THE HUMAN ENGINEER - RESKILLING IN THE AI ERA

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Abstract

The AI era requires engineering to adapt its focus away from solely technical proficiency towards an hybrid skill-set encompassing the integration of AI abilities, digital know-how, and understanding of sustainability principles. This paper relates the technological transition towards hybrid propulsion, renewable energy, smart port operations in the area of maritime sustainability with the redefinition of the "Human Engineer". Through the analysis of case-studies, relevant insights concerning successful integration of humans and AI are proposed in terms of lifelong learning, technological infrastructure changes and governance strategies. By converging technical expertise and transformation of the workforce, this work sketches a path towards success for engineers in the new AI-enhanced paradigm as supporters of sustainability and efficiency goals. This study is based on a narrative review methodology which has been developed by considering the literature available on maritime de-carbonization, smart port development, alternative fuels, AI-enhanced industrial change. Selected papers have been analyzed in thematic terms, aiming to isolate the needed engineering competencies, the retraining processes and the multidisciplinary skills that will support humans in the working environment defined by the human--machine hybridity paradigm. This study represents a theoretical synthesis, which links up the implications of Maritime sustainability transformation towards engineers' retraining needs in the AI era.

Keywords: *Human Engineer, Artificial Intelligence, Reskilling, Maritime Sustainability, Smart Ports, Human--AI Collaboration.*

INTRODUCTION

The issue of transport has attracted increasing focus particularly in the recent era of the global pandemic. Despite its being discussed within the framework of risk, digitalization, sustainability and gender equality all areas of transport can provide a vigorous launch pad for inquiry and analysis. Within this broad framework, and particularly relating to present day topics such as competitiveness and sustainability, shipping does appear somewhat unique. It is considered to be the backbone of international trade since it is used to transport almost 90% of goods through major navigable waterways. In recent years the sector has entered an era where the practices and pursuit of sustainability stand at the forefront of shipping companies' endeavors which includes a vast number of actions taken with regard to the environment. Such effort is far from one-dimensional: aside from guaranteeing our ecosystem, sustainability represents an important planning decision on the continued survival of a company within the shipping and logistics industry.

Although the movement to achieve green transport in the shipping industry has been somewhat successful there remain quite a number of challenges to overcome. Beyond environmental impact concerns, there also remain issues regarding the general human health, society and ethical consideration of the problem. Therefore, the move toward a green shipping industry requires more than just an effort at optimizing operational features but also a multitude of related maritime processes such as sustainable energy practices in ports, within the shipbuilding environment, and while ships are under construction or repair. Simultaneously, artificial intelligence applications are becoming ubiquitous across a wide range of disciplines and are increasingly modifying the nature of engineering expertise: its collection, retention, and updating. Such transformation leads us to revisit the role of the engineer, moving away from the concept of the engineer as merely a user of automated system(s) to a flexible and adaptive professional with domain knowledge coupled with the understanding of digital capabilities and sustainability.

In the context of the transportation sector, shipping is currently characterized as one of the "greenest" modes of transport while still accounting for an extensive portion of CO2 emissions worldwide and relying significantly on fossil-based fuel sources. Therefore, the pursuit of both technological and operational innovation-including the use of environment performance indicators, greener fuels, hybrid propulsion, smart ports and data-driven optimization-play an instrumental role in maritime transitions. Such trends are equally useful in the case of all other sectors since they provide analogies concerning the challenges that engineers must confront, such as the necessity of continuous reskilling, interdisciplinary knowledge, and human-AI collaboration, all of which led to the conception of the concept the "Human Engineer".

