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Environmental Sustainability of Seaports strategic analysis, modelling and simulation

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Abstract

Seaports are critical nodes in global trade and logistics systems, serving as gateways between maritime and inland transport networks. However, their intensive energy use, reliance on conventional fossil fuels, and associated greenhouse gas (GHG) emissions make them major contributors to environmental challenges. In the face of intensifying climate change, increasingly stringent international regulations, and growing societal pressure for cleaner operations, the pursuit of environmental sustainability in seaports has become both urgent and unavoidable. Achieving this requires comprehensive solutions that combine technological innovation, energy transition strategies, and operational optimization supported by advanced modelling and simulation techniques. This study proposes a holistic framework to examine seaport environmental sustainability across four interrelated dimensions: integration of renewable energy, sustainable transportation, LNG bunkering, and cold ironing. First, the research investigates opportunities for incorporating renewable energy sources such as solar, wind, and tidal power into port infrastructure. Through modelling and simulation, the study evaluates how these resources can reduce fossil fuel dependence while ensuring operational reliability.

Second, the analysis focuses on transportation systems within and around seaports, including port vehicle electrification, modal shifts, and multimodal logistics strategies. Alternative transportation scenarios are modelled to assess their potential to lower emissions while maintaining cargo-handling efficiency and hinterland connectivity.

Third, LNG bunkering is examined as a transitional fuel solution for maritime vessels. Scenario analyses compare LNG's environmental performance against conventional fuels, highlighting its greenhouse gas reduction potential, long-term viability, and infrastructure requirements.

Finally, the study explores cold ironing, the provision of shore-side electricity to berthed ships. By simulating energy flows and emission scenarios, the research evaluates cold ironing's effectiveness in reducing local air pollution and improving environmental conditions in port cities. Together, these four dimensions create a comprehensive framework that not only quantifies the environmental benefits of individual initiatives but also reveals trade-offs and synergies among them. The findings provide valuable guidance to port authorities, policymakers, and industry stakeholders seeking to design greener, smarter, and more resilient seaports capable of meeting future sustainability goals.

Abstract (IT)

I porti marittimi sono nodi cruciali nei sistemi commerciali e logistici globali, fungendo da gateway tra le reti di trasporto marittime e interne. Tuttavia, il loro intenso consumo energetico, la dipendenza dai combustibili fossili convenzionali e le relative emissioni di gas serra (GHG) li rendono tra i principali responsabili delle sfide ambientali. Di fronte all'intensificarsi dei cambiamenti climatici, alle normative internazionali sempre più stringenti e alla crescente pressione sociale per operazioni più pulite, il perseguimento della sostenibilità ambientale nei porti marittimi è diventato urgente e inevitabile. Per raggiungere questo obiettivo sono necessarie soluzioni complete che combinino innovazione tecnologica, strategie di transizione energetica e ottimizzazione operativa, supportate da tecniche avanzate di modellazione e simulazione. Questo studio propone un quadro olistico per esaminare la sostenibilità ambientale dei porti marittimi attraverso quattro dimensioni interconnesse: integrazione delle energie rinnovabili, trasporto sostenibile, rifornimento di GNL e cold ironing. In primo luogo, la ricerca indaga le opportunità di integrare fonti di energia rinnovabile come l'energia solare, eolica e mareomotrice nelle infrastrutture portuali. Attraverso la modellazione e la simulazione, lo studio valuta come queste risorse possano ridurre la dipendenza dai combustibili fossili garantendo al contempo l'affidabilità operativa. In secondo luogo, l'analisi si concentra sui sistemi di trasporto all'interno e intorno ai porti marittimi, tra cui l'elettrificazione dei veicoli portuali, i trasferimenti modali e le strategie logistiche multimodali. Vengono modellati scenari di trasporto alternativi per valutarne il potenziale di riduzione delle emissioni, mantenendo al contempo l'efficienza nella movimentazione delle merci e la connettività con l'entroterra.

In terzo luogo, il rifornimento di GNL viene esaminato come soluzione di carburante transitoria per le navi marittime. Le analisi di scenario confrontano le prestazioni ambientali del GNL con quelle dei combustibili convenzionali, evidenziandone il potenziale di riduzione dei gas serra, la sostenibilità a lungo termine e i requisiti infrastrutturali.

Infine, lo studio esplora il cold ironing, ovvero la fornitura di elettricità da terra alle navi ormeggiate. Simulando flussi di energia e scenari di emissione, la ricerca valuta l'efficacia del cold ironing nel ridurre l'inquinamento atmosferico locale e nel migliorare le condizioni ambientali nelle città portuali. Insieme, queste quattro dimensioni creano un quadro completo che non solo quantifica i benefici ambientali delle singole iniziative, ma ne evidenzia anche i compromessi e le sinergie. I risultati forniscono indicazioni preziose alle autorità portuali, ai responsabili politici e agli stakeholder del settore che desiderano progettare porti marittimi più ecologici, intelligenti e resilienti, in grado di soddisfare i futuri obiettivi di sostenibilità.

Keywords: Sea ports, renewable energy, modelling and simulation, Environmental sustainability, Integration of renewable energy in seaports, LNG Bunkering, Green transportation Modes, Cold ironing.

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Chapter 1. Introduction

1.1 Research Background and Significance

Seaports serve as vital links between inland and ocean transportation networks, making them crucial to the global economy. The flow of commodities, raw materials, and energy resources that support global trade and economic expansion is made easier by them. But because of their central location, they also contribute significantly to energy consumption and environmental effect. Modern ports generate significant greenhouse gas (GHG) emissions, air pollution, and other ecological stresses due to their heavy reliance on fossil fuels for vessel operations, cargo handling, and inland transportation. The environmental impact of port operations has grown to be a major issue for local communities, business executives, and governments alike as international trade and maritime traffic continue to grow [1,2].

The need for sustainable development has increased in recent decades, affecting all economic sectors, including maritime transportation, because of increased knowledge of climate change and its far-reaching effects. Both regional and international programs, such as the European Green Deal and the International Maritime Organization's (IMO) GHG reduction policy, have set aggressive goals to decarbonize transportation infrastructure. In this changing social and legal environment, ports are becoming increasingly acknowledged as key locations for putting sustainable environmental and energy strategies into action. In a time of swift environmental and technological change, their transformation offers a significant chance to improve competitiveness, resilience, and long-term viability in addition to being a requirement for compliance [3,4,5].

However, achieving environmental sustainability in seaports is a difficult task with many facets. It necessitates combining operational optimization, energy transition plans, and technology innovation while preserving dependability and efficiency. A comprehensive strategy that can identify interdependence across systems and assess their overall environmental consequences is necessary due to the variety of port activities, which include everything from cargo handling and vessel maintenance to logistics management and urban interface. For this reason, modelling and simulation tools have become extremely effective tools that enable practitioners and researchers to evaluate various scenarios, forecast results, and assist in evidence-based decision-

making. Using four interrelated dimensions renewable energy integration, sustainable transportation, LNG (liquefied natural gas) bunkering, and cold ironing (shore-side electricity) this thesis creates a thorough framework for evaluating and improving environmental sustainability in seaports. Every dimension is an essential part of the larger shift to energy-efficient and low-carbon port operations. The first aims to improve energy resilience and lessen reliance on fossil fuels by utilizing renewable energy sources including solar, wind, and tidal power [6,7,8].

The second investigates eco-friendly transportation options in and near port areas, such as vehicle electrification, modal changes, and multimodal logistics network optimization. The third analyses the possible environmental advantages and infrastructure consequences of LNG bunkering as a transitional route toward cleaner marine fuel substitutes. The fourth examines cold ironing, a widely used technique that reduces local emissions and enhances air quality in port towns by allowing ships to connect to an onshore power source while berthed [9,10].

The goal of this study is to measure each of these four factors' individual and combined contributions to port sustainability using a single analytical methodology. Also, it looks for best practices, trade-offs, and synergies that help direct the construction of seaports that are smarter, greener, and more resilient. To create integrated plans that support global sustainability goals and promote a cleaner maritime future, decision-makers including port authorities, legislators, and industry stakeholders are anticipated to find the findings useful [11,12,13].

1.2 Sea Ports

A seaport is a man-made harbour or wharf built to accommodate maritime vessels, including ships and barges. The term 'Seaport' is derived from the French words 'port' (harbour) and 'seafarer' (sailor). During the Middle Ages, the first seaports were established in Europe to facilitate trade and exchange of goods among merchants and explorers. A seaport is a port built on the sea, as opposed to being located on a river or lake. Rather than for vessels navigating the rivers, it acts as an access point for ships delivering goods or people to the city, they are frequently built in protected areas.

Seaports offer numerous advantages. They offer links to other nations, pathways for foreign trade and global business, and a means for products to transfer from one location to another. Seaports usually feature long wharves for docking ships. The area of a seaport where cargo is managed is called the quayside. At the pier's end closest to the

open ocean, large container ships can dock, while smaller or shallower-draft vessels can be accommodated at the pier head closer to the shore. Seaports enable us to participate in international trade without depending on an overland route, which would take considerably longer to reach its destination. This indicates that individuals residing close to a port are more prone to benefit

From an economic perspective, as their access to a greater number of goods will be facilitated. A seaport creates job opportunities for individuals in the transportation and trade sectors, granting them access to new markets and customers globally. Numerous seaports provide parking facilities (occasionally equipped with charging stations) for vehicles carrying cargo or passengers on cruise ships or ferries, this can be particularly advantageous for commuters seeking to evade traffic congestion during peak hours [17,18,19,20].

1.3 Types of Sea Ports

Ports can be categorized into various types to grasp their specific functions and roles.

Ports can be categorized based on various factors, such as:

a) Scale

The measurement of port size can be based on factors such as its area, the annual cargo throughput, the dimensions of its hinterland, the quantity of shipping services it links to, or the number of customers it serves. The economic and commercial significance of ports in the markets they serve is typically measured.

b) Geography

Depending on the geographical conditions of the coast and inland areas, port sites can be situated in various locations, such as a bay, along the coastline, on a river, or within an estuary. Ports may possess natural advantages, or they might need dredging and landfills to enhance the location. Although ports do not move, their locations are determined by their closeness and interaction with major shipping routes, hinterlands, cities, and urban areas.

c) Function

The port service range encompasses port services such as cargo handling, logistics, distribution, industry, and maritime services. Ports compete with one another because other ports can offer similar services.

d) Specialization

Port handling activities encompass containerized cargo, conventional dry-bulk cargoes, liquid cargoes, roll-on roll-off cargoes, and more. Some ports deal with passenger traffic, including cruise ships and ferries. Another instance of port specialization includes operations centered around the port, such as steel plants, energy facilities, automotive plants, and chemical businesses. Besides dealing with port-centric businesses, logistics activities play a significant role in port specialization.

e) Governance

Regardless of whether ports are publicly or privately owned, it is private companies that operate the terminals. The institutional arrangements of the port establish the conditions for land ownership and delineate the roles within public-private partnerships.

1.4 History of Sea port

The history of ports goes back to ancient times, when basic activities like fishing and transportation created the need for suitable docking locations. Initially, ports required little complex infrastructure, as natural barriers provided sufficient protection from waves and wind. Among the first civilizations to construct purpose-built docks and defined port areas were those in the East during the 3rd millennium BC, later followed by the Minoan and Mycenaean civilizations in the central Mediterranean [21,22,23].

The oldest known port is located at Wadi al Jerf on the Red Sea's Suez coastline. Dating to the era of the Egyptian Pharaoh Cheops around 2600 BC, it represents one of the region's earliest large-scale harbors. This port featured a modern dock like structure, and several artificial tunnels dug inland. Within these tunnels, archaeologists have discovered remainders of amphorae, stone anchors, navigational equipment, and the Diary of Merer the world's oldest known papyrus. Merer, an Egyptian official, documented prominent sailors who transported limestone blocks via waterways. These 4,500-year-old papyri detail how they moved roughly thirty-two ton blocks every ten days from Tura to Giza, emphasizing the port's critical role in efficiently transporting construction materials, likely for the pyramids [24,25,26].

Ports facilitated not only the movement of goods but also the effective transportation of people, enabling the burgeoning of civilizations like the Phoenicians.

A Semitic people settled in modern-day Lebanon and Syria, with their first known settlement in Sidon dating to the 12th century BC, the Phoenicians were expert navigators who established wide Mediterranean trade routes (Negbi O 1992). They are attributed with inventing the trireme, the most advanced ship of its era. Their maritime

skill allowed them to explore distant lands, contact new cultures, and found trading settlements, creating a massive commercial network. By acting as arbitrators, they boosted the exchange of goods and knowledge, facilitating the movement of people and achieving great prosperity. However, their gathered wealth and attractive trade hubs eventually attracted the attention of militarily powerful neighboring states, leading to conflicts [27,28,29].

Another important ancient maritime power was Athens, the cultural capital and structure of democracy in the 6th and 5th centuries BC. Athens built its prosperity on a powerful naval fleet. After the discovery of silver mines in the Laurion valley, the statesman Themistocles advised using this wealth to construct a formidable navy. This fleet enabled Athens to control dynamic sea routes, develop strong maritime trade, and transport troops, establishing its leadership in the Delian League, which transformed into the Athenian League in 478 BC (Tridems G 2015) [28,29,30].

This initially defensive maritime association effectively became an empire. Recognizing the need for a high-capacity port, Athens replaced the older port of Phaleron with the revived port of Piraeus in the 5th century. Protective walls were also built to secure the connection between the city and the port, which proved crucial for Athens' survival during the Peloponnesian War by ensuring a continuous flow of sea tolerated supplies even when surrounding territories were lost. This highlights the vital role of ports in a state's survival. Ultimately, Athens lost the war, and its navy and power declined. The subsequent destruction of its walls by enemies emphasizes how the maintenance of a port, commercial traffic, and military strength were directly linked to a state's prosperity and survival [31,32,33].

In following centuries, port technology and construction evolved through innovative structures and materials.

For example, the Romans used hydraulic concrete to build marine infrastructure like seawalls, which protected ports from strong waves and allowed for the construction of artificial harbours beyond natural coves. Known for their extensive road networks, the Romans also developed efficient sea and river trade connections. Ports were established near cities to meet commercial demands, leading to the creation of river ports. [34,35,36]

The ancient city of Rome, which began as a collection of villages in modern day Lazio, had a controllable port on the Tiber River by the 4th century BC. As Rome grew into a major Mediterranean power, it required more strategically located infrastructure, leading to the transformation of the nearby port of Ostia into a vital commercial hub.

Ostia became essential for supplying Rome, with ships from regions like North Africa arriving laden with goods such as wheat and oil. When Ostia's capacity proved insufficient, Emperor Claudius ordered the construction of another port in the Tiber delta to address food shortages. Rome established an efficient Mediterranean trade network, enabling goods to flow between provinces via maritime and land routes [37,38,39].

Following the fall of the Roman Empire, the West split into smaller kingdoms while the Byzantine Empire sustained in the East. During the early Middle Ages, Mediterranean maritime trade entered a crisis, marked by a decline in volume, especially in long distance transportation. The center of maritime trade shifted under the pressure of Arab expansion beginning in the 7th century. Arabs colonized large areas of North Africa and the Middle East, developing thriving trade networks. Their strategic locations, such as ports in Oman, facilitated trade connections across Africa, India, and Persia. They advanced navigation by employing astrolabes, the compass (a technology previously developed by the Chinese), and by studying wind patterns to construct vessels better suited to eastern waters. They traded highly adored materials from the Far East, such as spices and silk, the high value of spices relative to their volume was a key driver in developing extensive trade routes [40,41,42].

Meanwhile, after a period of instability following the migration era (7th–9th century), Western and Northern Europe began to recover economically and technologically. New maritime trade connections emerged in Northern Europe, with ports established along previously underdeveloped coastlines in England, the deltas of the Meuse and Rhine, and Northern France. Local governments promoted new port construction to facilitate trade and maritime control, especially as Viking expansions copied commercial relationships with inland regions [43,44].

The expansion of trade routes from the 9th century onward encouraged the development of Western economies and encouraged agricultural and manufacturing production inland. Contemporarily, innovations in navigation, such as the Latin sail, increased maritime traffic across the Mediterranean. Commercial exchanges between East and West contributed to the rise of new geopolitical powers, particularly the Maritime Republics in the territory of modern Italy. Port cities like Genoa, Venice, Pisa, and

Amalfi gained sovereignty from established powers, allowing them to develop independently, economically and culturally [45,46].

Their maritime strategy, supported by powerful navies and extensive commercial networks, significantly increased their wealth. Their strategic positions in the Mediterranean facilitated trade with Asia and Africa, enabling relationships with both the Byzantine and Arab worlds. Through territorial expansion, the establishment of colonies, and commercial diplomacy, these republics stretched their influence. [47,48] Many historians consider the discovery of America the beginning of globalization and the Contemporary Age. This period marked the establishment of colonies, new trade routes, and contact with diverse nations, providing a significant boost to the development of the Western world. Maritime traffic with the New World involved precious metals like gold and silver, as well as new possessions. Trade routes shifted to strategically positioned countries and their New World hubs, with ports being subjugated for trade, exploration, and as naval bases to control shipping lanes. This period saw the rise of new powers, such as the Portuguese and Spanish empires, which capitalized on their advantageous geographical positions in Western Europe for Atlantic access. Consequently, the center of trade gravity shifted from the Mediterranean to the oceans and the East Indies [49,50].

The struggle for naval sovereignty in the following centuries focused on controlling Atlantic routes, with power shifting from Portugal and Spain to the Dutch, then the French, and ultimately the English in the 18th century. New ports were constructed to facilitate these maritime connections, leading to the development of crowded urban centers that attracted merchants, sailors, and workers, resulting in important demographic and financial growth for these port cities.

During these centuries of continuous development, ports evolved to accommodate new fleets and technologies. Maritime traffic diversified significantly, with larger cargo ships demanding bigger docks, deeper harbors, and advanced loading equipment. Faster and more cost-effective access methods were adopted, further improving port operations. The Industrial Revolution was essential in this technological advancement. Steamships replaced marine vessels, while inland connections were strengthened with the construction of railways. Factories and resources in the localities became better connected to ports, facilitating a quicker flow of goods and extending port influence far inland. The rise of steamships created a strong demand for coal along transportation

routes, encouraging the British Empire to establish coaling stations. Some of these, such as Singapore, Shanghai, and Hong Kong, emerged as global trading hubs. [51,52,53] By the 19th century, European ports were connected to all continents, with England holding a predominant position. While London's ports were strategic, the development of Liverpool was particularly remarkable.

