among the energy system within the shipyards, which is a very complex environment with the engagement of various active actors, may lead to subjective errors. System thinking within the energy sector of shipyards is useful to identify the elements, disciplines, their association borders, and explain the existence of relationships and unexplained interactions that persistently appear in the energy system. However, it is more conceptual, and for more detail and precise analysis mathematical modelling or scenario building must be used [65].

Additionally, as in the shipyards energy sector various stakeholders with different priorities and benefits play crucial roles, to solve any related issues, various knowledge areas must be interacted to solve the shared problem. It means that in addition to a systematic approach, experts from various backgrounds have to break the silos and create a common language and consider a transdisciplinary approach within the shipyards' energy sector.

An interdisciplinary approach to energy system in shipbuilding industry

In the literature review, the authors found a lack of common language among sectors and stakeholders for analysing and developing energy sectors within the shipbuilding industry. The aims, tools, benefits, and measures of stakeholders such as business (shipyard owner, ship owner, charterer, cargo owner, etc.) are different from governments (administration, flag state, port state, etc.), and end-users are rarely aware of tools and measures of other sectors. In another word, there is a conflict of interest among the stakeholders in the energy sector of shipyards.

When there is a conflict of interest among stakeholders and if it is required to use different disciplines' expertise to solve any issue, the interdisciplinary approach must be taken into consideration [74]. Interdisciplinary approach develops integration collaboration among scientists in different disciplines [75]. The Interdisciplinary approach has two different levels, i.e. multidisciplinary and transdisciplinary [76]. Multidisciplinary is the lower degree of interdisciplinary, and in this type of approach the scientists from various disciplines do not break their silos and in parallel with another scientist by deploying their analytical tools, knowledge, methodology strives to solve the issue. However, in the transdisciplinary approach scientists break the silos, and they strive to create a common language, methodology, and analytical tool to solve the problem [77]. It means that in addition to the number and extent of knowledge in each discipline, integration among various disciplines must be taken into consideration. Transdisciplinary approach is useful when: (1) the issue's complexity is realized, (2) different stakeholders are engaged within the issue, (3) conflict of interest among stakeholders is existed, and (4) integration of different knowledge and disciplines is required to solve problems [69].

The energy sector within shipyards is a complex system [51]. The sector consists of the presence of various stakeholders, which each may have different priorities. Additionally, to solve any issue within the sector integration of different knowledge exist. In this regard, the best approaches regarding the energy sector in shipyards are systematic and transdisciplinary ones [76]. While the former is essential for identifying the elements and borders among them, the latter, that is, transdisciplinary approach identifies and utilizes the integration among the various disciplines to solve the issue.

Identifying the disciplines

The study considered a systematic and transdisciplinary approach to the energy sector within shipyards. Energy is categorized within the socio-technical system [65]. It means that to solve any problem not only technological solutions but also the environment and surrounding perspectives must be considered [78].

The authors, after a systematic literature review, divided the energy sector in shipyards into five main disciplines namely, the human factor, technology, policy and regulation, operation, and economics. It means that to improve energy efficiency and decarbonising in shipyards, five main perspectives must be considered. However, scientists and researchers in each discipline must follow the transdisciplinary approach. They have to break their silos and create a common language and methodology to solve the problem.

The energy transition can only take place in shipyards if does not only rely on technological and regulatory measures but also take people's decision-making and behaviour into consideration [79]. The human factor plays a crucial role in any organization. In the complex socio-technical system, the human factor must continuously redefine and be transformed by technological transformation [80]. Technology is the core of the socio-technology system and is crucial for sustainable energy transition within the shipbuilding industry. Additionally, the operation is a key player in general, and energy productivity and increase of energy efficiency within shipyards [48].

Furthermore, economic factors, indexes, and analysis play an essential role in many industries and decision-making for investment in energy efficiency [81]. Finally, policy and regulation as the main driver play a key role to accelerate decarbonising of the shipyards [82].

Categorization of energy sector in shipyards

Refer to the discussion in sections 4.1, 4.2, and 4.3 the authors categorized the energy sector in shipyards into three different systems (see Fig. 2):

- The energy supply chain system in a shipyard: It contains primary energy supply, distribution energy among equipment, production energy use, supporting energy use, and total energy use for production a ship. Additionally, the required technical and operational infrastructures and requirements, as well as human factor factors for

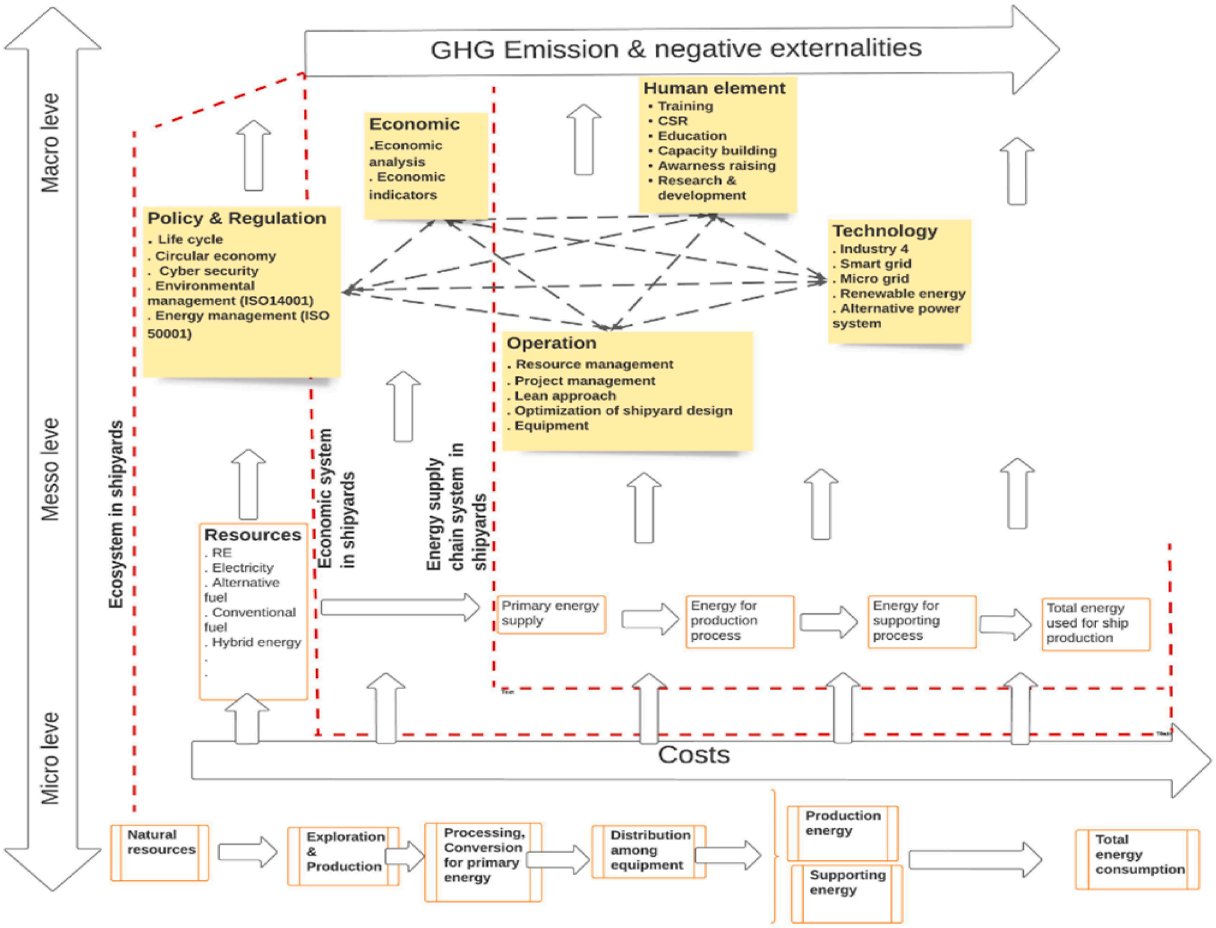


Fig. 2. The energy sector in shipyards.

the process are classified within this system. The system is nested in the economic system and ecosystem.