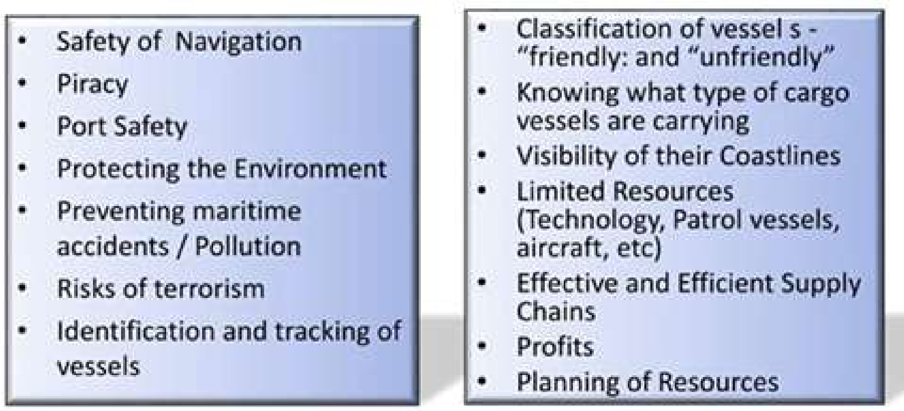

Figure 1. Challenges Faced in Maritime Industries.

The shipping industry acquires a more environmentally friendly nature, adopting practices that strive for the common good, protecting the marine ecosystem, and securing human health. Even though data indicate that shipping is currently the most sustainable mode of transportation, the industry is responsible for 3% of the world's carbon dioxide (CO_2) emissions, with almost 100,000 ships in operation, consuming on average 300 million tons of heavy fuel oil (HFO) per year. This number renders shipping a highly polluting sector, highlighting the need for a drastic shift to cleaner energy sources and alternative fuels. It is not just about following rules, it is about genuinely committing to sustainability practices. This shift in the shipping industry will add to a worldwide effort towards environmental protection.

The maritime industry has started to progressively address consumer demands for more environmentally friendly cargo transportation methods by creating an environmental sustainability framework, which is centered on metrics that evaluate the ecological footprint and wider effects of shipping operations. Global ecosystems are at serious risk from the toxic pollutants that ships are known to leak into the air and seas, such as “sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). 15% of global NO_x emissions, 13% of SO_x emissions, and 3% of all CO_2 emissions, or around 940 million tons of CO_2’’, were caused by the shipping sector between 2007 and 2012 (Wan et al. 2018). Beyond these numbers, there is cause for concern because the expansion of international shipping is directly linked to a rise in CO2 emissions worldwide in the near future (Hoang et al. 2022), endangering both human health and the environment. By 2050, the International Maritime Organization (IMO) wants to cut greenhouse gas (GHG) emissions by as much as 50%. This goal may seem difficult, but it is doable given the use of alternative propulsion techniques that seek to replace fossil fuels with cleaner and more sustainable forms of propulsion.

OBJECTIVE OF STUDY

To review technological advancements in AI-driven industrial transformation and develop reskilling strategies that enable engineers to adapt to hybrid human–machine systems while ensuring sustainability and operational efficiency.

PROBLEM STATEMENT

The rapid adoption of AI is reshaping engineering roles and industrial workflows, creating critical skill gaps. Without targeted reskilling, engineers risk reduced relevance and productivity in hybrid environments where human expertise and AI coexist. This study addresses how professionals can adapt, drawing analogies from maritime sustainability and port operations to illustrate strategies for balancing technological innovation with environmental and operational goals.

LITERATURE REVIEW

The recent literature of maritime sustainability can be categorized under three main themes: environmental performance indicators and measurement, decarbonization strategies, and digital transformation. The first thematic stream relates to various maritime environmental performance measurement tools and indicators including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Operational Indicator (EEOI), the Ship Energy Efficiency Management Plan (SEEMP) and the Clean Shipping Index (CSI). Such indicators are designed to assess the environmental performance of ships and to facilitate eco-friendly decision making. These tools represent a step forward in providing structured technical and operational indicators for the maritime sector in assessing its sustainability; furthermore, some recent studies have indicated that AI may be used to support monitoring, classification and optimization of environmental performance.

A second stream of literature focuses on practical strategies toward decarbonization. It covers analyses of operational strategies, such as slow steaming, route optimization, hull cleaning and fleet optimization, as well as lightweight design technologies that are implemented to save fuel consumption and reduce emissions without significant systemic modifications. At the same time, papers dealing with alternative fuels like LPG, LNG, hydrogen, or ammonia present a growing and strong research effort toward reducing the carbon footprint of shipping and meeting long-term global environmental targets. Taken together, the papers of these two streams show that maritime sustainability will not result from a single solution, but from a complex and interlinked application of several technical and operational strategies and a strong emphasis on fuel transition.