Figure 1-1 shows The Atlantic Ocean trade routes connected Europe, Africa, and the Americas, forming a major network for the exchange of goods, people, and resources. These routes supported the movement of manufactured products, raw materials, and enslaved people, shaping economic and cultural interactions across the Atlantic world. They played a central role in global commerce, exploration, and colonial expansion.

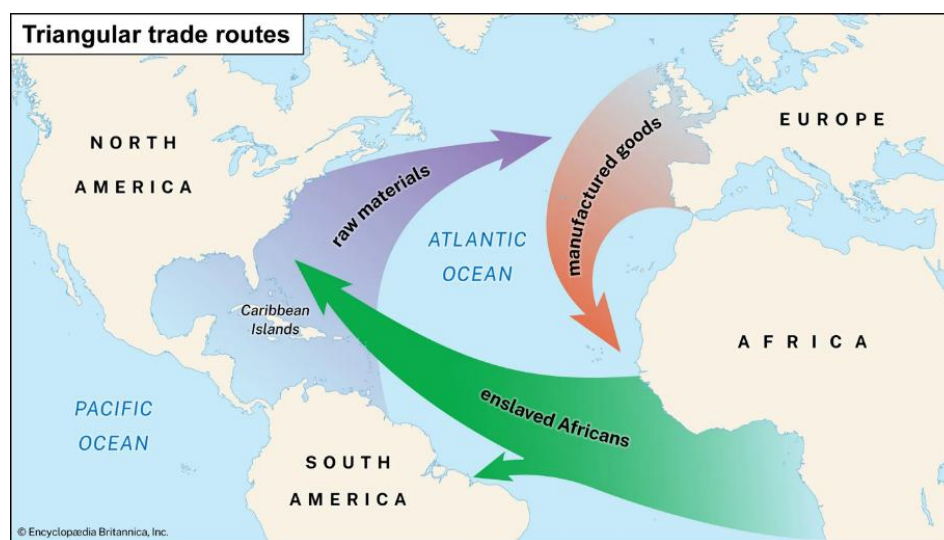


Figure 1-1 Atlantic Ocean trade routes. From Britannica

Having gained wealth in the 18th century through the slave and tobacco trades, Liverpool flourished on a global scale in the 19th century. The port served as the outlet for one of the era's most significant industrial environs, including the industries of Manchester and the cotton mills of Lancashire. Its favourable position facing the Atlantic allowed efficient trade with the United States and the Caribbean. The opening of railway lines further enhanced its ability to transport raw materials and manufactured goods, making Liverpool a thriving city through which 40% of global trade flowed [54,55,56,57]. Between the 16th and 19th centuries, the importance of trans-oceanic trade grew drastically, motivated by the investigation of the New World. One common triangular route, for instance, involved bringing rum and goods from Western Europe

to Africa, transporting enslaved people to the Americas, and returning to Europe with cargoes of cotton and sugar.

For many years, access to the sea has been considered a fundamental factor for long-term growth. For example, the Austrian Empire invested considerable effort in conquering and maintaining control over Trieste as a crucial hub for Mediterranean trade, which played an important role in the country's economic growth. Similarly, Russia's Tsar Peter the Great viewed access to the Baltic Sea as fundamental for the growth and modernization of his otherwise landlocked country, this goal was fundamental in determining Russia's international politics and the subsequent war against Sweden. In general, control over maritime flows and naval power is strongly connected with a state's overall growth [58,59,60].

The connection between ports and a country's interior has become important for the prosperity and survival of both. Access to production areas significantly enhances competitiveness in terms of time and costs, requiring continuous improvement and modernization of integrated infrastructure. This is evident in the ports of Northern Continental Europe: Le Havre, Antwerp, Rotterdam, and Hamburg, collectively known as the Northern Range. By the end of the 19th century, these ports were strongly connected to their neighborhoods via extensive railway networks. Despite the opening of the Suez Canal in 1869, these northern ports initially gained greater advantages over their Mediterranean contestants. However, in the long term, the Suez Canal allowed Mediterranean ports to regain global significance.

The 20th century introduced important innovations. Cargo shipping evolved drastically from general purpose vessels to specialized ships improved for specific cargo types [61,62].

Containerization, for example, required specialized ships and port equipment. As a result, port terminals adapted, specializing in different cargo and handling policies. New transport systems enabled the relatively safe handling of dangerous liquid and gaseous materials. The development of long-distance, high-capacity routes, such as the Asia-Europe corridor, required faster and more efficient material handling. A major trend has been toward building larger ships to feat economies of scale, forcing ports to adapt their quays to ensure acceptable handling, management space, and sufficient draft. [63,64]

A port's long-term survival depends not only on trade but also on its ability to adapt to changes in shipping technology. Other critical factors include the availability of

convenient and safe routes, such as the developing Polar Routes in the current global scenario and the safety and security of shipping paths from threats like piracy [65,66].

1.5 Concept of Green ports

Ports serve as key elements in the overall network of international airport and economic systems, acting as vital gateways that connect nations through the exchange of goods, passengers, and energy resources. It is estimated that over 80% of the world's trade is handled through maritime transport. There are more than 2,000 operational ports globally, serving as key hubs for logistics, storage, and distribution. Regardless of their indispensable economic role, ports are also significant contributors to environmental degradation [67,68].

Traditional port operations are heavily dependent on fossil fuels to power ships, cranes, trucks, and auxiliary systems, leading in substantial emissions of greenhouse gases (GHGs), particulate matter, nitrogen oxides, and Sulphur oxides. These pollutants contribute to air and water pollution, acid rain, and global warming, posing severe threats to human health, marine ecosystems, and climate stability. According to the International Maritime Organization (IMO), total GHG emissions from the global shipping industry including domestic, international, and fishing activities increased by 9.6% between 2012 and 2018, from 977 million tons to 1,076 million tons of CO₂ equivalent. Out of all global emissions, maritime transport alone accounts for roughly 11%. The IMO has therefore established an ambitious target to reduce international shipping emissions by at least 50% by 2050 relative to 2008 levels, a goal that requires significant transformation of both shipping operations and port management systems [69,70,71].

In response to these increasing environmental concerns, the idea of eco-friendly ports has emerged as a cornerstone of sustainable maritime development. A green port integrates environmental protection, economic efficiency, and social responsibility into its planning and operation. It seeks to reduce its ecological footprint by lowering emissions, saving energy and water, managing waste effectively, and adopting cleaner technologies. The idea is not entirely about reducing pollution but about redefining the entire operational framework of ports to align with global sustainability goals. [72,73] According to Parhamfar et al. (2023), green ports are designed on the principle of maintaining a balance between environmental impacts and economic benefits, ensuring that one does not outweigh the other. In this sense, a green port depicts a

system where economic productivity coexists with environmental stewardship, leading to long-term ecological and economic resilience.

The evolution of the green port concept can be traced back to growing environmental awareness in the late 20th century, when policymakers and researchers began to identify the growing environmental awareness of the late 20th century, when policy the growing environmental awareness of the late 20th century, when policymakers and researchers began to identify ports as significant nodes in global trade, recognizing them as major sources of pollution and energy consumption [74,75,76]. The European Sea Ports Organization (ESPO) played a revolutionary role in institutionalizing the concept of environmental management in port operations by publishing its first Environmental Code of Practice in 1994, later followed by the E the growing environmental awareness of the late 20th century, when policymakers and researchers began to identify ports as significant SPO Green Guide in 2012. [77,78]

These guidelines outlined environmental performance standards for European ports, focusing on waste reduction, air and water quality management, the growing environmental awareness of the late 20th century, when policymakers and researchers began to identify ports as significant noise control and sustainable energy use. Similarly, the Port of Long Beach in the United States adopted its Green Port Policy in 2005, establishing one of the earliest comprehensive frameworks for eco-friendly port management. As time passed, this policy serves as a model for many other ports around the world, encouraging the adoption of environmental certification systems, green logistics programs, and sustainability reporting frameworks. [79,80]

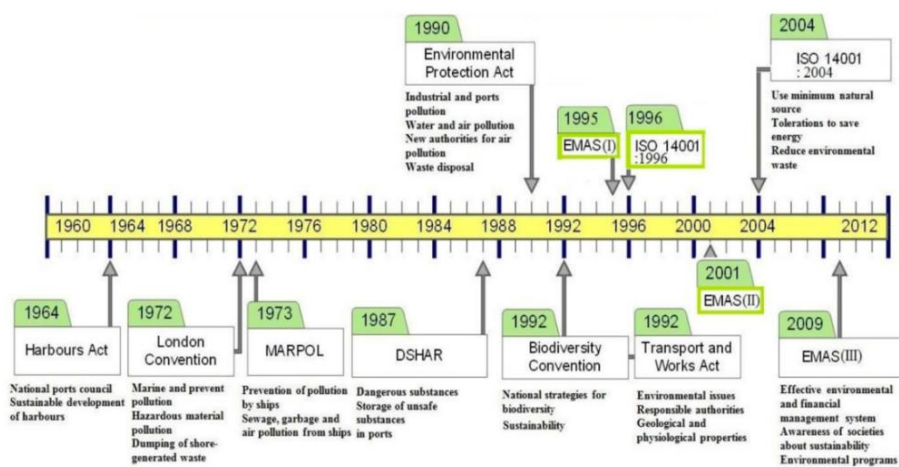


Figure 1-2 The historical path of green port legislation (Canbulat, 2014)

Today, numerous ports across the globe have integrated green strategies into their infrastructure and operations. The Port of Rotterdam in the Netherlands, one of the

largest ports globally, has invested extensively in offshore wind farms and hydrogen infrastructure to reduce its dependence on fossil fuels. The Port of Hamburg in Germany utilizes smart grids and onshore power systems to allow ships to connect to renewable energy sources while docked, eliminating the need for diesel-powered auxiliary engines. Singapore Port has introduced extensive waste recycling programs and electrified cargo-handling systems, while the Ports of Los Angeles and Long Beach in the United States are at the forefront of deploying hydrogen fuel cells and electric vehicles for port operations [80, 81].

The Port of Yokohama in Japan has developed hydrogen-powered yard trucks and implemented renewable energy generation systems. These examples demonstrate that the transition toward green ports is a global phenomenon driven by shared environmental goals and technological innovation.

A key feature of sustainable ports is the integration of renewable energy technologies (RETs) to replace or supplement traditional fossil fuel energy sources. Ports are energy intensive environments that operate continuously, consuming significant amounts of electricity for cranes, lighting, cargo movement, refrigeration, and administrative facilities. RETs such as solar photovoltaic systems, offshore wind turbines, tidal and wave energy systems, and hydrogen fuel cells have proven their capability in providing clean, reliable, and decentralized power to meet these needs. For example, floating solar photovoltaic (PV) systems, which can be installed on water surfaces such as docks or reservoirs, not only generate electricity efficiently but also reduce water evaporation and algae growth [82,83].

Offshore wind turbines take advantage of higher and more stable wind speeds at sea to generate large quantities of renewable energy. Ocean-based energy systems including tidal, wave, and ocean thermal energy conversion (OTEC) technologies offer an enormous but still underdeveloped potential for sustainable power generation. Hydrogen fuel cells, conversely, have capability to retain renewable energy and provide on-demand electricity for ships, vehicles, and port infrastructure while generating no direct emissions.

The adoption of these renewable energy technologies offers multiple benefits. Environmentally, RETs reduce GHG emissions, improve air quality, and decrease dependence on fossil fuels. Economically, they can lower energy costs, improve operational efficiency, and increase energy security by reducing vulnerability to fluctuating fuel prices. Socially, they contribute to cleaner air for port cities, create

green jobs, and improve the quality of life for local communities. However, integrating RETs into port infrastructure also presents challenges. High initial investment costs, technical complexity, maintenance difficulties, and limited available space are among the major barriers. In addition, productive implementation requires strong coordination among various stakeholder's port authorities, government regulators, energy suppliers, shipping companies, and local communities. Successful green port strategies, therefore, rely on holistic planning, policy incentives, and collaborative governance models. [83,84,85]

The environmental and economic foundation behind the green port movement is clear. Ports that adopt sustainable practices not only lessen their environmental impact but also improve their competitiveness on a worldwide scale. Studies have shown that green ports can improve energy efficiency by up to 17.6% and prevent the emission of approximately 25 tons of CO₂ annually per port. In the long term, these improvements lead to reduced operational costs, improved resilience to energy supply disruptions, and greater compliance with international regulations [86,87].

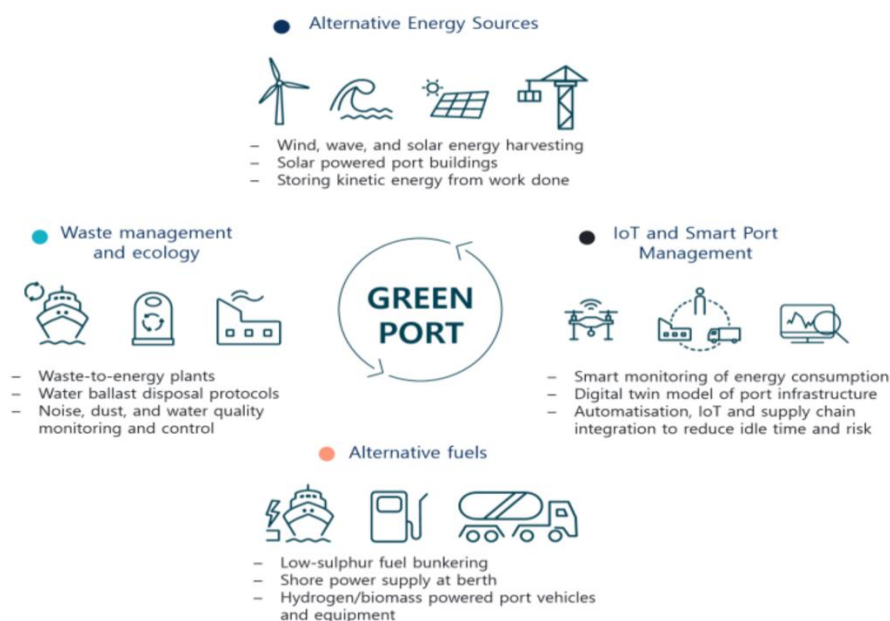


Figure 1-3 Main components of the green port concept (Naveiro, 2021)

In addition, the adoption of environmentally friendly technologies improves the image of ports, drawing the interest of environmentally aware investors, shipping firms, and cultivates to optimize energy management and monitor environmental performance. These digital tools allow ports to track energy use in real time, predict equipment breakdowns, optimize logistics routes, and reduce idle time all of which contribute to improved efficiency and reduced emissions. Smart microgrid systems and battery are

also being integrated into port infrastructures to balance power demand and supply, particularly when incorporating intermittent renewable sources like solar and wind energy. Ultimately, the concept of green ports signifies a paradigm shift in maritime and industrial operations. It extends beyond conventional port management toward an integrated model that highlights sustainability, technological innovation, and social responsibility [88,89].

Green ports symbolize the transition from pollution-intensive industrial hubs to intelligent, self-sustaining, and environmentally resilient ecosystems. As global trade continues to expand, the development of green ports will play a pivotal role in meeting international climate goals, supporting the decarbonization of maritime transport, and contributing to the achievement of the United Nations Sustainable Development Goals (SDGs) particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 13 (Climate Action), and SDG 14 (Life Below Water). [90,91] The path to achieving completely green and smart ports requires global collaboration, sustained investment, and continuous innovation.

Nevertheless, it is increasingly evident that transforming conventional ports into green ports is not merely an environmental necessity but also financial and ethical imperative for a sustainable and resilient future in worldwide maritime trade.

1.6 Modern Seaports

Modern seaports are among the most complex and technologically advanced infrastructures in the global transportation system. They serve not just as physical locations for loading and unloading ships but are highly integrated logistics and economic hubs that connect maritime, land, and air transportation networks. With the increasing globalization of trade and the digital transformation of industries, modern seaports have evolved far beyond their traditional roles. Present-day ports are centers of automation, innovation, data-driven management, and environmental sustainability. [92,93] They are vital in promoting effective supply chains, ensuring energy security, and contributing significantly to national and regional economies. Modern seaports can be viewed as multifunctional, multimodal, and multidisciplinary ecosystems. Their design and operation involve complex interactions between ships, terminals, logistics centers, warehouses, transport networks, and various service providers. They are equipped with advanced cargo-handling machinery, automated container terminals, intelligent transportation systems, and integrated digital platforms that enable real-time

monitoring and control. The transformation from conventional ports to modern smart ports has been driven by rapid technological innovation, growing trade volumes, stricter environmental regulations, and the demand for operational efficiency [94,95].

A key feature of contemporary seaports is the implementation of automation and digitalization in nearly all facets of their operations. The introduction of automated cranes, driverless trucks, and robotic stacking systems has revolutionized cargo handling, reducing human error, improving safety, and increasing throughput capacity. Container terminals such as the Port of Rotterdam (Netherlands), Port of Hamburg (Germany), and Port of Singapore are leading examples of this transformation. These ports have integrated Terminal Operating Systems (TOS) and Port Community Systems (PCS) that connect all stakeholders shipping lines, customs authorities, freight forwarders, and logistics companies on a unified digital platform. This allows seamless data sharing, efficient cargo tracking, and faster decision-making, ultimately reducing turnaround time and cost [97,98,99].



Figure 1-4 Modern sea ports image by Google

A significant development in contemporary seaports is the adoption of intelligent technologies, including Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), and blockchain. These technologies enable ports to become smart ports capable of monitoring their operations in real time and responding dynamically to changing conditions. IoT sensors are used throughout port facilities to collect data on vessel movements, cargo conditions, energy use, and environmental quality [96,97].

For example, smart sensors can monitor the temperature and humidity of containers, detect gas leaks, or measure emissions from ships and vehicles. AI-driven predictive

analytics help in optimizing berth allocation, scheduling maintenance, forecasting cargo demand, and managing port traffic flow. Blockchain technology, on the other hand, provides secure and transparent record-keeping for trade documentation and customs processes, reducing paperwork and fraud. Alongside technological advancements, contemporary seaports have experienced a strategic evolution in both spatial and infrastructural aspects. Historically, ports were situated close to urban centres to promote trade. However, the expansion of global trade and the need for deeper waters to accommodate larger vessels have led to the construction of deep-water ports and offshore terminals. For instance, the Port of Shanghai (China), which is one of the world's busiest container ports with advanced deep-sea facilities, and the Port of Busan (South Korea), known for its high-capacity terminals and integrated logistics zones. Modern ports are also developing intermodal transport systems that connect sea transport with railways, highways, and inland waterways to enhance connectivity and reduce congestion. These interconnections form what is known as a "port hinterland," which extends the economic influence of the port far beyond its physical boundaries.