- The energy economic system in a shipyard: The economic system plays a crucial role in any type of systems. Likewise, shipyards' energy sector cannot exclude the economic system. Understanding and evaluating the market, policy and regulations, competitiveness, capital investment, various costs (capital, operational, maintenance, dismantling), identifying the priorities of shipyards' in economic decision making and types of indexes and analysis (Levelized cost of energy, cost benefit, life cycle cost etc.) will provide information about the energy system of shipyards. Various costs are associated in every stages from exploration and production till total energy consumption.
- The energy ecosystem in a shipyard is a broader vision and includes both the energy supply chain system and the economic system. The energy supply chain system and economic systems are nested in the energy ecosystem. The environmental and societal costs from using the natural resources are associated in ecosystem.

The human factor, technology, and operation disciplines are nested in the energy supply chain system, and economic and policy and regulation disciplines are placed in the economic system and ecosystem, respectively. Although each system is independent, they have interrelation and interlink, and the level of each system can be different from micro to macro-level [83]. The GHG emission and the related negative externalities are placed in the Macro level. Additionally, the level of influence of each system from outside (degree of openness) of the system is an important factor. While the energy supply chain and the economic system within shipyards are open systems, i.e. the systems are continuously affected by the activities, information of outer elements, the ecosystem within the shipyard is a close system. It means that the ecosystem on a larger scale is less influenced by the outer elements [84].

Discussion and results

Discussion

In the previous sections, the necessity of a systematic and transdisciplinary approach for decarbonising shipyards was highlighted. Additionally, the structure of the energy sector in the shipyard was divided into five main disciplines: the human factor, policy and regulation, technology, operation, and economics. Based on the literature review within the shipyards' energy sector, as well as the other similar industries' kinds of literature, measures and tools were identified and classified within the disciplines (see table and Fig. 3). Table and Fig. 3 show the measures and tools in each discipline that have the potential to mitigate GHG emissions and increase energy efficiency within shipyards. In this section, the potential of measures and their combination in decarbonising shipyards will be discussed.

Human factor

The importance of human factor issues has been addressed by the major stakeholders in the shipping industry. Personnel can play a crucial role to improve energy efficiency and energy productivity [85]. The human factor role in the decarbonisation journey should not be underestimated. Any actions for energy transitions depend on the human factor. In human factor discipline concerning characteristics of shipyards, training [86], corporate social responsibility [87], education

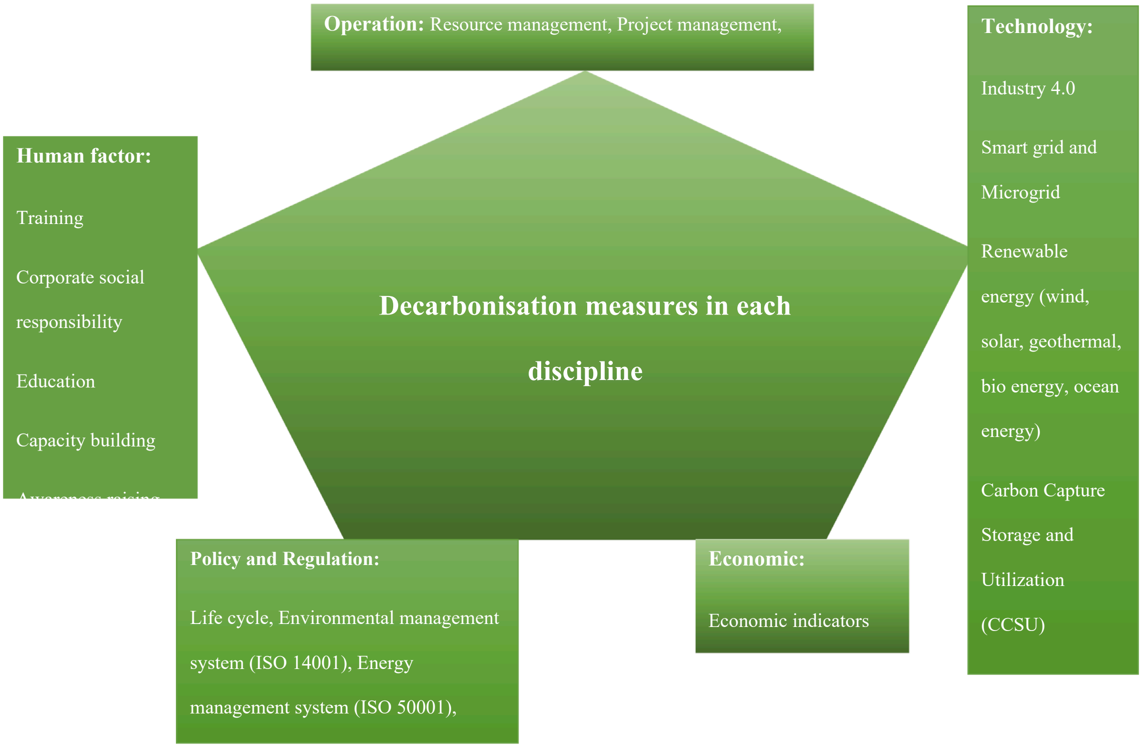


Fig. 3. Decarbonisation measures in each discipline.

[88], capacity building [89], awareness-raising [90], and research and development [91] were proposed.

The personnel behaviour must be adopted in the context of climate change and energy transitions [79]. To meet, the zero-emission shipbuilding industry, shipyards have to have significant changes in their energy sectors, such as using renewable energy, alternative fuels, new technologies, as well as adaptation with new and related (global, regional, local) regulations. To fulfil this transitional period human factor must be taken into consideration as they can play a key role in this transitional period [92].

Support of personnel to minimize energy consumption and improve energy efficiency in shipyards is crucial. Awareness-raising of personnel about climate change and necessity of emission reduction in shipyard activities, and their awareness about the positive consequence of their action in adopting energy efficiency practices such as healthier working place, energy productivity, reduce emissions, and economic benefits of the shipyard can be helpful in the decarbonisation of shipyards [93]. Additionally, Kemfert and Canzler (2016) [94] highlighted the role of training for the energy transition period. Taking shipyards into consideration, in the training of shipyards' personnel, new technologies, operational measures, policies, regulations, and social responsibilities must be considered.

Furthermore, as shipyards are considered as an energy-intensive industry, shipyards managers must address and highlight their social responsibility such as human and labour rights, stakeholder engagement, environmental performance, and social impacts [41,95]. There are three main potential motivating factors for responsibility in the energy sector; (1) internal drivers, (2) connecting drivers, and (3) external drivers [96]. Adopting corporate social responsibility as a response to social expectation and climate change in shipyards can lead to profitability, environmental commitment, climate change adaptation, promote the shipyards' reputation and competitiveness, and stakeholders' satisfaction [97].