A third stream is devoted to digital transformation, hybrid technologies and smart ports. Research here reveals the increasing use of AI, automation, prediction maintenance and data-enabled logistics to transform onboard operations and port operations as well. Nevertheless, there is literature discussing decarbonization technologies and digital tools for the maritime sector, however, few have dealt with the way such changes might impact engineers and their role in the future. The current paper intends to fill in this research gap through the consolidation of concepts drawn from maritime sustainability studies and studies of the effects of AI on industry transformation in order to build the Human Engineer as a professional figure whose work combines technical competence with digital fluency, ethical and sustainability literacy and flexibility.

METHODOLOGY

This study is a narrative review research of the intersection between maritime sustainability and engineer reskilling in the age of AI. The study is based on the cited literature presented throughout the paper on maritime environmental performance, operational strategies for emission reduction, alternative fuels and hybrid propulsion, as well as smart ports or digital transformation; this research does not consist in an empirical experiment or meta-analysis. Therefore, its aim is that of constructing an interpretative and conceptual synthesis.

The reviewed papers have been systematically analyzed on the basis of thematic content analysis and they can be organized into four main research themes, which have informed the analysis: environmental performance indicators and tools, maritime operation strategy based on emission reduction, alternative fuels and hybrid technologies as well as smart ports and digital transformation. These themes are then interpreted and interrelated through a general research question on how studies on maritime transformation might inform reskilling engineers in an increasingly AI-augmented environment.

A conceptual link between the adoption of technology in maritime transition and engineer skills development requirement in the future is then developed on the basis of this thematic synthesis. The methodology used has allowed a conceptual link between maritime technological transformation and future engineering skills requirements, that are hybrid and rely not only on the technical specialization, but on artificial intelligence literacy, system thinking, sustainability literacy and ethical considerations. The review-based approach of this paper is appropriate as it provides knowledge integration and theoretical development on a topic with interdisciplinary character.

Environmental Sustainability Indicators

The maritime sector has developed and implemented a number of metrics for tracking and regulating greenhouse gas (GHG) emissions in order to improve environmental performance in light of growing concerns about climate change and environmental deterioration. This section will list some of the most well-known environmental sustainability metrics used in marine operations today to evaluate how eco-efficient ships, fleets, or services are. More specifically, apart from the technical and operational energy efficiency measurement tools, which are already being utilized by shipping companies to enhance vessel performance and boost sustainability, the industry is subject to digitalization, with the recent trends referring to the deployment of technological tools in their attempt to support the green transition. Therefore, the paper analyzes the practicality of the Energy Efficiency Design Index (EEDI), the Energy Efficiency Operational Indicator (EEOI), and artificial intelligence (AI).

First, the Energy Efficiency Design Index (EEDI), a mandated measurement instrument approved by the International Maritime Organization (IMO) in 2011 and going into effect on January 1, 2013, is a key indication leading the shipping industry's green shift. Any vessel constructed after 2013 that weighs more than 400 GT is subject to the EEDI metric **(Mindykowski et al. 2024)**. As a response to the extensive release of CO_2 emissions from the ships' funnels, the IMO imposed stricter guidelines, amending Annex VI of MARPOL regulation to diminish the release of GHG emissions from ships to the atmosphere and promote fuel efficiency and more energy-efficient combustion engines for newbuilds. The EEDI assesses a vessel's energy efficiency based on CO_2 emissions, considering the ship's capacity, velocity, and emission levels. Nowadays, the EEDI is a crucial measure in international shipping and fosters a competitive edge in designing energy-efficient new ships **(Narula 2014).**

The Energy Efficiency Operational Indicator (EEOI) is an additional measurement tool that is used in conjunction with the EEDI to assess the operational energy efficiency of ships during each journey. Stated differently, this index surpasses the usefulness of EEDI since it may be used while the ship is in service, tracking its performance and contrasting it with the rest of the fleet for a predetermined amount of time. The EEOI, which is a component of the Ship Energy Efficiency Management Plan (SEEMP), is represented in terms of CO_2 emissions per ton-mile and provides a comparative measure for ships that are already in service as well as technological advancements for those ships. The EEOI's dynamic nature is highlighted by its sensitivity to a number of variables, including weather and navigation **(Narula 2014; Fong-Yuan 2014; Sun et al. 2019)**