Environmental sustainability has emerged as a crucial pillar in the development of contemporary seaports. As international awareness of climate change and pollution grows, ports are adopting green practices to minimize their environmental footprint. Modern ports are increasingly powered by renewable energy technologies, including solar photovoltaic systems, offshore wind turbines, and hydrogen fuel cells. Some ports are implementing cold ironing systems (also called shore-to-ship power), which allow vessels to connect to the local electrical grid while docked, eliminating the need to run diesel engines and thereby significantly reducing emissions. Waste management, water treatment, and noise reduction measures are also integral parts of modern port design. In Europe, for instance, ports such as Rotterdam, Gothenburg, and Antwerp have established comprehensive green port programs

that align with the European Union's decarbonization objectives. These initiatives include energy efficiency measures, alternative fuel promotion, biodiversity protection, and carbon-neutral infrastructure. Modern ports are also major economic growth engines that drive industrialization, innovation, and employment. They act as essential hubs within global value chains, facilitating the manufacturing, logistics, tourism, and energy industries. The port industry generates millions of jobs directly and indirectly and contributes substantially to national GDPs. Many ports have developed special economic zones (SEZs) and logistics parks adjacent to their facilities, attracting

international investment and enabling industries such as petrochemicals, automotive, and electronics to thrive. For instance, the Jebel Ali Port in Dubai, which is one of the largest man-made harbors in the world, operates within a free trade zone that hosts over 7,000 companies from more than 100 countries, offering integrated logistics and industrial services [98,99].

Another hallmark of modern seaports is their resilience and adaptability in the face of global challenges such as climate change, pandemics, and supply chain disruptions. The COVID-19 pandemic highlighted the vulnerability of global trade networks but also accelerated digital transformation in ports. Many ports adopted remote monitoring systems, automated gates, and contactless cargo handling to maintain operations safely and efficiently. In response to increasing climate risks such as sea-level rise and extreme weather events, ports are now investing in climate-resilient infrastructure, including elevated quays, flood barriers, and reinforced seawalls. Additionally, the development of energy storage systems, microgrids, and emergency power backup solutions has improved the energy reliability of modern ports, making them more resistant to external disruptions. Modern ports are no longer just maritime infrastructures they are integrated smart ecosystems combining technology, sustainability, and global connectivity. They are transitioning toward the concept of “Port 4.0,” which mirrors the principles of Industry 4.0, emphasizing full digitalization, automation, and intelligence in port management. Port 4.0 systems use cyber-physical integration to link machinery, humans, and digital platforms, creating self-regulating networks capable of autonomous operation. This approach leads to higher efficiency, lower operational costs, and reduced environmental impact.

Despite these advancements, modern seaports face several challenges. The increasing scale of vessels, the complexity of logistics, cyber threats, and the high capital costs of technological infrastructure all pose serious difficulties. Moreover, the need to harmonize international regulations and digital standards across ports remains a pressing issue. Balancing rapid technological progress with environmental responsibility also requires careful planning and governance. Nevertheless, global cooperation through organizations such as the International Association of Ports and Harbors (IAPH) and the World Ports Sustainability Program (WPSP) is helping ports share best practices and establish common frameworks for sustainability and innovation. In summary, contemporary seaports serve as the cornerstone of the worldwide economy and the leading edge of technological and environmental advancements. They are

evolving from traditional, labour-intensive facilities into intelligent, automated, and sustainable logistics ecosystems. Through digitalization, renewable energy integration, and collaborative governance, modern ports are setting new standards for efficiency, safety, and environmental stewardship. They symbolize the future of maritime transport one that is smart, sustainable, resilient, and fully aligned with the global transition toward a low-carbon economy. As a worldwide trade continues to expand, the modernization of seaports will be essential not only for maintaining economic competitiveness but also for achieving global sustainability and climate goals in the 21st century.

1.7 Challenges in renewable energy integration in seaports

The integration of renewable energy technologies (RETs) into the maritime sector, especially in existing ports, newly developed modern ports, and ships represents a vital step toward achieving global decarbonization and sustainability goals. Nevertheless, the shift from fossil fuel-dependent operations to clean and renewable energy systems is a complex and multifaceted challenge. This transformation involves not only technological adaptation but also infrastructural, financial, regulatory, and operational considerations. The maritime industry is one of the most energy-intensive sectors, and its transition to renewable energy sources requires coordinated planning among port authorities, shipping companies, energy providers, and policymakers. Despite the potential advantages of renewable energy, such as reduced emissions, energy independence, and lower operational costs, a range of obstacles continues to hinder their full integration into old and current port facilities and maritime vessels.

1.7.1 Modern Seaports

One of the main obstacles in incorporating renewable energy into both existing and modern ports is the technological complexity associated with adapting renewable systems to the unique operational characteristics of ports and ships. Unlike land-based industries, ports operate continuously, often 24 hours a day, requiring a stable and reliable power supply. Renewable energy sources such as solar and wind are intermittent and variable, depending on weather conditions and geographical location. Therefore, ensuring continuous energy availability, therefore, requires the incorporation of large-scale energy storage systems, such as batteries or hydrogen-based storage, which are still costly and limited in capacity. Retrofitting old port infrastructures to accommodate new technologies poses additional difficulties. Older ports were

designed around fossil fuel systems diesel generators, conventional grid connections, and combustion-powered machinery without consideration for renewable integration. As a result, existing electrical grids and distribution networks within these ports often lack the capacity or flexibility to handle decentralized renewable inputs like solar PV or offshore wind power. Integrating renewables would require substantial modernization of electrical systems, installation of smart grids, and deployment of digital monitoring systems to balance power flows.

In ships, technological challenges are even more pronounced. The maritime sector is heavily reliant on heavy fuel oil (HFO) and marine diesel oil (MDO), both of which provide high energy density. Renewable technologies such as hydrogen fuel cells, ammonia, biofuels, and wind-assisted propulsion systems require redesigning ships' propulsion systems, fuel storage configurations, and onboard power management. Hydrogen and ammonia, while promising as zero-carbon fuels, demand entirely new fuelling and safety systems due to their volatility and storage challenges. Similarly, solar panels and small wind turbines can be installed on ships, but their contribution to total energy demand is often limited because of restricted surface area and variable energy output. The technological transition for ships is therefore far more complex than for land-based systems.

1.7.2 Infrastructural Challenges

Infrastructure remains one of the biggest barriers to renewable energy integration in old and modern ports. Many existing ports were built many years ago, with rigid layouts and limited available space for new installations. The addition of large-scale renewable energy systems such as solar farms, wind turbines, or hydrogen production facilities requires significant land or water area, which is often not available in congested or urbanized port regions. For example, ports situated near dense cities like Rotterdam, Singapore, or Hong Kong face acute space constraints that limit the deployment of onshore wind or solar projects. The incorporation of offshore renewable energy such as offshore wind or floating solar systems requires specialized infrastructure for connection, maintenance, and grid integration. Offshore systems require subsea cabling, energy transmission substations, and corrosion-resistant anchoring structures, all of which are capital-intensive and technically complex. In

older ports, quay walls, docks, and electrical substations may need reinforcement or redesign to accommodate new loads and energy transmission systems.

Moreover, hydrogen infrastructure poses a unique challenge. The Production, storage, and distribution of green hydrogen require specialized facilities, including electrolysis plants, cryogenic storage tanks, and high-pressure pipelines. Hydrogen's flammable nature demands rigorous safety protocols and zoning requirements. Most current ports lack such facilities, meaning that hydrogen integration involves entirely new construction and redesign of existing spaces. The absence of globally standardized infrastructure for hydrogen bunkering also complicates the transition for international shipping operations.

1.7.3 Economic and Financial Challenges

The financial strain linked to integration of renewable energy stands as one of the most significant barriers. Despite renewable technologies have seen dramatic cost reductions over the past decade, the initial capital investment for installation, grid upgrades, and infrastructure modification remains high. For ports, the expenses of installing offshore wind farms, floating solar panels, or hydrogen plants can reach hundreds of millions of dollars, depending on scale and location. Numerous port authorities function within constrained budgets, and without strong financial incentives, such initiatives may not seem economically viable. Retrofitting old ports is often has higher costs than building new green ports from scratch. Existing infrastructure requires dismantling, retrofitting, or replacing legacy systems, which interrupts operations and generates additional costs. The return on investment for renewable initiatives in ports can also be long-term, often extending beyond a decade, which discourages private investors seeking faster payback. In the shipping sector, transitioning to renewable and alternative energy sources involves the replacement or retrofitting of vessels, which can cost several million dollars per ship. Hydrogen or ammonia-powered vessels, for instance, require new fuel storage systems, safety equipment, and propulsion technologies, significantly increasing capital expenditure. Moreover, renewable fuels such as green hydrogen, e-methanol, or advanced biofuels are currently much more expensive than traditional fuels, making them economically unattractive without subsidies or carbon pricing frameworks.

1.7.4 Regulatory and Policy Challenges

The absence of clear and harmonized international regulations for renewable energy use in ports and shipping is another major challenge. The maritime

sector operates across borders, and inconsistencies in national policies, incentives, and environmental standards complicate investment and implementation. Although organizations like the International Maritime Organization (IMO) and the European Union (EU) have introduced emission reduction targets, many countries still lack specific regulatory frameworks or incentives to promote renewable integration at the port level. Ports must also comply with multiple overlapping regulations related to safety, environmental protection, and energy production. For instance, building wind turbines or hydrogen facilities in port zones often requires environmental impact assessments, safety certifications, and coordination with local governments. The lack of standardized certification systems for green port initiatives can further delay project approval and financing. In shipping, regulatory uncertainty about acceptable low-carbon fuels (such as hydrogen, ammonia, or synthetic fuels) creates investment hesitation among shipowners and fuel suppliers.

1.7.5 Operational and Logistical Challenges

Renewable energy integration also introduces significant operational challenges. Ports are complex ecosystems where multiple energy-consuming activities such as cargo handling, refrigeration, and vessel power supply occur simultaneously. Balancing these loads with intermittent renewable generation requires sophisticated energy management systems and real-time data monitoring. Implementing such systems in old ports is difficult because of the lack of digital infrastructure and skilled personnel.

The maintenance of renewable systems in harsh maritime environments presents another issue. Saltwater corrosion, strong winds, humidity, and storms can damage solar panels, turbines, and electrical equipment. Maintenance operations are costlier and riskier compared to inland systems, especially for offshore installations.

In ships, logistical challenges include fuel availability and bunkering infrastructure. Renewable fuels such as hydrogen and ammonia require new supply chains and bunkering systems that are currently limited to a few pilot ports worldwide (e.g., Rotterdam, Singapore, and Los Angeles). Without a global network of renewable fuel bunkering stations, ships powered by alternative fuels face route restrictions and operational risks.

1.7.6 Social and Institutional Challenges

Renewable integration also faces institutional inertia and social resistance. Port authorities, shipping companies, and workers often operate under conventional frameworks that emphasize immediate efficiency and profit over long-term

sustainability. The shift towards renewable energy systems demands changes in management structures, staff training, and labor practices. In certain areas, unions or labor groups express concern about automation and new technologies reducing employment opportunities. Public perception is also significant, particularly in cases where renewable initiatives such as wind farms or hydrogen plants generate concerns about visual impact, noise, or safety.

1.7.7 Energy Storage and Grid Integration

Finally, one of the most significant technical barriers is the absence of efficient energy storage and grid integration. Renewable energy sources are naturally variable, and without adequate storage capacity, ports cannot ensure continuous power for operations or ships at berth. Battery technologies are advancing but remain costly and limited in scale. Hydrogen-based storage offers potential, but the required electrolyzers, compressors, and fuel cells are expensive and not yet widely available. Furthermore, integrating large-scale renewables into local or national grids often requires upgrading transmission systems and installation of smart grid technologies that can manage both bidirectional power flow and demand response.

1.8 Chapter Summary

The integration of renewable energy technologies into conventional and modern ports, as well as maritime ships, represents a transformative yet complicated change for the maritime sector. Traditional ports must retrofit old infrastructures, upgrade grid connections, and incorporate systems such as shore-to-ship power, solar installations, and green hydrogen production, all while maintaining operational efficiency and economic attractiveness. Modern ports, although more flexible, face challenges related to high capital costs, technological interoperability, and compliance with evolving international regulations. Ships face additional barriers stemming from limited onboard space, safety concerns associated with alternative fuels such as hydrogen, ammonia, and methanol, and the irregular global availability of renewable bunkering infrastructure, progress depends on a coordinated approach that includes technological modernization, international policy coordination, public-private investment, and workforce training. As renewable technologies mature and costs decline, their widespread acceptance across ports and ships is expected to become both technically feasible and economically advantageous, marking a significant step toward a sustainable, zero-emission maritime industry.

Chapter 2. Integration of Renewable Energy in Sea Ports

Ports serve as vital nodes in global trade and logistics, yet they are also significant contributors to greenhouse gas emissions, air pollution, and environmental degradation. As global decarbonization efforts accelerate, the integration of renewable energy within port infrastructure has emerged as a transformative pathway toward sustainable operations. This paper explores how renewable energy technologies such as solar photovoltaics, wind turbines, green hydrogen, and shore-to-ship power can revolutionize port activities by reducing carbon footprints, enhancing energy efficiency, and supporting the transition to smart, eco-friendly logistics hubs.

Several international initiatives and case studies are analyzed to highlight best practices and identify practical challenges in implementation. The study also emphasizes the role of policy frameworks, digitalization, and stakeholder collaboration in enabling this transition. The findings suggest that renewable energy adoption not only mitigates environmental impacts but also enhances the competitiveness and resilience of ports in the era of sustainable development.

2.1 Introduction

Ports have long been recognized as critical engines of economic growth and international trade, acting as gateways that connect nations, facilitate the movement of goods, and support industrial development [100, 101]. Their strategic position in global supply chains makes them indispensable nodes of commerce, yet this importance comes with substantial environmental costs. The traditional reliance on fossil fuels to power cargo handling, vessel operations, port machinery, and auxiliary services has positioned ports among the largest contributors to local air pollution, greenhouse gas (GHG) emissions, and disturbances to fragile marine and coastal ecosystems [102,103]. The heavy use of diesel generators, bunker fuels, and coal-based electricity has not only degraded local air quality but also intensified global carbon dioxide emissions, thereby undermining international climate change mitigation efforts [104].

Over the past two decades, the urgency of addressing these environmental concerns has grown significantly. Rising sea levels, stricter air quality standards in port cities, and international frameworks such as the International Maritime Organization's (IMO) decarbonization strategy, which targets a 70% reduction in carbon intensity by 2050, have placed ports at the center of sustainability debates [105]. Consequently, the call

for transforming ports into low-carbon, resilient, and environmentally sustainable hubs has become stronger than ever. Renewable energy technologies, ranging from solar photovoltaics (PV) and offshore wind to bioenergy and hydrogen-based systems, present a viable and increasingly practical pathway for this transformation [106,107]. Unlike conventional energy sources, renewables provide clean and abundant power that can drive port operations while drastically reducing carbon footprints.

The feasibility of renewable-powered ports is further strengthened by advancements in complementary technologies. Modern energy storage solutions, such as lithium-ion and flow batteries, ensure stable energy supply despite the intermittency of renewable sources [108]. Digitalization, using smart grids, Internet of Things (IoT) devices, and real-time monitoring systems, enhances efficiency by optimizing energy distribution and consumption [109]. Together, these innovations create the foundation for integrated, intelligent port ecosystems that align with the broader vision of smart and sustainable cities. Several pioneering ports around the world have already demonstrated the potential of renewable energy integration. The Port of Rotterdam has invested heavily in offshore wind and hydrogen infrastructure, positioning itself as a leader in Europe's energy transition [110]. The Port of Los Angeles has initiated solar and electrification projects to minimize emissions in one of the world's busiest shipping corridors [111]. Similarly, Singapore and Hamburg have introduced hybrid solutions combining renewable power with smart energy management systems, setting international benchmarks for sustainable maritime logistics [112].

These examples highlight that renewable energy adoption in ports is not only technically feasible but also economically advantageous in the long term.

Despite such progress, the journey toward widespread renewable adoption in ports remains fraught with challenges. High initial investment costs, infrastructural limitations, regulatory uncertainties, and institutional resistance to change continue to act as significant barriers [113]. Additionally, the heterogeneity of ports ranging from large international hubs to small regional terminals means that strategies cannot be uniformly applied, and context-specific solutions are essential.

This paper investigates the evolving role of renewable energy in reshaping ports into green hubs. It aims to provide a comprehensive overview of current progress, assess the key drivers and barriers influencing adoption, and propose strategies that can accelerate the energy transition in maritime infrastructures. By doing so, the study situates renewable-powered ports within the framework of the United Nations Sustainable

Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 13 (Climate Action) [114]. Ultimately, this work emphasizes that decarbonizing ports is not only an environmental necessity but also an economic and social opportunity, enabling ports to remain competitive, resilient, and aligned with global sustainability imperatives.

2.2 Literature Review

The environmental footprint of global port operations has been extensively documented in academic and industrial reports. Ports consume large quantities of fossil fuels for powering ships at berth, container handling equipment, cranes, and heavy-duty vehicles. As a result, they contribute significantly to greenhouse gas (GHG) emissions, Sulphur oxides (Sox), nitrogen oxides (NOx), and particulate matter, posing risks to urban air quality and marine ecosystems. With the International Maritime Organization (IMO) setting ambitious decarbonization targets such as a 50% reduction in shipping-related emissions by 2050 the role of renewable energy in port operations has become a subject of increasing academic interest [115,116,117].

2.3 The Concept of Green Ports

The term green port refers to a maritime hub that integrates environmental sustainability into its infrastructure, operations, and policies. Early studies on green ports focused primarily on pollution control measures, such as stricter emission standards and waste management systems. However, recent literature emphasizes a paradigm shift toward renewable energy deployment as a proactive strategy for decarbonization. Researchers argue that ports must evolve into energy hubs capable of producing, storing, and distributing renewable power, not only for their internal needs but also for vessels and surrounding communities [118,119].

2.3.1 Solar Energy Integration

Solar energy is among the most widely adopted renewable sources in port facilities. The flat rooftops of warehouses and administrative buildings provide suitable areas for large-scale photovoltaic (PV) installations. Several studies highlight the cost-effectiveness of solar power in reducing reliance on grid electricity, especially in sun-rich regions. For example, ports in Asia and the Middle East have reported substantial reductions in energy costs after deploying solar arrays. Moreover, solar-powered

lighting systems and charging stations for electric port vehicles have proven effective in enhancing sustainability [120,121,122].