Technology

Technology has a crucial role in achieving climate policy objectives [98]. In the technical disciplines concerning shipyards' characteristics, the study proposed digitalization (4th industrial revolution (*I*4.0)) [32,99], micro and smart grid [100,101], Carbon Capture Storage, and Utilization (CCSU) [102]. Additionally, the energy measures such as alternative and clean fuel [103], and alternative sources of energy such as renewable energy [44], electrification (battery, fuel cell, etc.) [104] were taken into consideration.

Industry 4.0.

Energy efficiency is the heart of the marine industry to reduce manufacturing costs, operational costs, and air emissions [105]. Industry 4 (*I*4.0) improves the energy efficiency between 15 % and 20 % [106], has a crucial role in decarbonisation of industries.

Deploying *I*4.0 technologies have a significant positive impact on shipyards' activities such as planning production, production engineering, supply chain, logistics, services, ship design, quality and efficiency, monitoring, operations, energy supply chain, as well as facilitating communication between shipyards and customer [107]. Implementing *I*4.0 technologies secure the continuous production of shipyards, and reduce types of machinery downtime by remote monitoring and prediction of the required maintenance. Moreover, it will enhance productivity by automation of the activities [32]. Furthermore, analysing the received data from sensors, (which are connected to types of machinery and different sectors) can lead to the reduction of inventories, improve the level of provided services, increase product quality, reduction of costs, and promote a lean system in shipyards [108].

Ships are designed and constructed based on the ship owners' requests, and each has its specific characteristics and feature [109]. Ship as a key player in the maritime cluster has to follow environmental regulations such as EEDI to reduce their carbon footprint. Appropriate ship design has a significant impact to attain the required EEDI [110], and reduction of ships' emission in the operational phase. With more powerful computers, utilizing simulations, and *I*4.0 associated technologies, shipyards can produce more efficient, cost-effective, and innovative ships [105]. However, within *I*4.0 contexts, shipyards become vulnerable to cyber-attack, and cybersecurity can play a crucial role in preventing the loss of companies' competitiveness [111].

Smart Grid.

For decarbonising of shipyards, the managers must control and manage the shipyards' energy supply chain appropriately. Electricity with a high range of contributions for ship production has a crucial role in the energy supply chain in the shipyard, and its role will be dominant by the advent of new technologies.

*I*4.0 infrastructure is essential for promoting smart shipyards [112]. Smart Grid is an automated electrical energy system, which by utilizing sensors and monitors, and thorough analysis of the data can automatically control and manage the electricity flow among users and stakeholders, and provide a sustainable, cost-effective, and reliable electricity supply [113]. In addition to the high cost that needs to invest to use smart grid in shipyards, such as information technology infrastructure and safety and security measures [114], the cyber-attack is an important challenge that must be taken into consideration [13].

Furthermore, as there are different types of sources of energy such as Renewable Energy (RE), fossil fuels, fuel cell, micro turbine, and energy storage system can be used in the energy supply chain system of shipyards [13], the Virtual Power Plant has provided the opportunity to integrate their operations to optimal energy management in shipyards energy supply chain system [115].

Micro grid.

The shipyards are needed to receive and provide adequate and various types of energy within their energy supply chain system. Different types of cranes, forklifts, vehicles, trucks, air compressors, winches, pumps, cutting, bending, and welding equipment are used in shipyards [116], which each may use different types of energies. However, electricity plays a crucial role in shipyards' energy supply chain.

Micro grid by decentralizing electricity sources can control the distribution of electricity sources and connect to the macro grid (it is usually a national grid) or act autonomously as "Island Mode" [117]. The micro grid provides the opportunity for shipyards' decision-makers to have more options of energy sources in their energy supply chain. Additionally, they can trust more on RE and its combination with other sources such as fossil fuel generators, and cogeneration or combined heat and power (CHP), as well as their integration with Battery Energy Storage Systems (BESS) [118].

By implementing micro grid and BESSs, shipyards can generate more cost-effective and sustainable revenues from the sale of additional electricity to the governments or other users [13] b). Utilizing micro grid enhances the energy security of shipyards by providing required energy at high peaks, as well as in the time of a loss of grid supply, and protect the shipyards' productivity [118]. Additionally, the net energy costs within the shipyards' energy supply chain would also be mitigated due to revenues from the provision of energy to the national grid or other end users [119].

Renewable Energy.

Renewable Energy (RE) has a non-trivial role in industries' decarbonisation [120]. The transition from the current energy supply chain system in shipyards towards a sustainable one requires renewable energy technology. Depends on the location, shipyards can utilize different types of RE i.e. wind, solar, geothermal energy, bioenergy, and ocean energy. Using RE has a significant impact on the mitigation of carbon footprint [44] from shipyards and accelerates in sustainable energy transition within shipyards' energy supply chain system. Additionally, the integration of RE, micro grid, and BESSs can enhance energy productivity and sustainable income for shipyards. Lack of space for installation of the technologies and cost are the most challenging is utilizing RE in shipyards [121]. However, due to improving technologies, economies of scale, competitive supply chains, and improving developer experience, the renewable power generation costs have fallen sharply over the past decade, and it is expected to decrease continuously [122].

Wind.

Wind turbine transfers the wind kinetic energy to mechanical rotational motion and then to electricity. The annual average wind speed is an important factor for utilizing the wind turbine. If the annual average of the wind speed in shipyards' locations is more than 5.6 m/s, the location is suitable for wind turbine installation [123]. Similar to the PV system, shipyards have space limitations for the installation of the onshore wind turbine. However, offshore wind farms' sizes are too big to integrate with shipyards' micro grid. Therefore, the shipyards can make a Power Purchase Agreement (PPA) with offshore wind farm authorities to provide them with their required energy [124]. In addition to space limitation for installation of the onshore wind turbine, the cost of installation of the wind turbine is also another challenge for shipyards' energy economic system. Although in 2020, the global average levelized cost of energy (LCOE) from onshore wind and offshore wind declined by 13 % and 9 % respectively in compared to 2019 [122], the installation cost is a crucial challenge in shipyards' energy economic system.

Solar.

Solar PV technology converts the sun's radiation light into electricity. As the power output from a solar PV depends on solar radiation incidents on the PV module surface [125], the amount of harnessed power depends on the location of shipyards, as well as seasons [126]. The PVs can be considered in the micro grid as one of the sources of energy, and the harnessed energy can be used for heating buildings, workshops, warehouses, and supply hot water. Although International Renewable Energy Agency (IRENA) reports that the global weighted-average LCOE of solar PV fell 85 % between 2010 and 2020 [127], the installation cost is an important challenge in shipyards' energy economic system. Additionally, the installation of PV systems requires sufficient space; however, due to the lack of space in shipyards, PVs can install on the roof of buildings, workshops, and warehouses [128].

Geothermal energy.

Geothermal energy is the source of renewable heat that exists on the earth's surface. Geothermal power plant technology and/or direct use applications [129] can consider as energy sources within the ship yards' energy supply chain system to assist in the sustainable energy transition from fossil fuels to RE and reduction of shipyards' carbon footprint.