The Clean Shipping Index (CSI) is an essential instrument for marine sustainability, designed to promote a cleaner industry and reduce pollution. It is a thorough, cargo-owner-driven index that assesses vessels according to their CO_2, NO_x, SO_x, and PM emission levels. The CSI measure, created by a nonprofit organization, gathers data from various members via a questionnaire that emphasizes environmental and operational factors of ships, ranking vessels based on their performance. CSI possesses a robust market incentive, since it assists cargo owners in choosing ecologically responsible ship operators while also rewarding vessels with superior environmental performance with discounts at several ports (Anderson et al. 2017). Furthermore, sustaining an eco-friendly character may produce economic advantages and incentives.

The function of artificial intelligence (AI) is essential in enhancing the CSI by offering profound insights into emission data, facilitating more sophisticated classifications of ships according to their environmental impact. Artificial intelligence can analyze extensive datasets to deliver more accurate and immediate assessments of vessel performance, fuel usage, and emission trends. This may result in more informed decisions about route optimization, maintenance scheduling, and operational modifications, hence further diminishing environmental impacts (Hultman and Skog 2023). Furthermore, AI-driven systems may facilitate real-time oversight and adherence to environmental legislation, guaranteeing that vessels comply with the most current sustainability criteria. The aforementioned constructions are presented in Table 1.

Table 1. The environmental sustainability inventory.

Environmental sustainability inventory	
Energy efficiency design index (EEDI)	**Narula (2014) and Mindykowski et al. (2024)**
Energy efficiency operational indicator (EEOI)	**Narula (2014), Fong-Yuan (2014), Sun et al. (2019)**
Ship energy efficiency management plan (SEEMP)	**Narula (2014)**
Clean shipping index (CSI)	**Anderson et al. (2017)**
Artificial intelligence	**Hultman and Skog (2023)**

Operational practices and technologies regarding environmental protection

The former indicators, along with artificial intelligence, comprise the first step toward the green transition, assisting shipowners and relevant stakeholders to measure ship performance and address main environmental concerns. From now and on, the paper transitions to an in-depth analysis of contemporary technologies and strategic approaches, such as propulsion alternatives and alternative energy sources.

Slow steaming

A traditional and well-practiced emissions reduction strategy that shipowners have been utilizing for many years and is subject to analysis in many research papers is slow steaming **(Wan et al. 2018; and Stathopoulou 2021; Tsaousis 2019).** Slow steaming is the process of decreasing the vessel's speed to drastically reduce fuel consumption and minimize the pollution caused by fuel combustion. Although this strategy was introduced to fight the rising bunker costs, many companies currently use this strategy as a response to the severe consequences of climate change, thus decreasing the CO_2 emissions released from ships. According to **Notteboom et al. (2021),** slow steaming occurs when the commercial speed of ships decreases from 23 to $18 knots (33.3\ km/h)$, while extra slow steaming and super low steaming are also applicable, lessening vessels' speed even more.

According to Wan et al. (2018), the use of slow steaming from 2007 to 2012 resulted in a reduction of CO_2 emissions by almost 10%, while concurrently assisting shipowners in lowering their operational costs. Fuel prices provide a significant motivation for slow steaming, accounting for up to 50% of total operating expenses. Currently, this incentive is amplified for shipowners due to the onset of the Ukraine-Russia conflict, which has led to a dramatic increase in marine fuel prices. A third advantage of slow steaming methods, as noted by Brynolf et al. (2016), is the diminishment of undersea noise, a significant environmental concern that can adversely impact the marine ecology. Maloni et al. (2013) found that implementing extra slow steaming, defined as reducing speeds to 15–18 knots (27.8–33 km/h), results in a notable 20% reduction in overall expenses for firms and a large 43% drop in CO_2 emissions.