2.3.2 Wind Energy Applications

Wind energy plays a particularly important role in coastal and offshore regions where ports are located. Literature on offshore wind integration emphasizes its scalability and capacity to meet significant portions of port electricity demand. Ports in Northern Europe, such as Rotterdam and Hamburg, have invested heavily in offshore wind farms that supply renewable energy not only to port operations but also to national grids. Studies also indicate that small-scale wind turbines can be installed on port premises to provide auxiliary power, though their intermittent nature requires hybrid systems with storage or grid support [123,124,125].

2.3.3 Case Study

The purpose of this analysis is to estimate the Annual Energy Production (AEP) and capacity factor for a wind energy project located in Porto Vado, Savona (Italy) using a Class III wind turbine. The assessment is based on ten-minute interval wind speed measurements recorded over a full year, extrapolated to a hub height of 50 meters, and analysed against a representative 2 MW wind turbine power curve. Wind Data Investigation, and Statistical Analysis

a. Description of the Site, Wind Data Investigation, and Statistical Analysis

Side description:

The measurement site is situated in Porto Vado (Savona), close to the Ligurian coast. The anemometer was installed at a height of 10 meters above sea level (slm), and data was recorded over the entirety of 2013.

Data Overview:

- Timestamp (10-minute intervals)
- Mean Wind Speed
- Mean Wind Direction
- Maximum Wind Speed
- Turbulence Intensities (Along-wind and Crosswind)

Data Handling:

Time formatting was corrected using Excel's date conversion.

Missing entries were imputed by interpolation using python.

Wind speeds were analysed statistically and plotted.

Wind Profile Observations:

The wind speed distribution (extrapolated to 50 m) shows:

- A peak frequency around 2–3 m/s, typical for Class III wind conditions.
- Moderate frequency of wind events exceeding 10 m/s.
- Low occurrence of extreme wind events (> 20 m/s).

Statistical Analysis:

Description of the Site, Wind Data Investigation, and Statistical Analysis:

This section presents the statistical investigation of one year of wind collected at 10 meters in Porto Vado (Savona). Wind speeds were extrapolated to 50 meters using a power law with an exponent of 0.14.

Key wind speed statistics at 50 meters:

- Mean Wind Speed: 4.85 m/s
- Standard Deviation: 3.69 m/s
- Maximum Wind Speed: 24.84 m/s
- Minimum Wind Speed: 0.00 m/s
- Weibull Shape Parameter (k): 1.37
- Weibull Scale Parameter (c): 5.33

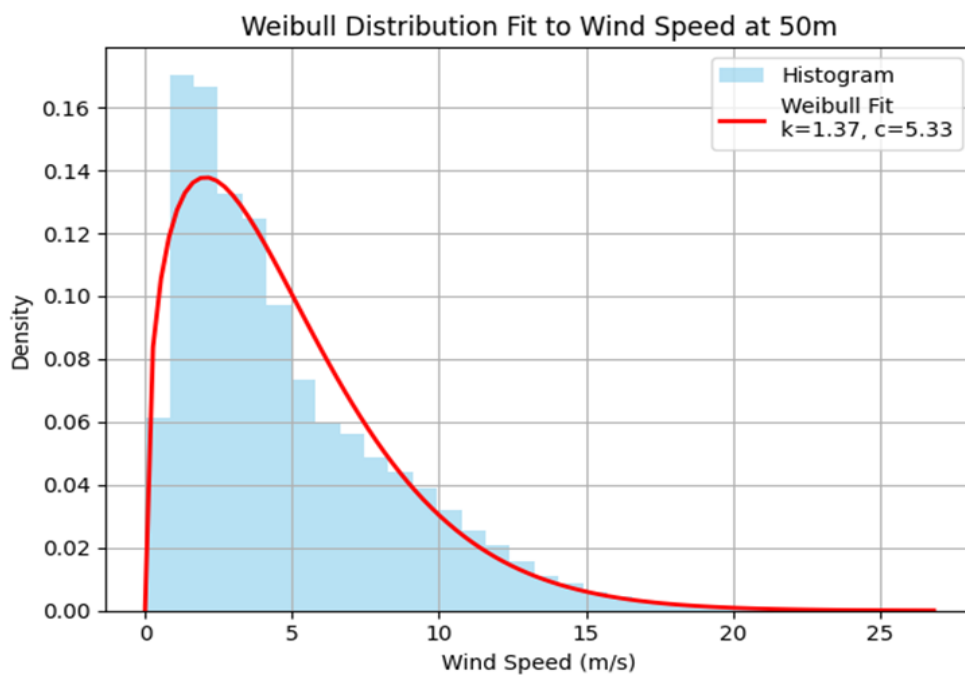


Figure 2-1 Weibull Distribution Fit

The Figure 2-1 displays the Weibull distribution fitted to a histogram of observed wind speeds at 50 m. The light blue bars (Histogram) show the actual frequency of different wind speeds, with the most frequent speeds being low (around 2-5 m/s). The red curve (Weibull Fit) is the mathematical model used to approximate this distribution, defined by the shape parameter ($k=1.37$) and the scale parameter ($c= 5.33$ m/s). This fit is

essential for wind energy resource assessment, as it allows engineers to calculate the long-term potential energy yield of a wind turbine at that location.

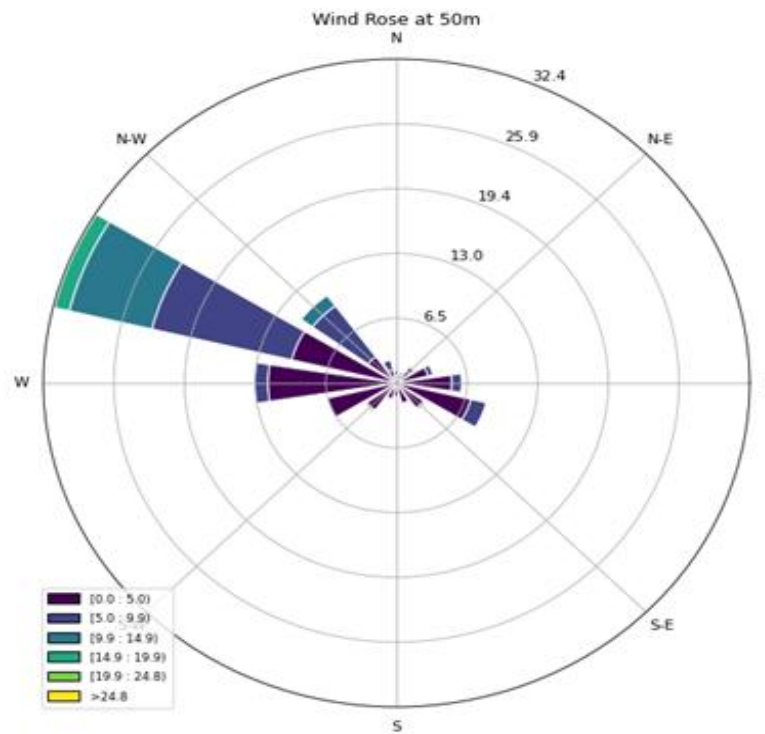


Figure 2-2 Wind Rose Diagram

The Figure 2-2 is a Wind Rose diagram, which is used to graphically represent how wind speed and wind direction are distributed at a specific location and height. The length of each spoke radiating from the center indicates the frequency (or percentage of time) the wind blows from that direction, with the scale marked on the radial lines. The concentric rings, marked with percentages show the frequency scale. The colors within each spoke represent different wind speed ranges as detailed in the legend. For this location, the diagram clearly shows that the predominant wind direction is from the West (W) to Northwest (N-W), with a significant portion of those winds falling into the higher speed ranges, which is crucial information for orienting wind turbines.

b. Turbine Selection and Brief Description of Characteristics

A generic IEC Class III wind turbine was selected for this assessment, suited for low-wind-speed sites. The key specifications used for simulation are summarized below:

Parameter	Value
Rated Power	2000 kW
Cut-in Wind Speed	3.2 m/s
Rated Wind Speed	12.5 m/s
Cut-out Wind Speed	26.0 m/s
Hub Height	50 m
Wind Class	III

Table 2-1 key design specifications of the wind turbine

Table 2-1 outlines the key design specifications of the wind turbine under study a 2 MW model engineered for Wind Class III conditions, indicative of moderate wind sites. Its operational envelope is defined by a cut-in wind speed of 3.2 m/s, at which it begins power generation, and a cut-out speed of 26.0 m/s, where it ceases operation to ensure structural integrity. The turbine achieves its rated power output of 2000 kW at a wind speed of 12.5 m/s. With a hub height of 50 meters, the turbine is positioned to access higher, more consistent wind flows, optimizing its energy capture potential within its designed wind regime.

c. Wind Speed Transfer to Turbine Hub

The original wind speed measurements at 10 m were extrapolated to 50 m using the power law:

$$V_{50} = V_{10} * (50 / 10)^{0.14} \quad (1)$$

where $\alpha = 0.14$ represents the wind shear exponent for open terrain. This extrapolation method is standard in pre-feasibility studies and introduces a small uncertainty when no vertical profile data is available.

d. Energy Production Assessment

Using Python (developed script appended below), the extrapolated wind speed and the defined turbine power curve, power output was computed at 10-minute intervals, and energy was summed to yield annual Figures.

e. Results:

- Annual Energy Production (AEP): 2318.33 MWh
- Capacity Factor: 13.23%

These values reflect moderate productivity, aligned with typical expectations for Class III wind regimes. While not optimal for large-scale commercial deployment, it may still be economically viable with feed-in tariffs or local demand offset strategies.

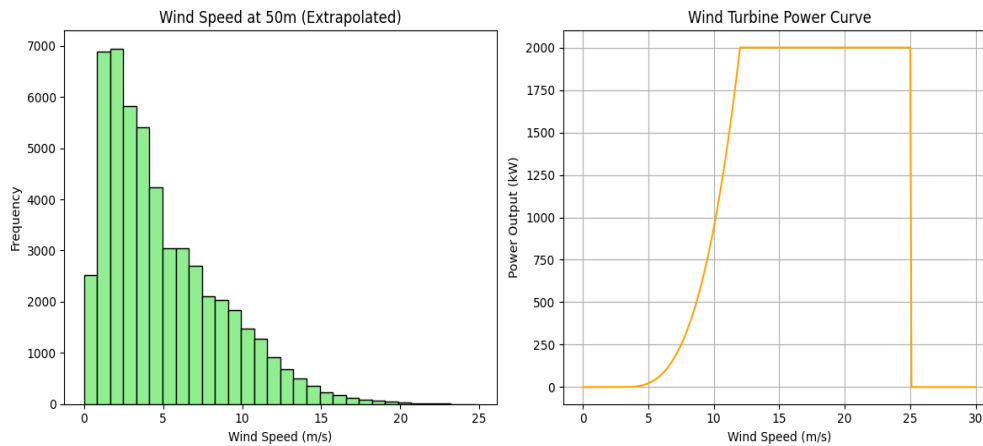


Figure 2-3 Frequency vs Wind speed and Power curve vs wind speed

This Figure 2-3 presents the synthesized wind resource at the project site alongside the turbine's performance characteristics. The bars represent the annual frequency distribution of wind speeds at the hub height (50m), showing how often each wind speed occurs. The overlaid power curve (the solid line) illustrates the corresponding electrical power output of the 2 MW turbine across these wind speeds. It visually demonstrates the correlation between wind resource availability and energy generation, confirming that the turbine begins producing power at the cut-in speed (3.2 m/s), reaches its rated output (2000 kW) near the rated wind speed (12.5 m/s), and maintains this output until the cut-out speed (26 m/s) is reached.

2.3.4 Hydrogen and Alternative Fuels

Hydrogen has emerged as a versatile energy carrier in port decarbonization strategies. Green hydrogen, produced through electrolysis powered by renewable energy, is gaining traction as a fuel for port vehicles, cargo handling equipment, and even ships. Literature suggests that hydrogen can serve as both a fuel and an energy storage medium, addressing the intermittency challenges of solar and wind. Case studies from European ports demonstrate pilot projects where hydrogen-powered trucks, forklifts, and buses are already in operation. Some researchers also emphasize the potential of ammonia and biofuels as complementary alternatives, though scalability and infrastructure readiness remain pressing challenges [126,127,128].

2.3.5 Shore-to-Ship Power (Cold Ironing)

A recurring theme in port sustainability literature is the provision of shore-to-ship power (also known as cold ironing), where vessels connect to onshore electrical grids instead of running auxiliary engines while docked. Studies reveal that this approach can

reduce local air pollutants by up to 90% and cut CO₂ emissions substantially. Renewable-powered shore connections have the added advantage of ensuring that the environmental benefits are not offset by fossil-based grid electricity. Ports in California, for example, have mandated OPS for large vessels, while European ports are increasingly coupling OPS systems with renewable energy sources [129,130,131].

2.3.6 Digitalization and Smart Grids

Another critical dimension explored in recent studies is the role of digitalization in managing renewable- powered ports. Smart grid technologies, artificial intelligence (AI), and Internet of Things (IoT)-based monitoring systems enable real-time optimization of energy generation, storage, and consumption. Literature highlights that such systems can balance fluctuating renewable inputs with demand from vessels and port operations, improving efficiency and reducing operational costs. Digital twins of ports virtual models that simulate energy and logistics flows are increasingly used in research to test renewable energy integration scenarios before implementation [132,133].

2.3.7 Policy and Regulatory Perspectives

The success of renewable energy adoption in ports is closely tied to supportive policy frameworks. Literature reviews on this subject underline the role of government incentives, international cooperation, and standardization in accelerating the transition. For instance, subsidies for renewable installations, carbon pricing mechanisms, and emissions trading schemes provide economic drivers for adoption. On the international level, the IMO and European Union directives have been instrumental in pushing ports toward cleaner energy practices. However, studies also point to regulatory inconsistencies across regions as a barrier to harmonized implementation [134,135,136].

2.3.8 Challenges Highlighted in Literature

Despite the progress, the literature also identifies several barriers:

Economic Barriers: High capital investment and uncertain payback periods deter smaller ports from adopting renewables.

Technical Barriers: Limited availability of large-scale storage solutions to constrain renewable integration.

Operational Barriers: Compatibility issues between renewable technologies and existing port equipment.

Social Barriers: Resistance from stakeholders due to perceived risks or lack of awareness.

Emerging Trends

Recent research suggests a growing interest in hybrid solutions, where multiple renewable technologies are combined with energy storage and digital systems. Another trend is regional

collaboration clusters of ports working together to share renewable infrastructure and best practices. The literature also indicates rising academic attention on life-cycle assessment (LCA) of renewable energy technologies in ports, providing insights into long-term environmental and economic impacts [137,138].



Figure 2-4 Research Background

2.4 Methodology

The methodology of this study is grounded in a conceptual framework that integrates both theoretical foundations and practical approaches relevant to the research objectives. The framework establishes the relationships between key variables, guiding the analysis through a systematic process of data collection, interpretation, and

evaluation. It begins by identifying the central concepts and their interdependencies, which inform the selection of appropriate qualitative, quantitative, or mixed-methods strategies. This structured approach ensures that each stage of the research, from problem formulation to data analysis, is aligned with the overarching theoretical principles. By linking conceptual assumptions with methodological choices, the framework provides a coherent pathway for understanding the research problem and generating reliable, valid, and evidence-based findings.

This paper adopts a conceptual and analytical methodology to investigate the role of renewable energy in transforming ports into sustainable green hubs. Rather than primary data collection, the approach involves

synthesizing secondary sources, policy reports, and documented case studies to derive a holistic framework. The methodology can be outlined as follows:

Energy Mapping of Ports: Reviewing studies on energy consumption patterns in ports, with emphasis on vessel berthing, cargo handling, warehousing, and administrative operations.

- **Technology Matching:** Identifying the most suitable renewable energy technologies (solar, wind, hydrogen, bioenergy) for each operational area within ports.
- **Integration Model:** Proposing hybrid energy systems where renewables are combined with energy storage solutions and supported by smart grids to balance supply-demand fluctuations.
- **Comparative Case Study Review:** Analysing global ports that have successfully implemented renewable technologies, with emphasis on their strategies, achievements, and barriers.

Evaluation of Drivers and Barriers: Categorizing the economic, technical, regulatory, and social factors that either accelerate or hinder renewable adoption. [39,40]



Figure 2-5 Research Methodology

This study will be conducted following a structured research methodology. The process will commence with a comprehensive Literature Review to establish a theoretical foundation and identify current knowledge gaps. Subsequently, Data Collection will be carried out to gather relevant operational and environmental data. This data will then undergo rigorous Data Analysis to evaluate the feasibility and potential impact of the proposed solutions. Finally, the results will be interpreted and contextualized in the discussion section, leading to conclusive findings and recommendations.

Case Studies of Renewable Energy

Adoption in Ports Case study 1

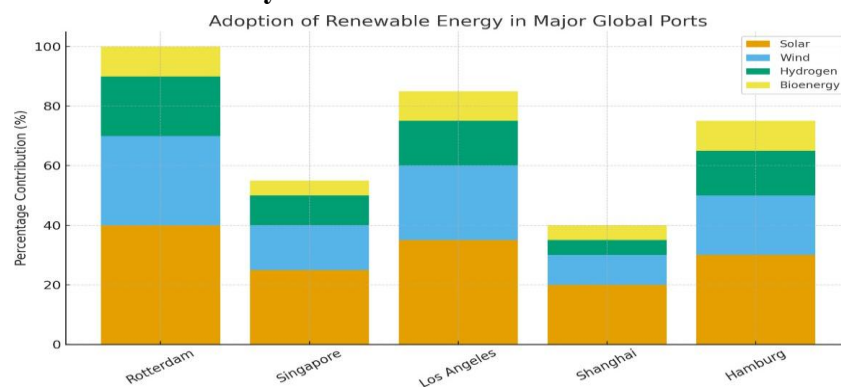


Figure 2-6 Indicating Bar Graph for Renewable Energy in Major Global Ports

Figure 2-6 is representing the bar graph of adoption of renewable energy in major Global parts it is representing percentage contribution of major ports in the world the detailed description is given bellow.

a. Description of the Bar Graph

- Rotterdam demonstrates the highest integration of renewables, with solar (40%) and wind (30%) being dominant.
- Los Angeles shows a balanced mix of solar (35%), wind (25%), and hydrogen (15%), reflecting its aggressive clean-energy policies.
- Singapore and Shanghai are emerging adopters, with modest reliance on hydrogen and bioenergy due to limited land for large-scale wind/solar.
- Hamburg shows a diversified portfolio, though at a smaller scale, with notable hydrogen integration (15%).

This graph highlights how ports worldwide are diversifying renewable energy sources, with solar and wind leading the transition, while hydrogen and bioenergy are gaining momentum to support sustainable port operations [141,142,143].