Geothermal energy can use to produce electricity [130], as well as used to directly deploy heat in industry, households, regardless of meteorological conditions [131]. Depending on the geographical zone, shipyards may use the energy directly or use it to produce electricity, which both ways of utilization can increase the standard of working of shipyards and living of communities around shipyards. Based on [132], the hybrid configuration of the energy can deploy for electricity production along with heat, air conditioning, refrigeration, drying, evaporation, and district heating.

Bio energy.

Sustainable production of biomass as a renewable source of energy can help to meet the Paris Agreement goals [133]. Power generation from bioenergy can achieve from a wide range of feed stocks, and various combustion technologies can be used. The matured and commercialized technologies are direct combustions in stoker boilers; low-percentage co-firing; anaerobic digestion; municipal solid waste incineration; landfill gas; and CHP [134,135]. The total installation cost depends on technology and a local cost component, which is different. While the project in developing countries has lower investment costs due to lower labour and commodity cost, the project in the OECD countries is more expensive [127]. Although the CHP biomass plant has higher capital costs, it has the highest efficiency (80 % to 85 %) [122] and can produce heat and/or steam for water and space heating for shipyards.

Based on IRENA, 2021 [122] RE cost report, the cost of the biomass plant depends on design (planning and engineering), infrastructure (construction, civil work, road, etc.), logistic (fuel handling), as well as grid and infrastructure connection. Bioenergy due to its low capital cost and low-cost feed stocks can provide electricity with LCOE as low around USD 0.04 /kWh, and it can reach USD 0.03/kWh in CHP systems. Concerning low capital cost, high efficiency (especially CHP), as well as providing the plant's fuel from shipyards' waste, bioenergy has a good potential to consider in shipyards' energy supply chain system. Additionally, the CCSU system can provide the biomass system with the required carbon for producing methanol [136]. The integration can assist in providing shipyards' energy supply chain system with alternative fuel and promote circular economy concept within shipyards. This approach assists in closing the loop of shipyards' energy supply chain system.

Ocean energy.

Ocean energy is harvested on a narrow scale from ocean waves, tides, salinity, and ocean temperature differences [137]. The bare harvesting of ocean energy is because of the development, and conceptual stage of technology [138].

The hydrokinetic devices, which are used to harvest energy from current, and tide are reached at a high readiness level [139]. There are three types of hydrokinetic devices; axial-flow, cross-flow, and oscillating systems [140], which are usually installed near-shore, off-shore and on-shore locations [141]. The predictability of sea current and tides makes the technology design more simple and attractive. However, sea fouling and creating underwater noise are negative impacts of the technology [124].

The Wave energy converters' principle is different from hydrokinetic devices. It is classified into three different types of oscillating water columns, oscillating body systems, and overtopping devices, which each has a different interaction with the wave motion (heaving, surging, pitching) [142]. In contrast to tidal energy converters, random variability of wave scale is a disadvantage of this type of energy converter [143].

Different types of ocean energy devices are used in Canada, China, France, Japan, South Korea, and Spain [44]. However, due to high investment and maintenance costs, low technology readiness levels, and relatively immature compared to solar and wind energy technology [141] deploying the technology may not be a realistic and appropriate solution to consider in shipyards' energy supply chain system.

Carbon Capture Storage and Utilisation.

Carbon Capture and storage (CCS) can play a significant role in global decarbonisation [144,145]. The technology deploys at different levels for capture, transport, storage, and utilization of CO_2 [146]. Carbon Capture Utilisation (CCU) gain more attention due to climate change mitigation as a societal issue [147].

Bioenergy with carbon capture and storage (BECCS) is a CO_2 mitigation technology that utilizes the combination of both bioenergy and CCS technologies. The BECCS is a suitable technology for sectors such as, aviation, shipping, iron, and steel that due to economic, technical, and political restrictions, have challenges to reduce emissions from their sector [102]. In this technology, the required CO_2 of the methanol and/or ethanol plants can provide from the CCS technology [148]. Shipyards decision-makers may consider BECCS within their energy supply chain system. However, lack of space, cost, and lower technology readiness level [149] of the technology compared with other technologies are the main challenges for considering it within the energy supply chain in shipyards.

Alternative cleaner fuel.

Alternative cleaner fuel plays a crucial role in the decarbonisation of transportations, industries, and power generations [150]. Shipyards, based on their characteristics, capacity, resources, and location, may use any types of alternative fuels or even a combination of them within their energy supply chain system.

Liquefied Natural Gas.

To meet stricter environmental regulations, the maritime industry needs clean, reliable and affordable alternative energy sources. Although Liquefied Natural Gas (LNG) cannot fully decarbonize the industry, its low price and its ability to mitigate SO_X (more than 90 %) and NO_X as well as a capability to 25 % reduction of CO_2 make it a suitable transition fuel for decarbonisation of the industry in comparison to other types of alternative fuels [151,152]. However, due to its methane slip, the potential of CO_2 reduction decreases dramatically [153]. The combination of LNG with liquid biogas increases the potential of LNG to reduce air emissions [154]. To have LNG in the list of clean fuels, it is necessary to decarbonize methane with decarbonisation technologies such as CCS [155]. In shipyards, LNG can be considered within the energy supply chain system to provide energy for equipment, cranes, vehicles, and trucks.

Methanol.

The increased use of methanol in various industries, the ease of storage and distribution arrangements and the potential for production of the fuel from renewable energy have made methanol a popular alternative fuel in industry to meet stringent environmental regulations [156]. The increase use of Methanol as an alternative fuel can reduce the different types of regulated emissions in both industry and transportation domains. Methanol does not have any sulphur, has a very low Particulate Matter (PM), and emits around 20 % lower than conventional marine fuel oil carbon dioxide [157]. Tian et al., 2020 [158] analysed the use of methanol in fuel mixture format and emphasized that green methanol as fuel results in decreases in well-to-wake CO_2 emissions compared to fossil fuels.

Additionally, producing methanol through RE energy (green methanol) and utilizing BECCS technology can assist in closing the loop and promote a circular economy within the shipbuilding industry. Methanol can be nominated as an appropriate source of energy for the transition toward cleaner production in shipyards and use as fuel to supply energy to equipment, vehicles, cranes, trucks.

Hydrogen.

Hydrogen (H2) is not only an important chemical in industries such as ammonia production, refineries and bulk chemicals, but also an important source of energy that can be used in various industries [159,160]. Hydrogen is produced by chemical reactions that separate it from water or hydrocarbons and there are different ways to produce hydrogen. Depending on the type of reactions and sources of hydrogen production, there are different colour codes. Brown hydrogen is produced by coal gasification and grey hydrogen by steam reforming reaction using natural gas. If the emissions from grey hydrogen are captured it is called blue hydrogen and if it is produced from renewable energy sources for electrolysis it is called green hydrogen [161].

Hydrogen technologies and fuel cells due to environmental issues, fossil fuel scarcity, and energy security problems are some of the most interested and improved solutions for decarbonising industries and maritime clusters [162]. The H_2 fuel cells generate electrical energy without the emission of CO_2. Additionally, it can use as storage for excess RE such as wind and solar and blend with natural gas for heating and decarbonisation of energy intensive industries [163,164].

Additionally, green H_2 (can produce from RE and any bio-based fuel such as methanol and ethanol) meets certain sustainability criteria [159,165]. Taking the above into consideration, shipyards in their long-term energy strategy, can use H_2 in their energy logistic supply chain system and even generate H_2 to act as an energy hub in the region.

Ammonia.