Route Planning Optimization

As per the operational strategies, opting for shorter shipping routes is an effective measure for emissions reduction. Optimized route planning describes a simple procedure where vessels arrive at the port of call safely within the required timeframe allowed while sailing at an optimal speed without extensive consumption. This practice fosters vessel idle time minimization and more efficient port cargo operations. As noted by **Rudzki et al. (2022),** such strategies culminate in ships being more cost-effective and having a reduced environmental footprint. Besides, effective route planning can prevent vessels from sailing during harsh weather conditions, such as storms or high waves and winds, a fact that can save time and fuel while also providing security for the vessel and its crew. Achieving the lowest possible operating costs does not come vis-a-vis from navigational practices, yet is highly associated with making suitable decisions about the vessel's propulsion system during navigation Those decisions are closely related to the ship's mechanical power and propulsion systems used to alter the vessel's speed and subsequently relate to the vessel's performance, operational costs, and environmental footprint.

Hull cleaning and hull fouling

Route optimization can become more environmentally friendly and have better outcomes if vessels obey operational standards and maintain a clean and hydrodynamic hull surface. This green initiative, hull cleaning, is a procedure in which the vessel's hull is regularly monitored to avoid the growth of marine fouling organisms, such as barnacles and algae, which can lead to vessel underperformance and increased emissions. Research indicates that hull fouling is a severe issue that shipowners face and can cause increased pollution to up to 15%. **Swain et al. (2022)** assert that shipowners ought to allocate funds towards anti-fouling paints and hull coatings capable of diminishing the skin friction component of resistance to inhibit the adhesion of foreign organisms to the hull. These paints provide attributes that safeguard the hull from corrosion, fouling, and the detrimental impacts of seawater and marine organisms. Through the implementation of ship hull optimization procedures, shipowners can preserve a streamlined hull surface, thereby diminishing wave drag, conserving fuel expenses, minimizing consumption, enhancing operational efficiency and agility, and reducing environmental pollutants**.**

Moreover, shipowners can significantly diminish the ecological footprint of their fleet by enhancing hull design and performance through weight reduction by utilizing suitable lightweight materials or by altering the hull shape to minimize water resistance. According to **Mindykowski et al. (2024),** underwater hull coating and lightweight ship hull construction are vital hydrodynamic elements for friction reduction and water resistance minimization that promote eco-efficiency while also having a direct relationship with improving the EEDI index of ships. The above practices assist ships in minimizing their environmental impact while reducing fuel consumption and operational costs.

Fleet management planning

Fleet management planning is an additional element that can significantly reduce the environmental impact of maritime operations. Effective planning is essential, markedly reducing the time of ballast voyages. This technique of improved fleet management not only reduces normal maintenance time and addresses technical problems more effectively but also enhances overall fleet efficiency. Chang and Danao (2017) assert that recycling used shipping materials, including packaging, cartons, and spent engine oil, can enhance operational efficiency, reduce costs, and generate economic benefits for shipowners, thereby advancing the industry's progress towards the IMO 2050 objectives.

Alternative fuels regarding environmental protection

The above analysis focuses on crucial practices that shipping companies shall adopt to reduce the carbon footprint of their vessels, become more sustainable, and contribute to the efforts of the IMO to minimize the amount of GHG emissions produced by the shipping industry. These practices can be applied to existing vessels, as they can be adopted without demanding further capital investments or altering current onboard equipment. Nonetheless, as the goal of IMO is to drastically reduce GHG emissions by up to 50% by the year2050, the maritime community strives towards more long-term energy solutions that promise a greener industry, one of the solutions to be the replacement of heavy fuel oil (HFO) with alternative fuels.

Figure 2. Emerging Technology and Future of Marine Fuels.

According to **Stenersen and Thonstad (2017),** LNG is a mature alternative fuel option that has been assessed and progressed, allowing shipowners to choose over a variety of engine types and combustion methods. At present, LNG can be combusted on vessels utilizing the following engine types: lean burn spark ignition engine, low-pressure dual-fuel four-stroke engine, low-pressure dual-fuel two-stroke engine (slow speed engine), high-pressure dual-fuel engine, and gas turbine. As previously indicated, there are five unique gas engine ideas, each with specific combustion characteristics that variably influence vessel performance and exhaust emissions. The above indicates that the type of technology used determines the environmental implications of the ship's operation.