Port	Technology Adopted	Initiatives	Reported Impact
Rotterdam (Netherlands)	Offshore wind + Hydrogen	Large-scale wind farms, hydrogen refuelling stations	Significant CO ₂ reduction, positioned as Europe’s green hub
Los Angeles (USA)	Solar + Shore-to-ship power	Zero-emission trucks, mandatory OPS for container ships	Reduced NO _x and SO _x emissions, compliance with IMO rules
Singapore	Solar + Smart grid integration	Solar rooftops, AI-based energy management system	Enhanced efficiency, reduced grid dependence
Hamburg (Germany)	Hydrogen fuel cells + Electrification	Pilot hydrogen vehicles, electrification of cranes	Improved local air quality, progress toward zero-emission mobility
Shanghai (China)	Hybris remeabile microgrids	Microgrid with solar and wind for container terminals	Improved energy reliability, reduce fossil fuel reliance

Table 2-2 Selected Global Examples of Renewable Energy Integration in Ports

Table 2-2 is a comparative analysis of green technology adoption in five major international ports, summarizing their key initiatives and environmental outcomes. The Port of Rotterdam and Hamburg are leveraging hydrogen and electrification, respectively, to reduce CO₂ emissions and improve air quality. Los Angeles and Shanghai have integrated solar power with smart microgrids and shore-to-ship power,

resulting in decreased NOx/SOx emissions and enhanced energy reliability. Singapore complements its solar initiatives with AI-driven energy management, boosting operational efficiency. Collectively, these case studies demonstrate how targeted technological investments—from renewable energy to digital systems—enable ports to achieve significant sustainability gains, including emission reductions and improved energy resilience.

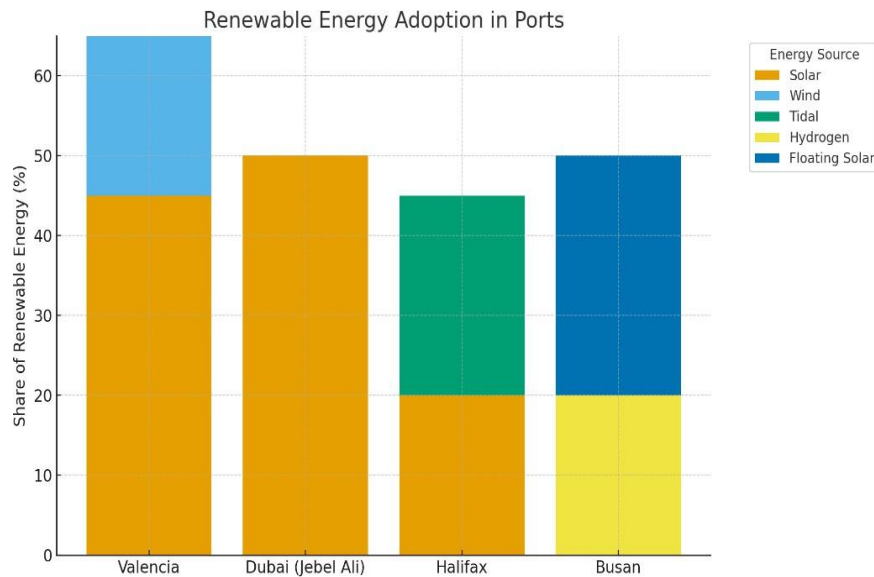


Figure 2-7 Indicating Bar Graph for Renewable Energy in Adoption Ports

The Figure 2-7 is a bar graph compares the adoption of renewable energy technologies across selected ports. Valencia stands out with the largest reliance on solar energy (45%) and a growing share of wind (20%), aligning with its goal of becoming the first fully renewable-powered port in Europe.

Dubai (Jebel Ali) shows strong solar integration (50%) due to large-scale rooftop installations, but limited wind contribution because of geographical constraints.

Halifax demonstrates early adoption of tidal energy (25%) alongside solar (20%), making it unique among global ports for exploring ocean-based renewables.

Busan highlights innovation through floating solar (30%) and hydrogen (20%), signalling Asia’s growing investment in next-generation port energy systems.

In summary, the graph underscores regional variations in renewable energy adoption: Mediterranean and Middle Eastern ports are capitalizing on solar, Atlantic ports are testing marine renewables, and Asian ports are advancing with hydrogen and floating solar technologies [144,145].

2.5 Summary

The integration of renewable energy in ports is no longer an optional initiative but a critical step toward achieving global decarbonization goals. Solar, wind, hydrogen, and digitalized smart grids provide viable solutions for transforming conventional ports into sustainable green hubs. Case studies from Rotterdam, Los Angeles, Singapore, Hamburg, and Shanghai demonstrate both the feasibility and benefits of such transitions. However, widespread adoption demands: Policy Harmonization: International standards and incentives to support renewable integration. Technological Innovation: Advancements in storage systems, AI, and hybrid solutions. Financial Mechanisms: Public-private partnerships, green bonds, and subsidies to offset high upfront costs. Stakeholder Engagement: Education and awareness programs to overcome resistance from port operators and users. Looking forward, ports are expected to evolve into energy hubs of the future, not only powering their own operations but also serving as renewable energy providers for vessels, industries, and surrounding urban areas. This transition aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 13 (Climate Action). By embracing renewable energy, ports can position themselves at the forefront of sustainable industrial transformation and global climate action.

Chapter 3. LNG Bunkering

Under the increasing pressure to cut its environmental impact, the maritime industry has found liquefied natural gas (LNG) to be a promising substitution for traditional marine fuels. Using LNG provides important environmental gains, such as a NO_x reduction of up to 90%, total elimination of Sox, and a reduction in CO₂ of 25%. In addition to these ecological benefits, LNG supplies economic perks such as cheaper fuel costs than oil-based fuels, rendering it a generous solution for ship operators. In answer to these influences, several seaports, particularly European, have initiated LNG bunkering, which involves transferring LNG from a supply vessel, terminal, or truck to a boat. The role of LNG bunkering in promoting sustainability in seaports is the subject of this paper. The paper focuses on the different bunkering strategies, looking at pipeline-to-ship (PTS), truck-to-ship (TTS), and ship-to-ship (STS) transfers, and evaluates the required infrastructure including LNG terminals. Also, the paper stresses the importance of safety regulations, given the flammable character of LNG, and examines how ports might guarantee the smooth and secure handling of LNG. In the context of analysing both the difficulties and benefits of LNG bunkering, the research provides practical advice for port facilities looking to raise their operational efficiency while adhering to worldwide environmental standards.

3.1 Introduction

Environmental sustainability has grown to be a key issue for sectors internationally, especially those with considerable carbon footprints [146]. Being responsible for roughly 90% of trade globally by volume, the maritime sector is critically important to this conversation because of its reliance on high polluting fossil fuels [147, 148, 149]. The traditional reliance of the shipping industry on heavy fuel oils (HFO) and other fuel types rich in carbon results in high emissions of sulfur oxides (Sox), nitrogen oxides (NO_x), and particulate matter, all of which raise serious health and environmental concerns [150]. Due to escalating environmental worries and the stiffening of international maritime regulations, there has been a major movement towards cleaner alternatives, with liquefied natural gas (LNG) becoming a frontrunner [151]. LNG acts as a cleaner environmental option when compared to standard marine fuels, such as heavy fuel oil (HFO) or diesel. When used instead of traditional marine fuels, LNG presents environmental benefits which may include reductions of up to 90% of NO_x,

100% of Sox and 25% of carbon dioxide (CO₂) emissions [152, 153]. Also, its economic advantages such as cheaper fuel costs when compared to fuel derived from oil further facilitate its uptake during a time when the shipping industry faces increasing scrutiny over its environmental influences [154].

Ports in Europe and elsewhere are turning more towards LNG as a marine fuel, pushed by both financial incentives and tough environmental standards such as the International Maritime Organization's (IMO) 2020 sulphur cap [155]. Bunkering of LNG, the act of moving LNG from a supply ship to a watercraft, has become important for ports that want to promote more sustainable marine practices. LNG does come with its own set of problems. The processing, storage, and shipping of LNG demand specialized infrastructure, safety practices, and the skill needed to mitigate risks tied to the fuel's readily combustible nature [156].

This article explores the importance of LNG bunkering in seaports, focusing on the processes, methodologies, and safety practices involved. The paper aims to assess the current methods used for LNG bunkering, including pipeline-to-ship (PTS), truck-to-ship (TTS), and ship-to-ship (STS) transfers, and highlight the critical role of LNG terminals in the handling, storage, and regasification of liquefied natural gas [157, 158]. Furthermore, the discussion will explore the various safety precautions essential to ensuring the safe and efficient transfer of LNG, and how ports can effectively integrate these practices to minimize environmental risks while maintaining operational efficiency. As the number of ports seeking or planning to develop LNG bunkering capacities increases, the evaluation of current physical and logistical infrastructures, the potential market for LNG, and the total safety measures should be undertaken. Such evaluations will not only improve the practicality of operations but will also come to support the international push towards cleaner marine fuel options for sustainability of the maritime industry. This systematic approach ensures that LNG bunkering can efficiently be carried out to support the maritime industry shift towards the use of cleaner fuel while at the same time maintaining the safety and efficiency of the process. Through a comprehensive review of the LNG bunkering process, this paper seeks to provide insights into how ports can transition to more sustainable fuel options and contribute to global efforts to reduce the shipping industry's environmental impact. By examining the methods, challenges, and safety protocols involved in LNG bunkering as shown in Fig.3-1, the paper also aims to offer practical recommendations for ports looking to improve their infrastructure and operational procedures in line with

international environmental standards. LNG bunkering has many risks because LNG is highly flammable and is stored notably at very low temperatures [159]. LNG bunkering services must be supported by developed advanced infrastructure, and they must meet with international safety standards to avoid occurrence of disasters [160].

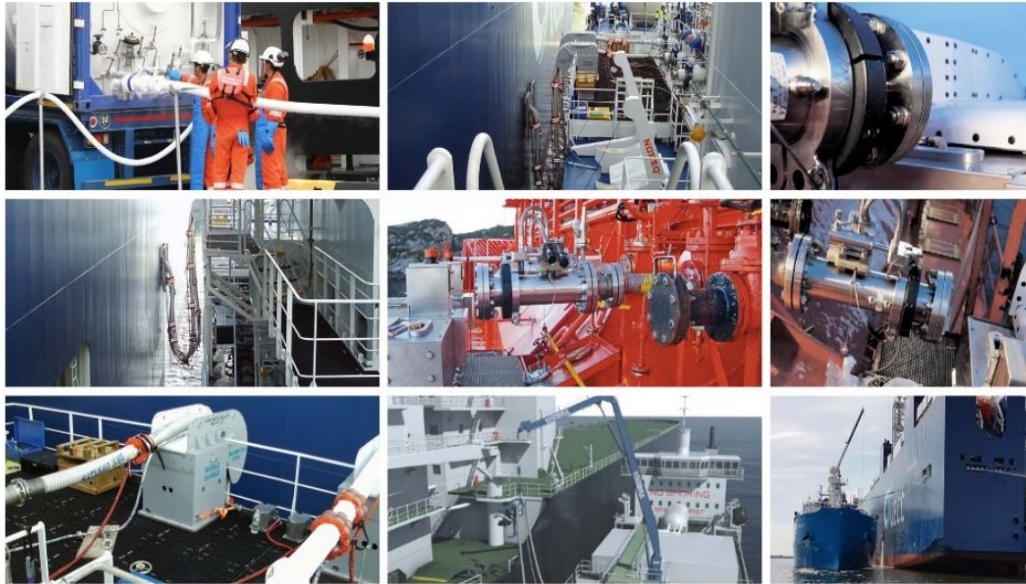


Figure 3-1 LNG bunkering pro

Various stages and equipment involved in the LNG bunkering process, including those connections, transfer systems, and safety protocols, emphasizing the complexity and precision required for safe and efficient operations. The maritime industry because it uses fossil fuel like heavy fuel oil (HFO) that emits dangerous gases including sulfur oxides (Sox) and nitrogen oxides (NOx). Methodology section captures the systematic way of evaluating methods of LNG bunkering in seaports. Specifically, the Results section contains the comparative assessment of the three LNG bunkering methods in terms of operability, throughput, and safety. In the Conclusion part of the paper, it largely concentrates on the fact that LNG would be the most effective solution when it comes to the fuel change in the shipping industry.

3.2 Related Work

An alternative solution which has gained importance in the global approach to minimize environmental effects of ships, LNG has emerged as an important fuel source for the maritime application [161]. Switching focus to LNG due to its low- emission profile is consistent with global initiatives requiring reduction of pollutants that emanate from ships including SOx, NOx, and CO2 emissions. Here, the major and relevant literature

is presented as regards to environmental, economic, and operational aspects for LNG Bunkering together associated challenges that may prevail in the implementation of the strategy, necessary infrastructures and safety measures for its proper implementation [162]. HFO has been central to the maritime industry for years; it is fuel composed largely of sulfur and other damaging elements. According to [3], the emissions of ships particularly SO_x, NO_x and particulate matter have negative impacts on air quality and human health in areas around the coastlines [163]. Besides this, the combustion of HFO generates significant volume of carbon dioxide (CO₂), which is a greenhouse gas that intensifies global warming [164]. These environmental issues have forced regulatory authorities such as IMO to set low emission regulations which include the implementation of IMO 2020 sulfur cap whereby the sulfur content of fuel used in ships cannot exceed 0.50. LNG is adjusting to be among the most viable marine fuels of the future because it has the potential of leading to a decreased emissions size. For instance, while using HFO, the emissions of nitrogen oxide (NO_x) can be slashed by up to 90%. As explained in [165], the economic benefits for the use of LNG are also provided, with the LNG in most cases being cheaper than oil derived fuels. For this reason and due to the relatively cheap nature of LNG compared to other fuels, it would be considered as one of the most suitable fuels for the industry, more so given the increasing pressure towards achieving environment goals.

The maritime industry remains a high emitter of greenhouse gases because it relies heavily on the use of fossil fuel [166]. Liquefied Natural Gas (LNG) is gradually growing as an attractive contender for conventional marine fuels such as heavy fuel oil (HFO) and diesel. More reservoirs of information present the environmental benefits of LNG that includes a decrease in the emission of NO_x by as much as 90%

The regulations imposed by the IMO through the 2020 sulfur cap have forced the worldwide maritime industry to turn its attention to cleaner fuel sources, with LNG in the lead [167]. The centers or ports round the world have started providing LNG bunkering services to promote the use of LNG as an energy source in the marine segment. LNG bunkering involves transferring LNG from supply sources to ships and is commonly carried out through three methods: PTS, TTS and STS refers to Pipeline-to-Ship, Truck-to-Ship and Ship-to-Ship respectively [166]. They both provide different operational, infrastructural, and safety requirements, which make each well suited to different port stagnation levels and capabilities.

LNG bunkering methods comparison on throughput and transfer time also show that PTS method is the most efficient [168]. The large volume of capital is needed to invest in the fixed structures for PTS, and the system is better suited for the large ports where high demand for LNG is expected. TTS is more operational flexible in its application and can be implemented even in those ports where pipeline systems are not constructed [168]. However, TTS is endowed with smaller and limited transfer ability and slower transfer rate, thus not fit for big boats. Ship-to-Ship (STS) bunkering, on the other hand, should be carried out in offshore and remote locations since the construction of land infrastructure is not possible. STS enables effective high-capacity transfers although their execution entails harmonization of the vessels which is very much prone to weather and/ or other physical impediments [169]. The use of LNG entails several fixed costs as well as compliance with very enormous measures on safety.

3.3 Methodology

This research method enables a detailed assessment of the LNG bunkering in seaports; the manners and techniques involved, support facilities and measures in place about safety. The aim is to identify and assess the strategies being employed by the ports for the purpose of enhancing the LNG bunkering solutions, more from an operational and safer perspective. The study makes use of data on LNG bunkering in European ports where the activity has been conducted to address the pollution problem prevalent in the shipping industry.

3.3.1 Data Collection and Literature Review

This process involved the collection of data, and a review of the literature based on the study's objective of determining the possibilities of generating new knowledge about earthquakes through computer algorithms [170]. Hence to gain a good vision of LNG bunkering for seaports the existing literature was reviewed. Second, primary information was gathered directly from scientific articles, industry reports, and case study sources using the experiences of ports in different European countries to implement LNG bunkering processes [171]. This literature review also included regulatory documents, including those from the IMO which stipulates safety guidelines and procedures for handling Liquefied natural gas especially on the seas.

Accumulated data involved two aspects of different LNGs bunkering techniques, namely, Pipeline-to-ship (PTS), Truck- to-ship (TTS) and Ship-to-Ship (STS). Accompanying sources enriched the general knowledge about infrastructure necessary

for the LNG terminals, the basic principle of regasification, as well as gave information about requirements for safety during the LNG transfer and storage.

3.3.2 LNG Bunkering Methods

The research identified three main methods of LNG bunkering currently in practice at seaports: Pipeline to Ship (PTS), Truck to Ship (TTS) and Ship to Ship (STS). These methods are utilized in the transferring of LNG to the receiving ships, which have been converted or newly designed for LNG utilizing intent. Each method is then discussed in terms of the compliance with the identified operational performance criteria, cost and safety considerations.

3.3.3 Pipeline-to-Ship (PTS)

Pipeline-to-Ship (PTS) is one of the most effective LNG bunkering techniques and is adopted in ports having existing LNG utilities [172]. In this method, LNG is taken from a storage centre mainly from an LNG terminal and transported by a pipeline which is permanently connected to the specific ship. It also demands significant capital outlay in the form of pipeline networks and large LNG storage vessels. The LNG is transported under regulated conditions to retain gas in its liquid form with a temperature range of approximately -162°C [173]. PTS is used where there is growing demand for LNG or where a reliably high supply of LNG is necessary. The fixed pipeline infrastructure also has several advantages of time compared to the truck or shipment that this process can be easily programmed and does not take much time [174]. Nonetheless the capital-intensive costs that encompass construction and maintenance of the LNG pipelines inhibit their uptake among the larger ports due to capital requirements.

PTS safety measures are well enhanced because it involves direct transportation between the storage terminal and the specific ship. Pressure control, temperature control, and issued spill control systems must be in place, which are generally complied with by international port and shipping safety standards. Maintenance and inspection are necessary to guarantee the pipeline assets remain in the best state possible.

3.3.4 Truck-to-Ship (TTS)

Truck-to-Ship (TTS), in bunkering, employs LNG trucks whereby LNG is transported from storage terminals to the ship. This method is also flexible and can be used in the ports, which lack a pipeline structure. In TTS bunkering, there are hoses and connectors used to transfer the LNG from the truck to the ship when the temperature of LNG is incredibly low [175]. TTS is beneficial in such ports and locations where the need for natural gas is not high enough to warrant establishment of a fixed pipeline delivery

system [176]. It is also used in ports that are converted but do not have LNG facilities to provide that large volume of LNG bunkering. The use of LNG trucks is flexible since it can move from one location to another within a port making it easy for operators to manage. The major concern about TTS bunkering is that LNG trucks have relatively small carrying capacities, implying longer bunkering duration, and that many LNG trucks will be required to supply a very large vessel [177].