Ammonia is considered an ideal carbon-free energy carrier and is also an important medium for the storage and transport of hydrogen. The superiority in long-distance transport and easier storage, which are the main obstacles for hydrogen, make it a popular future energy source [166].

Ammonia is considered an important and sustainable fuel for the decarbonisation of heavy transport, power generation, and energy-intensive industries [167]. While other liquefied energies such as liquid H_2 and methanol require a concentrated source of CO_2 in technologies based on carbon dioxide reduction, and each needs to be considered in terms of its relative utility and safety, ammonia has the potential to consider as the RE sourced fuel of the future [168]. Based on

MacFarlane et al., [169] there are three generations of technology exist for producing ammonia. Generation one technology which is called “blue economy” uses carbon offsets technologies to decarbonize ammonia production. Generation two technology is renewable ammonia, which employs renewable H_2 rather than fossil fuel sources. Generation two technology has the advantage that existing plants can be transitioned to this new hydrogen supply without major disruption. Generation three technology refers to the electro reduction of N_2 to ammonia by direct or mediated means. Concerning ammonia’s potential, shipyards’ decision-makers may consider ammonia with their energy supply chain system as a sustainable source of energy to transition to a zero-emission industry.

Alternative power system.

Electrification and hybridization are two other sources of power that may be considered in shipyards’ energy supply chain system. This measure provides the opportunity for shipyards to reduce their carbon footprint and mitigate their dependency on fossil fuels. This approach helps for sustainable transition for shipyards’ decarbonisation.

Electrification applies in many operations in shipyards [170] and provides the industry with a cleaner energy concept. Additionally, considering a battery as an energy storage device can assist shipyards in a sustainable transition to a cleaner source of energy. However, to reduce environmental pollution life cycle assessment must be conducted to interpret the environmental impact of batteries. Battery electric energy can use in shipyards’ energy supply chain system for providing the required energy to cranes, vehicles, trucks, forklifts, and types of machinery such as bending machines.

Due to conventional energy scarcity and to meet the global warming goals, hybrid energy harvesting has been paid attention in recent years [171]. Hybrid energy does not only mean scavenging energy from various types of energy but also means various mechanisms to convert energy to electricity [172]. Hybridization supports shipyards’ energy supply chain with different sources of energy. Integration of hybridization with micro grid systems and BESSs can promote shipyards’ energy security, energy efficiency, and energy productivity, and accelerates the sustainable transition of shipyards toward decarbonisation. Trucks, cranes, vehicles, and various pieces of machinery may use hybrid energy to accomplish the shipyards’ operations.

Integration.

Following the above discussion, Fig. 4 shows the interrelation among the technologies. Smart grid can be the centre of electricity management in shipyards. The orange arrows represent the information flow among smart grid, national grid, micro grid (combination of the power plant, RE, and conventional generators), BESS, and end-users (vehicles, cranes, trucks, forklifts, equipment, buildings, etc.). The red arrows show the electricity production and its flow. The produced electricity from different sources (RE, power plant, conventional generators) can be supplied directly to end-users or saved at BESS. The system can be managed and control by smart grid. In addition, the supplied electricity can be controlled by Virtual Power Plant and operated in island mode through the implementation of micro grid.

The conventional fuel or shipyards’ waste may be used as the primary sources of fuel for the power plant. The end-users can use the produced power directly, and shipyards can produce the blue H_2 (blue arrow) by gasification. Additionally, if they use and integrate with CCSU technology, they can produce e-methanol.

Furthermore, shipyards can produce the green H_2 (green arrow) by considering electrolyzing the RE electricity, and by the combination of H_2 with nitrogen, they can make ammonia. The cycle can be closed by the production of H_2 through the electrolysation of liquid ammonia, which has high hydrogen capacity.

The produced fuels can use in different activities and support intermodal transportation (ship and train) with clean fuels. Additionally, shipyards can provide clean fuels to other sectors and industries, and act as a hub of energy. The produced clean fuels ammonia, H_2, and e-methanol can secure the sustainable transition of shipyards toward a zero-emission industry and support shipyards’ energy supply chain system.

Operation

Efficient operations assist in the reduction of GHG emissions from shipyards’ activities [20]; however, controlling the operational cost is one of the challenges in shipyards. The appropriate operation has a significant impact in increasing productivity and efficiency, as well as

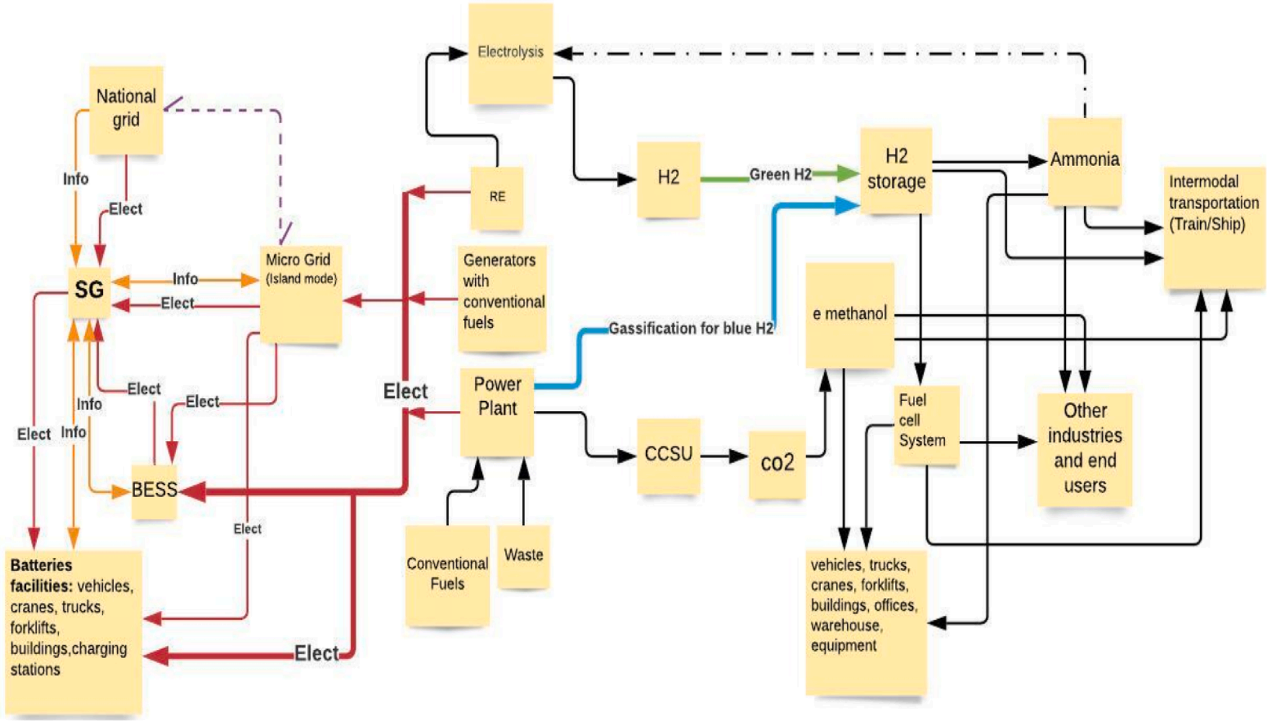


Fig. 4. Integration of technologies in shipyards.

reduction of costs [173]. In addition, promoting operational measures in shipyards leads to reduction of labor costs and production time, which are the main elements in improve of shipyards' productivity [174].

Resource management.