The environmental benefits of LNG combustion, compared to those of HFO, comprise the main reason for shipowners to adopt this alternative **(Wang et al. 2022).** The higher hydrogen-carbon ratio of LNG composition results in a significant NO_x, SO_x, PM, and CO_2 emissions reduction. As industry data highlight, LNG has approximately 50% fewer emissions than HFO, while in comparison to very-low sulfur fuel oil (VLSFO), LNG reduces CO_2 emissions by up to 20%. In addition, NO_x emissions are reduced by approximately 90% on a lean-burn gas-fuelled engine **(Stathopoulou 2021).**

Another alternative capable of changing the dynamics of the shipping industry, highly obeying the IMO 2050 regulation standards, is liquified petroleum gas (LPG). Produced by a mixture of hydrocarbons, mainly propane (C_3H_8) and butane $(C_4H_{10}), LPG$ is a clean, energy-efficient, and portable fuel with a low-price tag and wide availability worldwide. LPG is liquified by cooling to $-50°C$, reducing cargo volume by almost 100%. While LPG has been recently identified as an alternative fuel, it offers a wide range of environmental benefits compared to other alternative options **(Wang et al. 2022).** Specifically, LPG lowers the carbon-to-hydrogen ratio and reduces the amount of CO_2 emissions compared to HFO by 15%, while it also decreases SO_x by 99%, NO_x by around 20%, and PM by 90%. Besides, LPG is a non-toxic gas, which makes its handling safer. LPG marine engines can achieve noise reduction since LPG engines are quieter compared to other oil-based engines, such as diesel engines **(Stathopoulou 2021).** Currently, LPG is mostly produced from natural gas and oil extraction activities; nonetheless, as new technologies and techniques emerge, LPG may be produced from renewable sources, using feedstocks such as vegetable oil and residues. In addition, bio-LPG is yet another variation of LPG, constituting a by-product of the biodiesel production process that can reduce emissions by an additional 80% compared to traditional LPG fuel.

Hydrogen (H_2) is an alternative for the shipping sector (Atilhan et al. 2021), with its combustion yielding minimal CO_2 emissions, contingent upon the production method employed. The aforementioned indicates that the suitable production method may substantially reduce atmospheric carbon dioxide emissions. Atilhan et al. (2021) and Stathopoulou (2021) assert that hydrogen, owing to its energy density relative to other chemical fuels, might enhance engine performance and reduce fuel consumption.

Ammonia (NH_3) is a nitrogenous compound devoid of carbon atoms. Ammonia, similar to hydrogen, can be combusted in fuel cells or utilized as a hydrogen transporter. McKinlay et al. (2020) assert that fuel cells represent the most efficient method for extracting energy from ammonia. Solid oxide fuel cells (SOFC) represent an efficient choice for ammonia combustion, as they may be directly supplied with this alternative fuel. Ammonia is non-combustible in air, often necessitating a feedstock (such as hydrogen) to ignite fire. An further application of ammonia is as a "hydrogen transporter". In this scenario, ammonia would be stored and transported prior to being converted back into hydrogen for use in ship propulsion.

Hybrid Systems and Emerging Technologies for Workforce Transformation

The rapid evolution of artificial intelligence (AI) is transforming industrial sectors, much like renewable and hybrid technologies are revolutionizing maritime operations, these technological transitions highlight how human expertise must adapt to work alongside intelligent, automated systems rather than replace them. Just as the shipping industry is leveraging cleaner fuels and hybrid propulsion to mitigate climate change, organizations across domains are integrating AI with human-led oversight to achieve efficiency, sustainability, and resilience.

AI-Augmented "Battery" Systems in Human Skills

Battery-electric technologies in shipping parallel the role of targeted AI tools in industry — both are powerful, low-emission, high-efficiency systems that enhance performance but require infrastructure, design adaptation, and operational changes. For engineers, this translates into acquiring skills that complement AI capabilities, such as system optimization, data interpretation, and problem-solving under constraints. As in short-sea shipping where battery systems excel in specific conditions, AI adoption often begins in well-defined, narrow-use scenarios before scaling to complex operations **(Nguyen et al., 2020; Brynolf et al., 2016).** The lesson for the human workforce is to master niche applications first, then evolve skills to manage broader AI integrations.