3.3.5 Ship-to-Ship (STS)

Ship-to-Ship (STS) bunkering is the process where LNG is transferred ashore from one ship to another. This mode is most often adopted when working in the zones that have no shore-based LNG infrastructure or in the offshore areas [178].

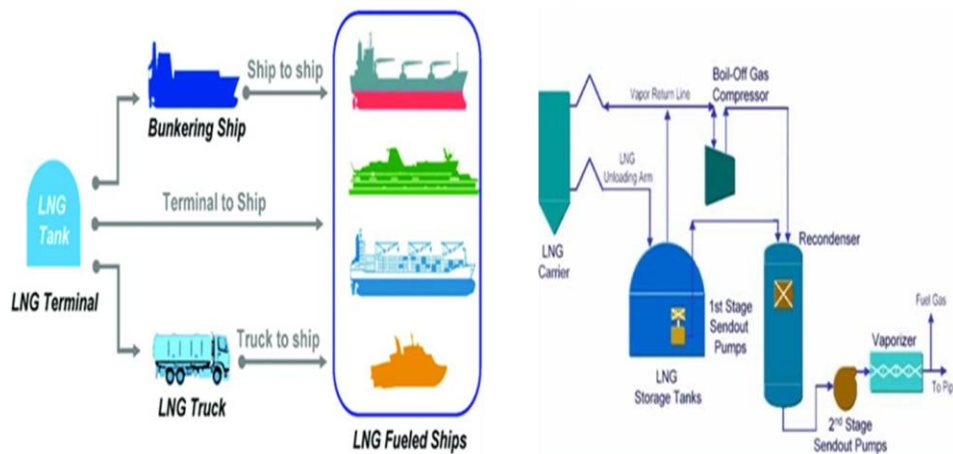


Figure 3-2 Pipeline-to-Ship (PTS) from an LNG terminal, Truck-to-Ship (TTS) using LNG trucks, and Ship-to-Ship (STS) transfers between vessels

Figure 3-2 Pipeline-to-Ship (PTS) from an LNG terminal, Truck-to-Ship (TTS) using LNG trucks, and Ship-to-Ship (STS) transfers between vessels, showcasing the operational flexibility in fueling LNG-powered ships at seaports. A bunker vessel used to transport LNG docking beside the receiving vessel and the LNG products transferred via cryogenic hoses. The process is almost the same as TTS, but it deals with far larger capacities of cargo since bunker ships can hold much more LNG than trucks [179]. They found that STS is more preferred where there is high demand for LNG, but storage capacity onshore is scarce [180]. It enables constant bunkering to occur unabated without the need of fixed terminals which are sometimes impossible to develop ashore. However, STS operations are much more complicated compared to all other types of vessel operations and call for precise cooperation of the vessels in question. The risks involved in STS are also magnified because both large volume vessels are closely coupled during the transfer operations [181]. thus, prone to the state of the art and sea

states, and any existing navigational challenges. In terms of safety, the current arrangements for STS bunkering of naval vessels are properly coordinated with the use of modern monitoring systems to ensure controlled transfer of the LNG [182]. A special focus is made for international rules and regulations associated with STS operation such as prevention of oil spillage, incorporation of emergency shut down mechanism and required certification of the crew.

3.3.6 Process of LNG Storage and Vaporization

The boil-off gas compressor works for natural gas that is likely to evaporate when the LNG is stored in the storage tanks after unloading. This gas is compressed and sent back to the recondensing unit, where it is turned back into a liquid state and returned to storage tanks to reduce wastage. This step is essential to optimize LNG storage since there is always loss of a large percentage of the gas as vapor [183]. When required the stored LNG is transferred to the send out pumps [184]. At the first step, LNG is pressurized, in other words, a process of regression to the gaseous state is initiated with its help [185]. The LNG flows through the Figure 3-2: Process flow of LNG terminal operations, including storage, boil-off gas management, and vaporization for distribution recondensing unit to capture and store all the vaporized gas to the system to reduce on loss. Another important stage that follows distillation is vaporization. The LNG is pumped to the vaporizer unit where the LNG is converted back to natural gas through heating [186]. The vaporizers employ heat energy from other sources like sea water or propane to warm the LNG so that it volatiles again. This stage is crucial as it facilitates the use of LNG In multiple utilization sectors including home heating, electricity production, and other civil uses [187]. The next step is the second send out stage where the LNG is vaporized, and the gas is metered and sized for pressure and flow rate so that it can be transmitted with pipelines [188].

These pipelines are used to transport the gas to the end users where it is consumed for generating electricity, heating homes, or meet the energy needs engaged in industrial processes that use natural gas [189]. The operating cycle in LNG terminals is very stringent and starting from the fact that LNG is a liquefied gas whose handling involves very low temperature increased safety measures must be put in place [190]. Pressure relief system helps in preventing overpressure in terminals which may lead to accidents, fire and gas detection and suppression along with emergency shutdown systems to protect the human life [191]. Due to their important role in providing LNG for bunkering, LNG terminals must be efficient [192]. These centre hold LNG and degasify

it and supply it to ships [193]. The kinds of facilities that solicit the construction of LNG terminal include tanks, pipelines, compressor, and vapor return lines [194].

The regasification process draws the liquefied gas back into gaseous form fit for usage in power station or as fuel [195]. Both PTS and STS bunkering can be provided by ports in possession of an LNG terminal because the terminal stores and provides LNG for distribution [196]. Currently the LNG terminals can be large or small depending on the capacity of the port to accommodate large amounts of LNG for export or import. LNG is highly flammable which makes the safety of LNG terminals paramount [197]. Special equipment must be fitted in Terminals such as Fire suppressing system, gas tester kits and Pressure relief vessels [198].

3.4 Result

It provides the findings considering reviewing and analysing the concept of LNG bunkering, functioning of LNG terminal, and safety measures related to it. The findings are under- pinned by data and illustrations showing the LNG bunkering techniques and practices to illustrate equipment and activities in LNG transfer to ships effectively and securely.

3.4.1 LNG Bunkering Methods

Bunkering Method	Capacity (tons)	Transfer Speed (tons/hour)	Advantages	Challenges
Pipeline-to-Ship (PTS)	High (5000)	100-200	Efficient, fast, direct connection to ships	Requires significant investment in fixed infrastructure
Truck-to-Ship (TTS)	Medium (20-50/truck)	10-30	Flexible, can operate in smaller ports	Limited by truck capacity, slower transfer, road transportation risks
Ship-to-Ship (STS)	High (5000)	100-250	Suitable for offshore or remote locations	Requires careful coordination between ships, weather dependent

Table 3-1 Comparison of LNG Bunkering Methods

Table 3-1 is showing three primary LNG bunkering methods are utilized in ports around the world: The shuttle models involve the Pipeline-to- Ship (PTS), Truck-to-Ship (TTS) and Ship-to-Ship (STS) [199]. All three methods were compared based on their

performance, modularity and safety aspects. These methods are suitable for varying ports, different sizes, constraints and demand for LNG. PTS is said to be the swiftest and most proficient means of bunkering LNG since the LNG storage infrastructure can easily be connected to the ship receiving it through a pipeline [200, 201, 202]. However, as with pipelines distribution; it involves a large capital outlay to put down the necessary pipes and equipment implying that it may only be appropriate for Major LNG ports [203, 204]. TTS is more flexible and is used for ports that are not directly connected to an LNG pipeline system [205]. However, this method enjoys lot of operational flexibility but is restricted by the carrying capacity of LNG trucks, hence not suitable for busy ports. The slower transfer speed also becomes a problem whenever servicing large vessels in the port [206, 207]. Ship-to-Ship is applied mainly in the ports or in the areas with limited or deficient conventional shore facilities [208, 209]. STS facilitates large scale bunkering but requires the integration of ships and is affected by weather factors as opposed to other techniques [210, 211].

Bunkering Method	Capacity (tons)	Volume Per Day (tons/day)
Pipeline-to-Ship (PTS)	High (5000)	2400-4800
Truck-to-Ship (TTS)	Medium (20-50/truck)	240-720
Ship-to-Ship (STS)	High (5000)	2400-6000

Table 3-2 Total LNG Volume Capacity Per Method (Estimate)

Table 3-2 represents the total LNG volume capacity per method estimate, from the table we can make analysis that the best pertaining to capacity of transfer is Pipeline-to- Ship (PTS) that can transfer more than 5000 tons in one operation with the daily transfer rate between 2400-4800 tons [212]. This makes it the most convenient approach in the ports with high throughput of LNG. Truck-to-Ship (TTS) method has the average intermediate capacity of 20-50 tons per a truck and the daily flow that does not exceed 240-720 tons [213]. This method is flexible, but the limitation is that the amount of shipment will depend on the capacity of the trucks preferably with small ports in mind and less demand for LNG. Ship-to- Ship (STS) method also offers high capacity like PTS and can transfer over 5000 tons dropping to 2400-6000 tons daily; thus, suitable to offshore environments where facilities are minimal [214].

While Table 3-3 provides the same information as Table 3-2 but highlights the ton per hour transfer efficiency of every method offered. Compared with PTS and STS have at least 100-200 tons/hour transfer speeds, PTS has up to 2400-4800 tons per day, while STS up to 2400-6000 tons per day, respectively. TTS, however, works within the transfer speed of (10-30) tons/hour and, therefore, its optimum daily capacity cannot exceed (240-720) tons [215]. Despite the flexibility of TTS, it is not as effective as PTS and STS for transporting large amounts of LNG.

Bunkering Method	Transfer Speed (tons/hour)	MaxTransfer per 24h (tons)
Pipeline-to-Ship (PTS)	100-200	2400-4800
Truck-to-Ship (TTS)	10-30	240-720
Ship-to-Ship (STS)	100-250	2400-6000

Table 3-3 Transfer Efficiency Per Method (Tons Per Hour)

Figure 3-3 shows analysis of the estimated operational costs of ship to transfer 1000 tons of LNG. The PTS is represented as giving the highest transfer efficiency as well as the highest transfer capacity, and it would offer the least cost of operation at a cost of 20000 to 30000 per 1000 tons [216].

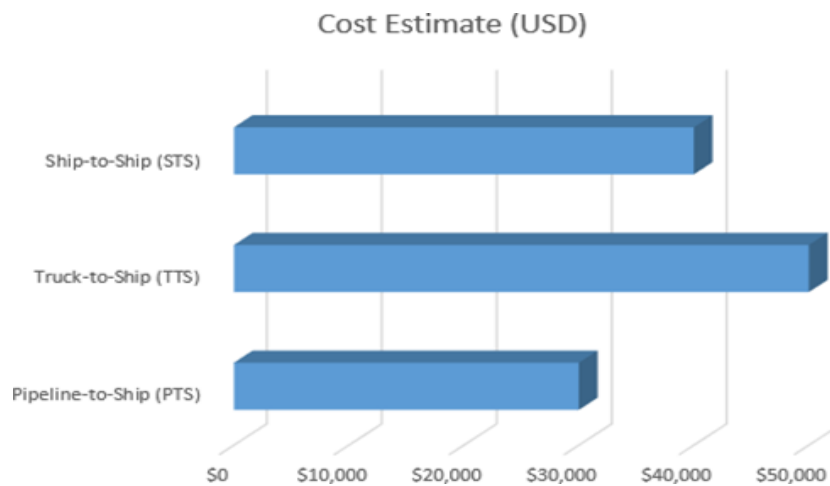


Figure 3-3 Cost Estimate (USD) Image by Google

Compared to the more efficient TRS, TTS has a slower transference rate which requires multiple use of trucks and thus has the highest estimation of cost amounts to between 40,000–50,000 per 1000 tons [217]. Thus, this analysis proves that PTS and STS are suitable for demanding ports and large-scale operations, but TTS is reasonable for the ports with low demand but larger operational costs, and slower rates of LNG transfer.

Bunkering Method	Cost Estimate (USD)	Cost Efficiency
Pipeline-to-Ship (PTS)	\$20,000 - \$30,000	High
Truck-to-Ship (TTS)	\$40,000 - \$50,000	Medium
Ship-to-Ship (STS)	\$30,000 - \$40,000	Medium-High

Table 3-4 Estimated Operational Cost Per 1000 Tons Transferred

Table 3-4 compares three primary bunkering methods Pipeline-to-Ship (PTS), Truck-to-Ship (TTS), and Ship-to-Ship (STS) based on estimated cost and cost efficiency. Pipeline-to-Ship is the most cost-effective method, with the lowest estimated cost (\$20,000-\$30,000) and a high efficiency rating. Truck-to-Ship is the most expensive (\$40,000-\$50,000) and offers only medium efficiency, likely due to its lower capacity and logistical constraints. Ship-to-Ship falls in the middle, with a cost of \$30,000-\$40,000 and a medium-high efficiency, making it a viable and flexible alternative when pipeline infrastructure is unavailable.

3.4.2 LNG Terminal Operations

LNG terminal operations are core for the storage, regasification and distribution of LNG to ship [218]. As such, these operations comprise many functions, none of which is less significant than the others, to guarantee safe handling of the LNG and efficient distribution [219]. The terminal process involves vaporizers, where the LNG is taken from carriers, put into insulated tanks and turned from liquid to gas. This is important because insulated tanks are necessary to keep LNG at a low temperature of -162 degrees Celsius. Pressure, temperature, and tank data report confirm the safety and containment of the liquefied natural gas. Boil-Off Gas compressors are used to handle the gas which is produced through the natural evaporation process of storing gas and make sure none is chucked away of LNG to ships [220]. These operations involve multiple components, each playing a critical role in ensuring that LNG is safely handled and efficiently distributed. Boil-Off Gas compressors manage the natural gas that evaporates during storage, ensuring that none is wasted. It is an important process as it helps the organization avoid polluting the environment and losing its products. Recondenses reinject any boil-off gas back into the storage system making the best use of the LNG and losses are minimized [221].

These appliances help change the state of LNG from its liquid state to make gas [222]. The gas can then be used through pipeline for several uses such as in the shipping industry for fuel and in power generation [223]. Permeating pumps then transfer the LNG or the gas to the distribution system at high pressure to meet the end user requirements effectively.

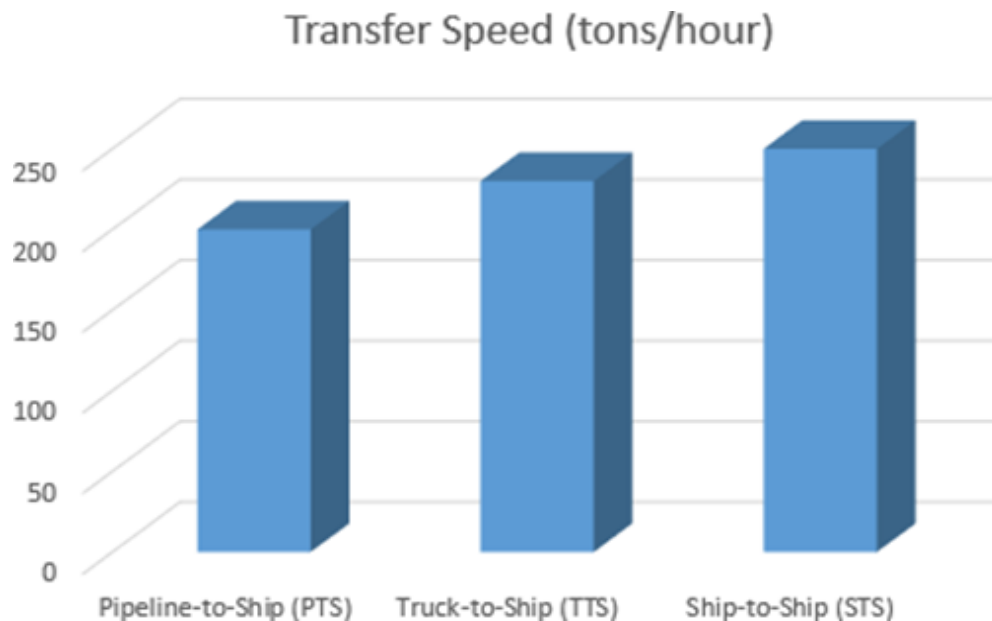


Figure 3-4 Max Transfer per 24h (tons)

The Figure 3-4 compares the operational transfer speeds, measured in tons per hour, for the three primary bunkering methods. As illustrated, Pipeline-to-Ship (PTS) is the most efficient method with the highest transfer speed, followed by Ship-to-Ship (STS). Truck-to-Ship (TTS) has the slowest transfer rate by a significant margin. This data clearly demonstrates that PTS is the superior method for rapid fuel delivery, a critical factor for reducing port turnaround times, while TTS is the least efficient in terms of speed.

3.5 Chapter Summary

LNG bunkering offers an elegant way of managing the energy needs of floaters while exercising environmental consciousness, but its effectiveness is only possible through careful step by step adherence to set guidelines and formation of appropriate physical facilities. PTS, TTS and STS, are therefore chosen based on the capabilities offered by the port and the overall logistics involved in the bunker operation. PTS is normally preferred when there is need to transfer massive volume of LNG that is likely to be handled in the port infrastructure. This method has the advantage of pipeline supply,

and a direct and large amount of LNG can be supplied all the time. On the other hand, TTS is used where the demand for LNG is low, or where the physical structure of the port and its size disallow pipeline transport of the gas. This method is flexible as it permits LNG to be delivered directly from road transport vehicle ships. However, this method is energy and time-consuming as compared to the others.

STS is essential for ports that have limited land infrastructure or where geographic and marine characteristics make direct supply cumbersome. This method involved handling of LNG between two ships and is effective in regions that have poor port facilities. It enables significant volumes to be managed though it comes with higher coordination and operation necessities as well as severe safety measures to counter the high risks demanded by transferring inflammable liquids on the sea. In all LNG bunkering, there is a clear emphasis on the safety of operations without compromise. Specific regulations regulate movement of LNG such that the occurrence of disaster is well minimized; the regulation covers issues such as spill control measures, shutdown of a vessel, and even frequent mock disasters for employees. These measures are necessary to avoid failure in managing this inherently risky operation the handling of LNG – without creating risks to port officers and marine ecosystems. From the above findings any port intending to develop or expand LNG bunkering services needs to evaluate existing port infrastructure, the market for LNG, and safety precautions needed for successful and sustainable services.