Compared to other industries, the construction industry has lower productivity [175]. Shipbuilding is a complex activity that dealing with different projects, and each project and tasks compete for restricted resources [176]. Resource management has a crucial role to prevent cost overruns and schedule slippage [177] in the shipbuilding industry. Implementation of appropriate resource management can reduce project duration and costs in shipyards operation.

Resource management is classified into different categories of Resource-Constrained Project Scheduling Problem (RCPSP), Multi-Mode Resource-Constrained Project Scheduling Problem (MRCPSP), Resource-Constrained Multi-Project Scheduling Problem (RCMPSP), Resource-Constrained Project Scheduling Problem with flexible resource profile (FRCPSP), and Multi-Mode Resource-Constrained Multi-Project Scheduling Problem (MRCMPSP), which each can promote the project's productivity [178]. Choosing and implementing the appropriate resource management can assist in improving the energy efficiency and energy productivity of shipyards and support them in sustainable transition to decarbonising the industry.

Project management.

Shipbuilding is a large and complex project-based industry [178], and shipyards conduct several projects simultaneously [179]. Due to limited key resources (such as docks and quay) and their direct impacts on shipyards' productivity, the role of appropriate project management is highlighted to guarantee continuous production without or minimum delay. Additionally, project management helps to identify the risks and assess the risks within high budget and long-term ship construction projects [143].

Implementing appropriate project management requires sufficient data and the development of an information management system. Implementing appropriate project management promotes inefficient use of shipyards' resources, increases shipyards' productivity, and prevents any delay within the shipyards' activity [180]. Additionally, it supports shipyards' economic and energy supply chain system and assists in sustainable transition toward a decarbonized industry.

Lean approach.

Implementing a Lean system is an essential tool to improve performance in shipyards [181]. Lean production refers to the elimination of waste and non-value-add processes within shipyard operations and supply chain to improve the customers' satisfaction and increase productivity [182]. Implementing a lean system assists in sustainable transition toward a zero-emission shipbuilding industry. Simultaneous execution of six tools of the lean system in different sections enhances efficiency and productivity improvement in shipyards. The lean system's tools are classified to:

Just In Time (JIT).

Just In Time (JIT) refers to receive and produce the materials only when needed. The concept highlighted that reducing the waste (within the capacity and inventory) and cutting any non-added value processes in the appropriate time assists shipyards to be more efficient and productive [183]. Implementing JIT within shipyards' operation processes promote their energy supply chain system.

Kaizen.

Kaizen is a Japanese phrase that emphasizes continuous improvement. Implementing the lean approach can continuously identify the area needed for improvement within their operations and activities. This leads to increasing the shipyards' productivity and quality [184].6S Refers to Japanese terms, which each begins with S (sorting, straightening, shining, safety, standardizing, and sustaining). Implementing 6 S helps shipyards in performing lean systems [81].

Corrective and Preventive Actions.

Corrective and Preventive Actions (CAPA) is a method to minimizing human errors. Implementing the CAPA process assists shipyards' decision-makers to identify and eliminate any errors, non-conformities from the system [185]. The CAPA can improve the energy supply chain system and economic system of shipyards, and support them for a sustainable transition to a zero-emission industry.

Root Cause Analysis.

Root Cause Analysis (RCA) is essential to identify the problem and non-conformities source. It helps to prevent the reoccurrence of the same non-conformities and problems [186]. This approach will improve the efficiency and productivity of shipyards.

Specific, Measurable, Achievable, Realistic, and Timed Objectives.

Choosing Specific, Measurable, Achievable, Realistic, and Timed (SMART) objectives is essential to observe the improvement of any organization. Depends on shipyards' characteristics and features, managers have to choose appropriate SMART objectives for each sector and system [187]. Identifying SMART objectives in shipyards' energy supply chain system helps managers to monitor their improvements in transition toward a zero-emission industry.

Optimizing the shipyard design.

Appropriate design and layout of shipyards can promote efficiency and productivity in shipyards. Shipbuilding is a complex project and requires accurate planning, controlling of the project, which contains different tasks such as order, design, purchase, procurement, and production [188].

The starting point of ship construction is in a shipyard. Shipyards' models and layout play a crucial role to implement the lean system, which can enhance efficiency and productivity. For the construction of a shipyard, four kinds of engineering, which are civil, building, utility, and production layout are required [189]. The production layout is the most important part of shipyards' design as it acts as the foundation of other engineering parts. As the yard area plays a crucial role in the productivity and efficiency of shipyards, the layout determines the shipyard capacity from a life cycle perspective [190].

The most efficient and productive design and layout concerning shipyards' resources and features must be chosen at the early stage of shipyards' construction, as it is difficult to change the design and layout of shipyards in their life cycle. In addition, the designer must consider appropriate design and space for utilization and integration of new and future technologies such as CHP, micro grid, biomass plant, RE, CCSU, and alternative fuel infrastructure.

Furthermore, improving the intermodal transport must be taken into consideration. Providing the resources and materials to shipyards through rail, barges, and ships is an important step to reduce CO_2 [191] from shipyards activities.

Equipment.

Shipyards focus on avoiding downtime and delay in handover the product and be sure about the quality of ship with right price [192]. Utilising appropriate equipment can accelerate shipbuilding process and minimise the downtime and delay and increased productivity in the shipbuilding industry. Utilising more effective, efficient pollution abatement equipment [193], such as plasma cutters, welding machines, cranes, furnaces, and sheet-metal rollers can promote the sustainable transition to a zero-emission shipyard.

There are various methods to improve the efficiency and productivity of equipment in shipyards. The first method is the Modernization of equipment with replacement of old equipment with new, modern, and automated equipment, which is more productive and efficiently such as welding machines [194]. The second method is retrofitting by adding new features, such as sensors and modern technologies to monitor and control the emissions [195].

Policy and regulation

The shipbuilding industry strives to develop environmentally friendly shipbuilding technologies with the cooperation of other related organizations and stakeholders [196]. However, to accelerate and support the sustainable transition to zero emissions industry, the adoption and implementation of appropriate policies and regulations are crucial.

While IMO as the international policymaker for international shipping focuses on decarbonising the operational phase of the shipping industry, to decarbonising the shipping industry a broader and life cycle perspective must be considered. Therefore, international regulations for the decarbonisation of shipbuilding industries must implement. Additionally, addressing the GHG emissions from shipyards requires regional [100] and national commitments [197]. Some of the important regulations and policies that can help shipyards to mitigate their GHG emissions are listed as follow:

Life cycle.

To decarbonising industries, a life cycle perspective must be taken into consideration. This helps to better evaluation of the abatement measures, and include the indirect emissions in producing the materials and productions [198]. For example, alternative fuels play a crucial role in the energy supply chain system of shipyards to reduce the environmental and climate impacts of shipbuilding activities. However, to evaluate their potential for mitigation of GHG emissions, a life cycle analysis must be conducted. Considering the life cycle thinking assist in exploring the efficiency and total emission of each option in a broader vision [199]. To have a sustainable transition toward a zero-emissions shipyard, the life cycle thinking must be considered in any operations and in defining the border of shipyards' energy supply chain system.

Environmental management and Energy management systems.

Considering and implementing environmental management system (ISO 14001), and energy management system (ISO 50001) can support the sustainable transition toward zero-emission shipbuilding. Environmental management (ISO 14001) is an improved tool for sustainability. ISO 14001 is an international standard to identify the environmental aspects systematically and managed properly for better environmental performance [200]. Shipbuilding is an energy-intensive industry with a significant amount of environmental pollution [17]. Considering Environmental Management System (ISO 14001) (EMS) within the shipyard's activities can reduce the shipyards' environmental footprint.