Hybrid Models – Humans and AI in Tandem

Hybrid propulsion in maritime — combining traditional engines with battery power — mirrors the human-AI collaboration model. Hybrid vessels save fuel, improve efficiency, and meet environmental targets, just as AI-assisted engineers can improve productivity and reduce operational errors while retaining human judgment in critical tasks **(Christodoulou & Cullinane, 2020).**

The most successful hybrid shipping projects, like Stena Line's methanol-diesel conversion, relied on continuous investment in training, operational optimization, and infrastructure. In the AI era, hybrid human-AI systems similarly demand reskilling programs, change management strategies, and ethical frameworks to ensure alignment between technology and human values. Engineers must learn "AI peak-shaving" — strategically using AI to handle intensive computational tasks while humans focus on creativity, ethics, and decision-making.

Solar Energy – Continuous Learning

Solar energy in maritime applications supplements primary propulsion, much like continuous learning supplements core professional expertise in the AI era **(Paulson & Chacko, 2022).** Engineers cannot rely solely on foundational education; instead, they must draw on "solar-like" knowledge sources — micro-courses, AI-driven training platforms, and collaborative knowledge networks — to sustain career relevance. While solar panels cannot currently replace ship engines, lifelong learning cannot replace domain mastery, but it can enhance adaptability and resilience in a changing technological landscape.

Wind Power – Harnessing Human Potential

Wind energy's return to maritime technology represents a revisiting of traditional strengths through modern innovation **(Thies & Ringsberg, 2022).** Similarly, in the AI age, the most valuable engineers will integrate timeless engineering principles — systems thinking, safety awareness, precision — with AI-powered analytics, design tools, and simulation environments. Just as wind-assisted vessels like the Orcelle Wind aim for up to 90% emission reduction, AI-empowered human engineers can aim for massive efficiency gains while minimizing human error and environmental impact.

The shift toward hybrid and renewable energy in shipping provides a compelling analogy for reskilling in the AI era. It shows that technology adoption is not simply about replacing the old with the new but about layering innovation onto existing strengths. For the Human Engineer, this means developing a flexible, hybrid skill set — blending domain expertise, AI fluency, and adaptive learning — to remain relevant in an era where technology is both a partner and a driver of change.

Port strategies to reduce the environmental impact of ships and enhance port operations

Decarbonizing maritime operations requires coordinated action between ships and ports, as the ship–port interface significantly influences environmental performance **(Hoang et al., 2022; Xiao et al., 2024).** Modern "smart port" concepts integrate digitalization, automation, and AI to optimize monitoring, control, and planning **(Makkawan & Muangpan, 2021).** Strategies such as the Time Window Concept and Just-In-Time scheduling reduce vessel idle time, cutting emissions and improving operational efficiency.

Corporate Sustainability (CS) practices extend these benefits by addressing environmental, economic, and social goals, enhancing competitiveness while fostering long-term resilience **(Ashrafi et al., 2019).** Initiatives include greenhouse gas reduction, waste minimization, water quality improvement, and stakeholder training. Global frameworks — such as the UN Sustainable Development Goals and World Ports Climate Initiative — guide these transformations.

AI plays a growing role, from automating container loading and unloading to predictive maintenance and traffic optimization **(Agarwala et al., 2021).** For the Human Engineer, this shift means reskilling to manage AI-integrated systems, data-driven decision-making, and sustainable infrastructure planning. As ports adopt cleaner vehicles, renewable energy, and intelligent logistics, engineers must combine technical expertise with environmental and digital literacy, ensuring that sustainability targets are met while maintaining operational excellence

CONCLUSION

AI integration is not about replacing engineers but enhancing their capabilities through human–machine synergy. Lessons from maritime sustainability show that technological innovation must be layered onto existing strengths, supported by reskilling, infrastructure, and policy alignment. The "Human Engineer" of the future will need to combine domain expertise with AI fluency, adaptability, and a commitment to sustainability. Continuous learning, ethical responsibility, and collaborative innovation will be essential to navigate this transformation. Strategic investment in training, research, and industry–academia partnerships will ensure that engineers remain indispensable contributors in shaping an AI-powered, environmentally conscious future.

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