Chapter 4. Green Transportation Modes

Maritime logistics plays an important role in Italy's economy and international transportation, supporting the flow of goods through some of Europe's busiest and most strategically located ports. Major Italian seaports including Genoa, La Spezia, Livorno, Naples, Trieste, Venice, and Civitavecchia operate as key hubs for container shipping, bulk cargo, and cruise traffic, linking Italy to global trade networks. However, the rapid growth of maritime trade has subsidized expressively to greenhouse gas emissions and air pollution, which pose challenges to environmental sustainability. While much research on green shipping has determined reducing emissions during navigation through measures such as speed optimization and route design, emission management during vessel anchoring and berthing remains relatively underexplored [1, 2].

Vessels must berth at ports or nominated anchorage areas for operational purposes such as loading and unloading cargo, waiting for canal or lock clearance, and refuelling. During these periods, vessels continue to consume fuel to power onboard facilities and essential systems. For example, in the Port of Genoa, crowding and operational procedures can result in vessels waiting for long periods, consuming significant amounts of fuel. Similarly, ports such as La Spezia, Livorno, and Trieste, which handle large volumes of containerized and bulk cargo, face similar challenges. A bulk vessel with an auxiliary engine of 100 kW may consume approximately 22 kg of fuel oil per hour, producing around 0.228 kg of Sox per hour, which adds significantly to greenhouse gas emissions and local air pollution.

To address this issue, several Italian ports have begun implementing shore power systems (cold ironing), which allow berthed vessels to connect to onshore electricity and reduce fuel consumption while docked. For instance, Genoa has installed shore power facilities primarily for cruise ships, reducing emissions in the busy port area. La Spezia and Livorno have extended these facilities to container and bulk vessels, while Venice and Civitavecchia have focused on cruise shipping. Shore power provides a cleaner alternative to traditional fuel based onboard electricity, offering environmental benefits including lower emissions of CO₂, Sox, and NO_x. Its adoption is particularly relevant for international trade routes along the Mediterranean, where differing fuel standards across countries can complicate vessel fuel management. Electricity supply differences are primarily limited to voltage, which can be managed through onboard

converters, making shore power a practical solution for environmentally sustainable port functions in Italy [224, 225, 226].

Despite its benefits, shore power adoption in Italian ports faces several challenges. First, the cost of installing onboard connection equipment may deter vessel owners. Equipment costs vary widely depending on vessel size, ranging from approximately 5,000 EUR for small river or coastal vessels to several hundred thousand EUR for large sea-going ships. Vessel owners require clear evidence of long-term economic benefits to justify these investments. Second, integrating shore power into operational planning introduces complexity, as vessel owners must optimize energy use, fuel replenishment, and scheduling. Third, government policies including subsidies for equipment installation, discounted electricity rates, and penalties for greenhouse gas emissions affect adoption decisions, adding further layers of complexity. Effective implementation requires coordinated collaboration between port authorities, electricity providers, and vessel operators.

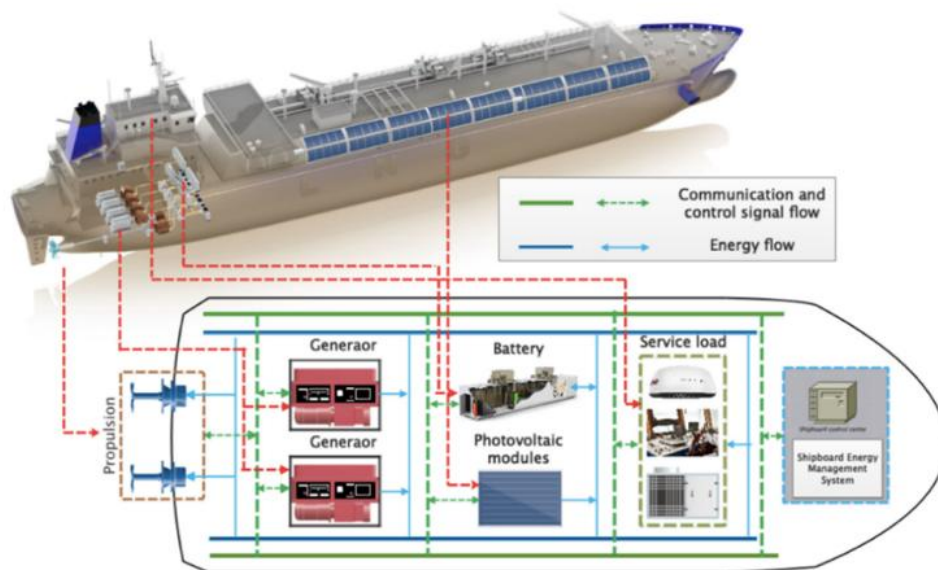


Figure 4-1 Topology of AES Image by google

The Figure 4-1 depicts a shipboard energy management system designed for green transportation. This integrated system utilizes multiple energy sources, including a generator, battery storage, and photovoltaic (solar) modules. The flow of energy and control signals is managed by a central "Shipboard Energy Management System," which intelligently distributes power between the propulsion and service loads. This

setup allows for optimized efficiency, reduced emissions, and the integration of renewable energy, representing a shift towards more sustainable marine propulsion.

The necessity for green shipping has therefore become an important global priority as part of the broader evolution toward a sustainable, low-carbon transport system. Green shipping means to the adoption of technologies, operational measures, and regulatory frameworks that lessen the environmental footprint of maritime transport. This includes a range of strategies designed to improve fuel efficiency and reduce harmful emissions throughout a ship's lifecycle. Among these strategies, the introduction of alternative and cleaner marine fuels such as liquefied natural gas (LNG), hydrogen, ammonia, methanol, and advanced biofuels plays a fundamental role. Each of these fuels offers different benefits and challenges in terms of energy density, storage requirements, cost, and carbon reduction potential [227, 228, 229].

In parallel, the addition of renewable energy technologies including wind-assisted propulsion systems, solar energy installations, and even wave energy converters propose opportunities to supplement traditional energy sources with clean, renewable alternatives. Novelties in vessel design and propulsion systems, such as hull optimization, air lubrication, and hybrid or fully electric propulsion, have shown considerable potential for improving overall energy efficiency. The use of lightweight combined materials and advanced coatings further improves vessel performance by reducing drag and maintenance necessities.

Additionally, the implementation of digital and data-driven solutions is modernizing the maritime sector. Smart routing algorithms, energy management systems, digital twins, and predictive maintenance technologies empower real time decision making that reduces fuel intake and improves vessel operations. Automation and the Internet of Things (IoT) are also transforming port logistics through the development of "smart ports," where automated port operations, electrified control equipment, and shore power connections (cold ironing) help reduce emissions during berthing.

Adopting these sustainable practices allows the maritime sector to considerably reduce its carbon footprint while ensuring long-term operational and economic flexibility. Green shipping initiatives align with international regulatory frameworks such as the IMO's Initial GHG Strategy, which aims to reduce total yearly GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels, as well as with the objectives of the Paris Agreement. Furthermore, these initiatives encourage

corporate social responsibility, enhance stakeholder reputation, and enterprise innovation across the global supply chain [230, 231, 232].

Eventually, the transition to green shipping is not merely an environmental necessity but also a strategic economic chance. It inspires investment in clean technologies, supports green job creation, and fosters effectiveness in an increasingly sustainability-driven global market. As maritime nations and companies co-operate toward decarbonization, sustainable shipping will serve as a foundation in achieving global climate goals while maintaining the ecological balance of the world's oceans [233].

4.1 Alternative marine Fuels

Traditionally, marine vessels have relied on fossil-based fuels such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), which are both carbon rich and high in Sulphur content. The combustion of these fuels releases large quantities of CO₂, Sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, leading to severe environmental and health impacts. In recent years, increasing international awareness of climate change and narrower environmental regulations have created strong pressure for the maritime sector to reduce its environmental footprint. The International Maritime Organization (IMO) has set aspiring targets to reduce greenhouse gas (GHG) emissions from international shipping by at least 50% by 2045 compared to 2010 levels, and to trail efforts toward complete decarbonization within this century. These goals have driven the investigation and adoption of alternative marine fuels energy sources that can replace or supplement normal fossil fuels while minimizing emissions and improving overall sustainability. Alternative marine fuels include a wide range of options, each with distinct properties, technological readiness levels and environmental impacts. Among the most promising intrants are Liquefied Natural Gas (LNG), ammonia, hydrogen, methanol, and biofuels. LNG, for instance, significantly reduces emissions of Sulphur oxides and particulate matter, though it still emits CO₂. Methanol and ammonia offer pathways to carbon neutral or even carbon free operations when formed from renewable sources. Hydrogen, regarded as a clean energy carrier, emits only water vapor when used in fuel cells, but its storing and distribution remain challenging. Biofuels, originated from organic materials, can be used in existing engines with minimal modification and offer instant reductions in lifecycle emissions depending on feedstock and production methods. Despite their potential, the widespread implementation of alternative marine fuels faces numerous challenges.

These include the high production costs, lack of global refuelling infrastructure, safety concerns and technological limitations related to handling and storage. Furthermore, the conversion to new fuels requires coordinated action among shipowners, fuel producers, port authorities and policymakers to establish clear standards, incentives, and investment frameworks [234,235].

Nevertheless, alternative marine fuels represent a crucial step in the maritime industry’s transition toward sustainability. Their development and placement not only support fulfilment with international emission regulations but also drive innovation in ship design, energy systems and engine technology. As research and investment continue to expand, these fuels are expected to play a vital role in shaping the future of greener, cleaner, and more efficient maritime transport [236,237].

4.1.1 Liquefied Natural Gas LNG

Liquefied Natural Gas (LNG) has appeared as one of the most mature and widely accepted alternative marine fuels in modern times. It consists primarily of methane and is stored at very low temperatures (around -162°C) to preserve its liquid form, allowing for efficient storage and transport. When used as a marine fuel, LNG offers substantial environmental benefits compared to traditional fuels such as heavy fuel oil and marine diesel. It virtually eradicates sulphur oxide (SO_x) emissions, reduces nitrogen oxides (NO_x) by up to 85%, and cuts carbon dioxide (CO_2) emissions by around 20%.

In adding to its cleaner combustion, LNG subsidises to improved air quality around ports and seaside [17,18].

Fuel Type	CO₂ Reduction (%)	SO_x Reduction (%)	NO_x Reduction (%)	Energy Density (MJ/kg)
Heavy Fuel Oil (HFO)	0	0	0	40
Marine Diesel Oil (MDO)	10	95	20	42
Liquefied Natural Gas (LNG)	20	100	85	50

Table 4-1 Comparison of marine fuels

Table 4-1 provides a comparative analysis of alternative marine fuels against the conventional baseline of Heavy Fuel Oil (HFO), quantifying their potential for emission reductions and their energy content. The data illustrates a clear trade-off: as the fuel type becomes cleaner, moving from HFO to Marine Diesel Oil (MDO) and finally to Liquefied Natural Gas (LNG), the percentage reductions in CO_2 , SO_x , and NO_x

emissions generally increase. LNG demonstrates the most significant environmental benefits, virtually eliminating SO_x and substantially cutting NO_x emissions, while also offering the highest energy density. This data is crucial for a thesis, as it offers empirical evidence to evaluate the environmental efficacy and operational implications of different fuel choices in the maritime sector's decarbonization efforts.

Though, challenges remain regarding the high cost of LNG infrastructure, limited global bunkering facilities, and fears about methane slip unburned methane that escapes into the atmosphere, which can offset some of its climate advantages. Despite these challenges, LNG is currently viewed as a feasible transitional fuel that can help the shipping industry move toward lower emissions while paving the way for future carbon neutral fuels such as ammonia, bio-LNG, or hydrogen.

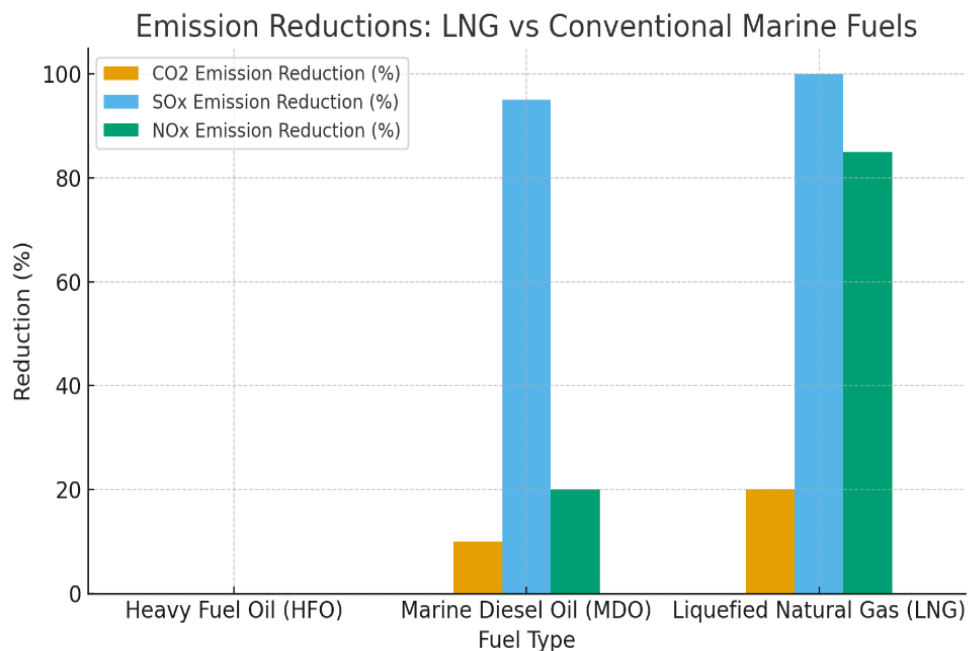


Figure 4-2 Emission reduction comparison image by AI

Figure 4-2 visually summarizes the key environmental advantage of Liquefied Natural Gas (LNG) as a marine fuel, directly comparing its percentage reductions in CO₂, SO_x, and NO_x emissions against conventional options like Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). For a thesis, this Figure serves to quickly and effectively illustrate the progressive improvement in emission profiles across the fuel types, highlighting LNG's superior potential in mitigating SO_x and NO_x pollutants specifically, which is a central argument for its adoption in green shipping corridors.

4.1.2 Hydrogen as Marine fuel

Hydrogen is highly recognized as one of the most likely alternative fuels for achieving zero emission maritime transport. As a clean energy carrier, hydrogen produces only water vapor as by product when used in fuel cells or combusted, making it an ideal solution for decarbonizing the shipping sector. When hydrogen is produced through renewable sources such as water electrolysis powered by solar, wind or hydroelectric energy hydrogen becomes a fully green fuel with virtually no lifecycle greenhouse gas (GHG) emissions.

The maritime industry's interest in hydrogen stems from the urgent need to fulfil with international decarbonization targets set by the International Maritime Organization (IMO) which aim to cut total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels. Hydrogen offers a pathway to meet these targets, especially for vessels operating in emission control areas (ECAs) and regions with strict environmental regulations. It can be used either directly in internal combustion engines adapted for hydrogen or more efficiently in fuel cell systems that convert hydrogen into electricity to power electric propulsion systems [238, 240].

One of hydrogen's major advantages is its zero exhaust pipe emissions, removing carbon dioxide (CO₂) sulphur oxides (SO_x) and particulate matter completely. Additionally, hydrogen fuel cells are quiet, highly efficient and have fewer moving parts than conventional engines which can reduce maintenance requirements. However, despite these benefits, several significant challenges delay the widespread adoption of hydrogen in the maritime industry.

The storage and handling of hydrogen remain complicated due to its low volumetric energy density. To achieve practical energy storage, hydrogen must be either compressed to high pressures (typically 350–700 bar) or liquefied at extremely low temperatures (around 253°C). Both methods require specialized equipment insulation and safety measures which increase system costs and space requirements serious factors in ship design. Furthermore, the current global infrastructure for hydrogen production, transportation, and bunkering is limited, and scaling it up for maritime use will need large investment and coordination among governments, shipbuilders, and energy companies.

Safety is another important concern, as hydrogen is highly flammable and can leak easily due to its small molecular size. Therefore, the development of vigorous safety standards leak detection systems and crew training is most important for its successful

Fuel Type	CO₂ Emission Reduction (%)	SO_x Emission Reduction (%)	NO_x Emission Reduction (%)	Energy Density (MJ/kg)
Heavy Fuel Oil (HFO)	0	0	0	40
Marine Diesel Oil (MDO)	10	95	20	42
Hydrogen	100	100	90	120

Table 4-2 Comparison of hydrogen and conventional marine fuels

Table 4-2 is a critical comparative analysis for a thesis on maritime decarbonization, positioning hydrogen as the ultimate clean fuel against conventional benchmarks. The data demonstrates that hydrogen achieves complete elimination of CO₂ and SO_x emissions (100% reduction), along with a 90% reduction in NO_x, vastly outperforming both Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). Furthermore, its exceptionally high energy density of 120 MJ/kg highlights its potential for powerful propulsion. This quantitative evidence solidifies hydrogen's technical viability as a pathway to zero-emission shipping, while also underscoring the significant energy transition required from current fuel infrastructures.

deployment. Despite these obstacles, hydrogen holds massive potential as a cornerstone of the maritime energy transition. Ongoing research and pilot projects such as hydrogen powered ferries, and coastal vessels are paving the way for commercial implementation. As renewable hydrogen production becomes more cost-effective and infrastructure expands, hydrogen is expected to play an important role in realizing a sustainable, zero-emission future for global shipping [241,242,243].

4.1.3 Ammonia as Marine fuel

To reduce greenhouse gas emissions ammonia (NH₃) has emerged as a promising carbon free fuel for ships. Unlike traditional marine fuels, ammonia contains zero carbon, so its combustion does not emit CO₂. When produced from renewable energy sources and nitrogen from the air “green ammonia” it offers a truly sustainable fuel option, associating with International Maritime Organization (IMO) targets to cut shipping emissions by 50% by 2050. Ammonia can be stored as a liquid under reasonable pressure, making it practical for long trips. It can be used in dual fuel internal combustion engines (ICEs) alongside standard fuels or in dedicated ammonia engines.

Research is also exploring fuel cells that consume ammonia, either directly or after decomposition into hydrogen. Major engine makers and classification societies are developing engines and safety protocols to handle ammonia's high ignition temperature, slower flame speed, and toxic nature. Proper after treatment systems are needed to achieve nitrogen oxide (NO_x) and ammonia slip emissions.