Additionally, ISO 50,001 is a standard to guide the adoption of an Energy Management System (EnMS), which is estimated to influence up to 60 % of the world's energy industry [201]. As shipbuilding is an energy-intensive industry, ISO 50,001 is a powerful tool to improve the energy performance in shipyards.

Furthermore, ISO 50,001 within the energy supply chain system of shipyards provides both operational and economic benefits in terms of time, efficiency, flexibility, costs, quality, general and energy productivity, and optimization [202].

Circular economy.

The circular economy (CE) concept is a popular approach by the EU, as well as many other countries such as Canada, China, Japan, and the USA [203]. The CE concept promotes the materials cycle in a modern way and enhances sustainable production and consumption [204]. It is estimated that CE produces 600 billion Euros of annual economic gains from the manufacturing sector [205]. However, the concept of circular economy is not very well established in the maritime industry [206], especially in the shipbuilding industry. It is crucial that the shipbuilding industry considers "close to loop" to minimise waste and increase shipyard revenues. Implementing the CE concept in shipyards can save materials, energy resources, costs, reduce waste [207] and support sustainability in shipyards [21] and accelerate the transition of shipyards to a zero-emission industry.

Cyber security.

*I*4.0 is the 4th industrial revolution, and it plays a crucial role in improving the energy efficiency of industries [105]. In addition, the information system is becoming important in the maritime sector and like other aspects of maritime business [208], the shipbuilding industry is also undergoing a digital transformation. Shipyards are using *I*4.0 technologies, such as digital twinning, in both the operation and construction phases, which increases the efficiency, productivity and effectiveness of shipyard operations [107] and even the safety of shipbuilding industry depends on cyber systems. However, cybersecurity is a complex issue for companies relying on the *I*4.0 industry [209]. To prevent shipyards from losing their competitiveness due to cyber-attacks, they need to consider cybersecurity in their context and policies.

Economic

As discussed, energy is a socio-technical system, and to solve any issues within the energy context, the surrounding, and various aspects must be taken into consideration. The economic system plays a crucial role to solve the problems within the energy aspects in shipyards [210].

Choosing the cost-effective energy efficiency and decarbonising measures within shipyards' energy supply chain system promotes shipyards' activities in both economic and in reduction of negative environmental impact. To meet the targets shipyards' decision-makers must consider both environmental and economic indicators [211].

Various economic factors, indicators, and analyses such as capital cost [212], finance [213], Life Cycle Analysis (LCA) [214], life cycle cost [215], LCOE [46,216], cost-benefit analysis [217], cost of energy [84], maintenance cost [218], and societal and environmental costs [219] may be taken into consideration by shipyards decision-makers to choose the best available GHG mitigation measures. Choosing the best analysis and indicators depends on the technologies, measures, and priorities of the shipyards' decision-makers team.

Taking the above into consideration, trade-offs among the economic system, energy supply chain system and ecosystem in shipyards' energy sector is crucial. The trade-off promotes the shipyards' competitiveness on a national, regional, and global scale. In addition, it can secure shipyards' benefits in alignment with a sustainable transition toward a zero-emissions industry.

Results

In order to validate the potential of the proposed framework and the suggested measures and tools to reduce air emissions and improve energy efficiency in shipyards, the proposed framework has been applied to an Italian shipyard. The socio-economic and environmental results of the case study are presented in this section.

Use of hybrid energy systems in shipyards

The Italian shipyards have been considered as a case study to implement the proposed framework, taking into account the discussion in the discussion section. The yard builds merchant ships, passenger ships, offshore vessels and naval vessels and is also active in ship conversion and repair. In the first step, the FAHP and FTOPSIS methodologies were used to identify the yard's decision-makers' priorities in terms of reducing carbon emissions from their operations. The proposed framework has been applied to the shipyard and as Table 4 shows, the

Table 4

Priorities for shipyard decision-makers to improve energy efficiency and reduce carbon emissions from shipyard operations.

Disciplines	Alternatives	closeness coefficient (Ci*)	Ranking
Human element	Capacity Building	0.4796177	4
	Corporate Social Responsibility	0.4478793	5
	Research and Development	0.4440906	6
Technology and Innovation	Renewable Energy	0.5311721	1
	Digitalization	0.5311721	1
	Alternative fuel	0.3170993	11
	Electrification	0.5154256	3
	Changing the old EQP	0.5154256	3
Operation	Resource Management	0.5260930	2
	Optimum shipyard design	0.4257986	7
	Prodution planing	0.4257986	7
Regulations and Policy	ISO 50,001	0.3918515	8
	ISO14001	0.3839696	9
	Voluntary agreement	0.3359675	10

shipyard's decision makers are interested in using renewable energy and digitalisation in their energy system.

In the second step, a feasibility study was carried out on the use of hybrid energy systems at the yard, with reference to the priorities of the yard's decision-makers. The economic system plays a crucial role in accelerating the reduction of air emissions in the shipbuilding industry [210]. In the case study, the economic model was developed and four economic indicators, i.e. NPC, NPV, LCOE and initial cost of capital, were used for the economic analysis.

Solar energy is an important function of the smart grid as one of the energy sources and the produced energy can be used for heating buildings, workshops, warehouses and for providing hot water. Moreover, as the LCOE of solar energy decreased by 85 % between 2010 and 2020 [122], the technology is becoming more popular in smart grids. As Fig. 5 shows among six different scenarios, Case 1 (solar PV) with $ 2.87 million net present cost, 0.053 kWh levelized cost of energy, 11 % internal rate of return and 6.2 years discounted payback period is the most economical off-grid plant design, and Case 6 with $ 3.65 million net present cost, 0.109 kWh levelized cost of energy, higher internal rate of return (28.9 %) compared to the other cases is the best case after case 1. In addition, the analysis shows that the annual electricity production from solar energy can satisfy 60.2 % of the annual energy demand of the studied yard and that it is 43.6 % for wind energy. The use of solar energy can reduce the cost of electricity by $361,667 and 1.34 tonnes of carbon dioxide per year. These figures are $616,608 and 2.18 CO_2 for wind power.

Conclusions

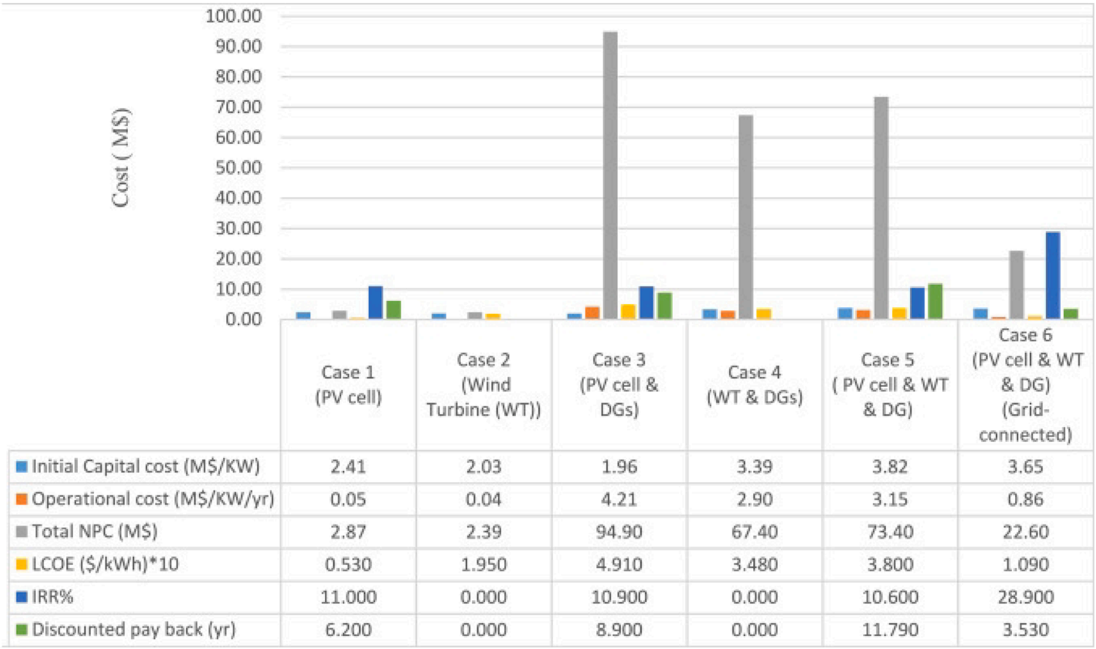
Most of the research and studies in the shipbuilding industry focus on improving ship design to minimise ship emissions during the operational phase and to improve quality assurance, safety and security. These studies pay less attention to reducing carbon emissions from shipbuilding and its relation to urban sustainability. Although technological research and development within the area may lead to improve energy efficiency and help in decarbonising shipyards, it is a single-dimensional approach. It is crucial the research and development projects regarding energy aspects within shipyards conducting. The projects must be holistic, systematic and should consider the various disciplines within the sector. Additionally, by the transdisciplinary approach, the integration of each discipline must be taken into consideration.

This study contributes to the decarbonisation of the shipbuilding industry as one of the most polluted and energy-intensive industries from a life cycle perspective. The outcome of the study can be accelerating zero emission road in the maritime industry and can be considered as a guideline for shipyards' owners, policymakers, and corresponding governance, who are active to decarbonize the maritime cluster at international, regional, and local levels. Considering the above, choosing and utilizing the measures needs feasibility and case studies. In addition, the proposed measures must be adopted with shipyards' features, and the trade-off considered based on the priorities of the decision-makers.

The authors through the systematic approach created the borders between the energy elements in shipyards and defined the nested systems, which are energy supply chain system, economic system, and ecosystem. Additionally, the authors identified five main disciplines of the human factor, technology, operation, policy and regulation, and economics as the main disciplines for the classification of mitigation measures of GHG emissions from shipyards. Due to the complexity of the issue (presence of various actors with different benefits and priorities), the authors broke the silos among the disciplines and found the integration among the measures to develop a transdisciplinary approach.

The measures and tools in each discipline were identified despite their differences, functions, types, sizes, abatement potential, and shipyards features, sizes, and management models. Shipyards' managers concerning their features, local, potential, priorities, and strategies may choose the measures to implement within their activities to mitigate their GHG emissions. The classified measures in each discipline have potential in the decarbonisation of shipyards. However, evaluation and feasibility studies must be conducted to choose the most appropriate package of measures to mitigate GHG emissions in shipyards. Additionally, shipyards' managers concerning their capacities, potential, and priorities should trade-off between benefits and dis-benefits of the package.

A series of technologies, product designs, and operational approaches in the combination of skilful and trained staff and appropriate policies can swiftly and cost-effectively reduce energy consumption and assist in decarbonisation in shipyards and combination of measures in different disciplines can enhance their potential in decarbonisation of



	Case 1 (PV cell)	Case 2 (Wind Turbine (WT))	Case 3 (PV cell & DGs)	Case 4 (WT & DGs)	Case 5 (PV cell & WT & DG)	Case 6 (PV cell & WT & DG) (Grid-connected)
■ Initial Capital cost (M$/KW)	2.41	2.03	1.96	3.39	3.82	3.65
■ Operational cost (M$/KW/yr)	0.05	0.04	4.21	2.90	3.15	0.86
■ Total NPC (M$)	2.87	2.39	94.90	67.40	73.40	22.60
■ LCOE ($/kWh)*10	0.530	1.950	4.910	3.480	3.800	1.090
■ IRR%	11.000	0.000	10.900	0.000	10.600	28.900
■ Discounted pay back (yr)	6.200	0.000	8.900	0.000	11.790	3.530

Fig. 5. Energy system costs associated with each investigated case.

the industry. Personnel can improve productivity and efficiency in shipyards. Skilful and well-trained labour is essential for utilizing new technologies and cooperating in the decarbonisation of shipyards' activities. Using new technologies plays a crucial role in the decarbonisation of the shipbuilding industry. Integration of *I*4.0 with other technologies is a milestone in shipyards' productivity and reduction of shipyards' GHG emissions. Additionally, electrification and alternative fuels' roles in shipyards' decarbonisation are significant, and their role can be more important in sustainable transition in shipyards' energy supply chain system if they are integrated with RE harnessing. However, the amount of using RE depends on commitment of shipyards' managers in decarbonising their activities and the level of integration of technologies. Taking the above into consideration shipyards can act as an energy hub for shipping and other industries.

While technologies have a crucial role in the reduction of GHG emissions in shipyards, they have positive impacts in promoting shipyards' operations toward decarbonisation. Utilizing modern and automated technologies, such as robots for welding and automate cutting types of machinery leads to the reduction of GHG emissions in shipyards' operational disciplines, as well as implementing *I*4.0 can promote lean systems within the operational discipline.

Policy and regulations can act as a driver for the decarbonisation of the shipbuilding industry. While there is not any international regulation for the decarbonising shipbuilding industry, the regional and national regulations can play a crucial role to meet the goal. Significant changes in the energy sectors, such as using electricity in combination with RE can be supported and enhanced by related governance and adoption of appropriate policies. However, it needs strong cooperation among stakeholders to enable policies to lead sustainable energy transformation in shipyards. The level of implementing policies and regulations depends on shipyards' and governors' commitment to the reduction of GHG emissions in the field. In addition, the implemented policies must have integration with other measures that are considered to utilize in shipyards. As an example, cybersecurity policy is crucial if the shipyard move toward digitalization and managers' commitment to the reduction of GHG emissions can be promoted by complying with ISO 50001.

The energy supply chain system is nested in the economic system in shipyards. The economic aspects of any actions in mitigation of GHG emission within shipyards' energy supply chain must be considered and evaluated. Depends on the nominated measures and shipyards' priorities different economic indicators and economic analysis in the feasibility study may be considered. In the shipbuilding industry, which is placed in a competitive market increasing revenue and decreasing the costs can maximize the profits. Implementing the proposed framework at an Italian shipyard demonstrates that the use of modern energy systems can accelerate the sustainable transition towards decarbonisation by increasing overall productivity and energy production and lowering the costs of waste management, maintenance, energy consumption and carbon dioxide, thus maximising the economic benefits. In addition, their commitment to reducing carbon emissions can improve the working environment and the health and satisfaction of staff, as well as increasing production quality and capacity. This will lead to promote the shipyards' position in the competitive market and promote their reputation, as well as acts as a brand in the market and placed them in a favourable position in dealing and negotiating with customers and investors.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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