Even with its potential, there are still several challenges. Unless substituted with green ammonia, most of the ammonia produced today from fossil fuels leads to upstream emissions. Its reduced energy density demands the use of larger storage tanks, which affects ship design. Due to its toxic and corrosive nature, ammonia requires strong safety precautions during bunkering and operations. Additionally, there is currently a lack of port infrastructure for ammonia supply, and the economic affordability of green ammonia is still uncertain. Ongoing research and early trials indicate that ammonia could play a major role in decarbonizing deep-sea shipping. Dual fuel vessels are currently undergoing tests, and engines that run solely on ammonia are expected to become available shortly. Though adoption will occur gradually, ammonia offers a practical option for achieving carbon-free maritime transport, working alongside other fuels like hydrogen and methanol. To sum up, ammonia provides a hopeful answer for sustainable shipping. With its carbon-free characteristics and suitability for long-distance operations [244,245,246,247].

4.1.4 Methanol and Biofuels

To lower greenhouse gas emissions and enhance air quality, the global energy sector is quickly moving toward sustainable alternatives. Among these, methanol and biofuels have been recognized as adaptable and eco-friendly choices. They are appealing options for a cleaner energy future due to their ability to adapt to current engines and infrastructure, along with their reduced emissions. Methanol (CH₃OH), a straightforward alcohol, can be synthesized from natural gas, coal, biomass, or a combination of captured CO₂ and green hydrogen. It can be utilized in internal combustion engines (when mixed with gasoline) or in fuel cells for effective electricity generation that produces very few emissions. Due to its adaptability and ability to work with existing systems, methanol serves as a practical bridge fuel in the transition to low-carbon energy.

Biofuels, which come from plants, algae, and agricultural waste, are classified into first-generation (food crops) or second-generation (non-food biomass) categories. They offer considerable ecological advantages by lowering CO₂ emissions and airborne

contaminants, all while being suitable for current engines. Bioethanol and biodiesel are seeing growing global usage, showcasing their versatility and promise as substitutes for a fraction of fossil fuels. Both methanol and biofuels aid in the transition to cleaner energy by lowering greenhouse gas emissions, as well as reducing nitrogen oxides (NO_x), particulate matter, and sulphur oxides. Government policies, blending mandates, and industry investment, especially in the transportation and maritime sectors, support their increasing adoption. Ships powered by methanol and vehicles powered by biofuel demonstrate their practical use in achieving global emissions targets. Challenges remain, including production costs, infrastructure adjustments, and potential competition with food supply. However, advancements in renewable methanol production, second-generation biofuels, and engine technology are addressing these issues.

To sum up, methanol and biofuels are versatile, low-emission fuels that are becoming increasingly adopted worldwide. They are crucial for decreasing dependence on fossil fuels and aiding the sustainable energy transition, providing a practical and immediate route to a cleaner, low-carbon future [248,249,350].

4.1.5 Synthetic Fuels (E-Fuels)

Marine fuels like diesel and heavy fuel oil, which are traditional options, produce significant emissions of sulphur oxides, nitrogen oxides, and carbon dioxide. This exacerbates global warming and air pollution. With the global shift toward cleaner energy, synthetic fuels commonly referred to as e-fuels have surfaced as a hopeful option for realizing carbon neutral shipping. Synthetic fuels are made from green hydrogen and captured carbon dioxide (CO₂). Green hydrogen is produced via water electrolysis powered by renewable energy sources like wind, solar, or hydropower. These components can be transformed into liquid hydrocarbons via chemical methods such as Fischer-Trosch synthesis or methanol synthesis when they are paired with CO₂ captured from industrial emissions or directly from the atmosphere.

The fuel produced is chemically akin to standard diesel or marine fuel but operates on a closed carbon cycle: the CO₂ released during combustion matches the CO₂ captured in its production, rendering it nearly carbon neutral [251,252].

In the maritime sector e-fuels provide various benefits. They have a high energy density that is equal to with that of conventional fuels, which allows for long-distance journeys without major alterations to storage capacity. E-fuels can be used in current ship engines and fuel systems with minimal retrofitting, making them a practical "drop-in"

solution. In addition, they cut emissions of sulphur oxides, nitrogen oxides, and particulate matter by a large margin, thus enhancing air quality and assisting ships in meeting the standards set by the International Maritime Organization (IMO).

However, difficulties persist E-fuels are several times more expensive than conventional fuels due to the high energy consumption and costs involved in producing green hydrogen and capturing CO₂. Additionally, the mass production of goods requires huge quantities of renewable energy and infrastructure that are still in the process of development. Even with these limitations, ongoing technological progress and the decline in costs associated with renewable energy are anticipated to enhance the economic viability of e-fuels in the next few decades. Synthetic fuels appear to have a bright future in the maritime industry. International policies advocating for low-carbon shipping are bolstering investments by governments and companies around the globe in pilot projects aimed at producing e-methanol, e-diesel, and e-ammonia. As renewable energy capacity expands and costs decline, e-fuels are likely to become a key component in achieving the maritime sector's 2050 decarbonization goals. Synthetic fuels, with their ability to provide carbon-neutral energy using current systems, are an essential advancement for a sustainable and cleaner future in global shipping [253,254].

4.2 Electrification of Ships

Marine propulsion systems of the traditional kind are based largely on fossil fuel-powered internal combustion engines, such as those running on marine diesel and heavy fuel oil. These engines produce significant amounts of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter, and carbon dioxide (CO₂). With worries about climate change and ecological deterioration growing stronger, global entities like the International Maritime Organization (IMO) and the European Union (EU) have set tough goals for cutting emissions.

The evolution of these regulations, along with the increasing demand for cleaner technologies, has hastened the shift toward more sustainable and energy-efficient ship propulsion systems. One of the most promising solutions for achieving sustainable maritime transportation is the electrification of ships. Electrification includes the replacement or supplementation of conventional propulsion systems with electric or hybrid-electric alternatives that rely on batteries, fuel cells, or renewable energy sources. Electric propulsion systems provide multiple benefits, such as enhanced energy efficiency, diminished noise and vibration, reduced maintenance costs, and

exhaust emissions that are either non-existent or greatly decreased. Additionally, with the ongoing progress in renewable energy technologies, the combination of shipboard power generation with solar, wind, or hydrogen-based systems can improve the ecological performance of electrified vessels [255, 256].

Although it holds promise, the electrification of ships encounters various technical and economic hurdles that need to be overcome to enable its broad implementation. Due to their high costs and limited energy density, current battery technologies are primarily used for short-distance or coastal shipping operations.

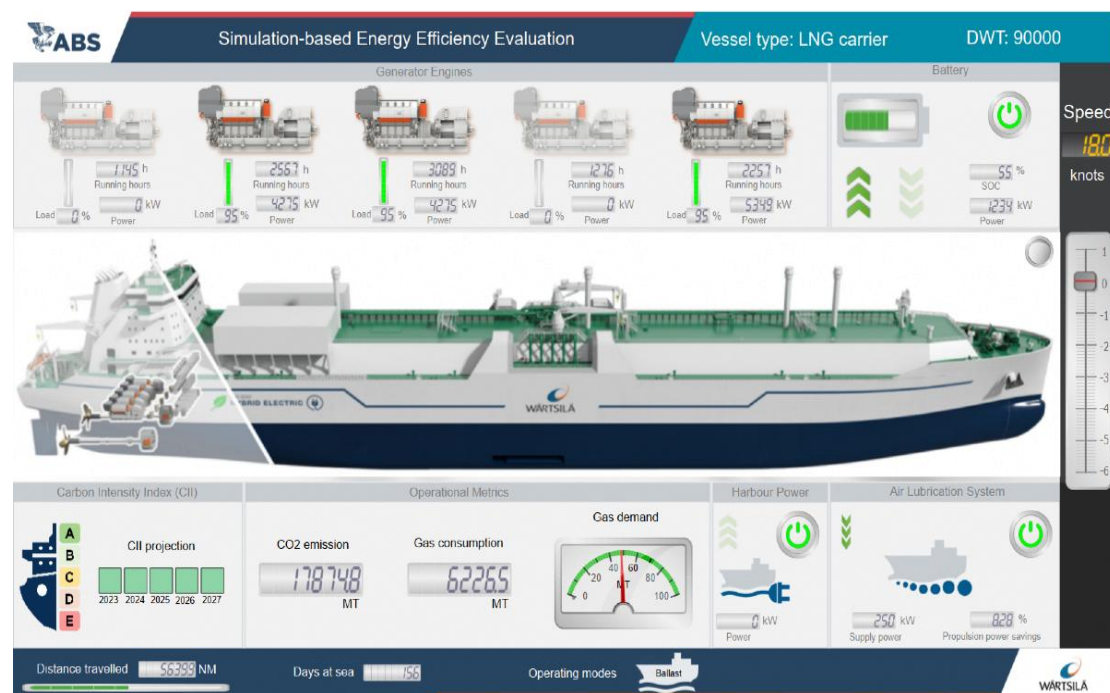


Figure 4-3 development of a hybrid-electric LNG transport (source: ABS)

Figure 4-4 illustrate the architecture of a simulation model used to evaluate energy efficiency, likely in the context of ship electrification. this Figure demonstrates the methodological approach of using a detailed simulation to quantify the energy efficiency, load management, and performance gains achievable through the electrification of shipboard power and propulsion systems.

To guarantee suitable range and power capacity, long-distance ships need hybrid systems or alternative fuels like hydrogen or ammonia. Moreover, the establishment of standardized charging infrastructure at ports and efficient energy management systems on vessels is essential to facilitate widespread adoption. Tackling these challenges will necessitate collaborative efforts from shipbuilders, energy providers, policymakers, and researchers. Overall, the transition to electric ships constitutes a major advance in efforts to reduce carbon emissions from maritime activities. It is in close alignment with

global sustainability goals and the International Maritime Organization's target of cutting total annual greenhouse gas emissions from international shipping by at least 50% by 2050 in relation to the 2008 Figures. Not only does this transition hold the promise of reducing the environmental effects of marine activities, but it also paves the way for innovation, enhancements in operational efficiency, and economic benefits over the long haul. With ongoing research and technological progress, ship electrification is set to transform the future of marine transportation, leading to a cleaner and more sustainable global shipping industry [257, 258].

4.2.1 Battery Electric ships

Ships that operate on battery electricity constitute one of the most advanced and sustainable options for maritime transport over short distances. These vessels depend exclusively on electric propulsion systems that are powered by onboard batteries, thus removing the necessity for internal combustion engines and fossil fuel combustion. Consequently, battery-electric vessels generate no emissions while in use. This makes them an essential technology for lessening the environmental impact of maritime activities, especially in coastal regions, inland waterways, and urban ports where air quality and noise pollution are significant issues. The concept behind battery-electric propulsion is quite straightforward: electric motors, which turn the vessel's propellers, are powered by electrical energy from high-capacity batteries. The batteries can be recharged at shore-based charging stations, which are often powered by renewable energy sources like wind or solar. Some ships may use regenerative energy recovery systems, enabling them to capture energy while braking or manoeuvring and store it in their batteries. This renders the system efficient as well as eco-friendly [259, 260].

Battery-powered ships are ideal for short-distance routes, including ferries, passenger vessels, and service boats operating on inland waterways or between adjacent islands. This suitability is primarily due to the current limitation in battery energy density and capacity. Although present-day lithium-ion battery technologies are advancing quickly, they still cannot supply the energy needed for long-distance ocean trips without causing a significant increase in the weight of the vessel or a reduction in its cargo capacity. However, for routes generally taking less than a few hours, battery-electric propulsion provides exceptional performance, great reliability, and low operational costs. Battery-electric ships have the remarkable advantage of being able to function without noise or direct emissions. This renders them perfect for areas that are sensitive to environmental changes, like lakes, rivers, and fjords. In such places, conventional diesel-powered

boats add to pollution and disrupt aquatic organisms. Additionally, due to having fewer moving parts and not depending on complex fuel and exhaust systems, electric propulsion systems demand much less maintenance than internal combustion engines. Although the initial investment is comparatively high, this leads to reduced operational costs and extended system lifespans over time. Several countries have already integrated battery-electric vessels into their public transport and freight systems. As an example, Norway has emerged as a worldwide frontrunner in the use of fully electric ferries, like the Ampere, which runs a 6-kilometer route on the Sognefjord. The vessel is driven by lithium-ion batteries with a capacity of 1,000 kWh and can be completely recharged in roughly ten minutes at every port. In Denmark, Finland, and the Netherlands, similar initiatives are being carried out, as inland waterway transport is significant for regional logistics in these areas. The practical feasibility and economic advantages of electric ships in short-distance applications are illustrated by these examples. However, there are still some hurdles to the widespread implementation of battery-electric ships. The limited range and the charging times that are relatively long can create logistical challenges, especially on busy ferry routes with high frequency. Moreover, establishing high-capacity charging infrastructure at ports necessitates considerable investment and collaboration among ship operators, port authorities, and energy providers. Another major issue is the environmental effect of producing and disposing of batteries, which needs to be handled with care through recycling and by using sustainable materials [261, 262].

ships powered by batteries are an essential advance for sustainable marine transport. They are especially well-suited for short-distance ferry services and inland waterways, where their environmental and operational advantages can be fully exploited. As battery technology continues to advance, along with faster charging systems and the integration of renewable energy, battery-electric ships are anticipated to become increasingly pivotal in reducing carbon emissions within the maritime sector and fostering cleaner, quieter, and more efficient water transport systems.

4.2.2 Charging infrastructure

To successfully adopt battery-electric ships, it is crucial to develop charging infrastructure that is both efficient and dependable. The operational feasibility and economic viability of electrified maritime transport depend on the availability and accessibility of shore power and fast-charging stations, as these vessels rely entirely on stored electrical energy for propulsion. The establishment of a meticulously planned

charging network guarantees minimal vessel downtime and facilitates the incorporation of renewable energy sources, aiding in the creation of a cleaner, more sustainable maritime environment. Shore power, referred to as cold ironing or shore-to-ship power (SSP), enables ships to link up with the local electrical grid while they are docked in ports. This system provides the required electricity to run the ship's auxiliary systems and recharge onboard batteries, thus removing the necessity of operating diesel generators while docked. The use of shore power leads to a major decrease in greenhouse gas emissions, noise, and air pollutants like NO_x, SO_x, and particulate matter in port areas providing advantages for both port workers and surrounding communities. Electricity for shore power can come from renewable energy sources such as wind or solar farms, which further minimizes the carbon footprint of maritime operations.

Fast charging stations are especially crucial for battery electric ships that operate on short routes. These systems are engineered to provide high amounts of power in a brief timeframe, enabling vessels to recharge quickly between trips without delaying the schedule. To guarantee safety and efficiency in the charging process, fast charging technologies employ sophisticated power converters, automated connection systems, and energy management software. Ports often use automated robotic charging arms or inductive charging pads for completely autonomous charging, which minimizes the need for human involvement and shortens turnaround times.

An illustration of successful execution can be observed in Norway, which is at the forefront of electric ferry operations. Norway's fjord ports feature high-capacity fast charging systems that can recharge ferries in just 10 to 15 minutes while passengers are being loaded and unloaded. These systems are often backed by onshore battery banks that accumulate energy from renewable sources and discharge it during peak charging times. This method aids in balancing the demand on the local power grid and guarantees a stable electricity supply even during peak traffic times. Countries such as Denmark, Finland, and Canada are now developing similar systems, as short-distance ferries are a vital component of their transportation networks [263, 264, 265].

However, there are numerous technical, economic, and regulatory obstacles to the development of charging infrastructure. A key barrier is the considerable upfront investment required for the installation of high voltage charging systems, enhancement of port electrical capacity, and incorporation of smart grid technologies. Moreover, the absence of standardization in charging interfaces, voltage levels, and connection

protocols for various ports and types of ships impedes interoperability and global adoption. To tackle this problem, entities like the International Electrotechnical Commission (IEC) and the International Maritime Organization (IMO) are striving to create worldwide standards for shore power and marine charging systems. Another key aspect to consider is the capacity and stability of the grid. Ports and ships becoming electrified brings about considerable electrical loads that need to be managed with care to prevent disruptions. To ensure a dependable electricity supply, it is necessary to integrate smart grids, energy storage systems, and demand response strategies. To attain energy independence and resilience, ports situated in remote, or energy scarce regions might have to integrate local renewable sources like offshore wind or floating solar installations with battery storage. To conclude, the establishment of shore power and fast charging infrastructure is essential for facilitating the widespread use of battery electric and hybrid electric vessels. These systems cut emissions, enhance air quality in port cities, and facilitate the shift to sustainable maritime practices. Despite the ongoing challenges related to cost, standardization, and grid integration, continued investment, technological innovation, and international cooperation are creating pathways toward a fully electrified maritime future. With the demand for cleaner transport on the rise, contemporary ports will progressively transform into smart energy hubs, becoming pivotal to the global effort to decarbonize shipping.

4.2.3 Energy storage advances

Progress in energy storage technology has developed into a key factor for the electrification of maritime transport. With the shift from traditional diesel engines to battery-electric or hybrid propulsion systems in ships, the operational feasibility of these vessels is closely linked to the performance, safety, and efficiency of their onboard energy storage. Modern energy storage solutions aim to enhance battery energy density, lifetime, safety, and charging speed factors that are essential for promoting the use of electrified shipping on both short and long maritime routes. Enhancements in energy density are among the most important technological advancements in the development of marine batteries. Energy density, expressed in watt-hours per kilogram (Wh/kg), dictates the amount of energy that can be stored for a specific weight, which directly affects the ship's range, payload capacity, and overall efficiency. Marine applications once commonly used traditional lead-acid batteries; however, their low energy density and weightiness severely restricted ship performance. Lithium-ion batteries have transformed energy storage for maritime

transportation due to their much greater energy densities, quicker charging capabilities, and extended cycle life. The capabilities of energy storage have been further improved by recent advances in lithium-ion chemistries, including lithium iron phosphate (LFP), nickel manganese cobalt (NMC), and solid-state lithium batteries. As an example, NMC batteries boast a high energy density and a relatively small size, making them apt for ferries, workboats, and hybrid cargo ships. Meanwhile, LFP batteries are characterized by enhanced thermal stability and longevity, making them ideal for vessels that need to cycle often and rely on performance in challenging marine conditions. Another essential factor regarding energy storage in maritime applications is the safety of batteries. Ships function in environments that are highly dynamic, contending with vibrations, variations in temperature, and the potential for exposure to water, salt, and severe weather conditions. Due to the risk of fire from thermal runaway, short circuits, or mechanical damage, strong safety systems are essential. Modern marine batteries come with sophisticated battery management systems (BMS) that provide real-time monitoring of voltage, current, temperature, and state-of-charge, ensuring safe and efficient functioning. Safety measures also encompass cell-level monitoring, thermal management systems, and redundant protective circuits, which help reduce risks and extend battery life. Advancements in solid-state batteries and the development of safer cathode and electrolyte materials further diminish fire hazards while providing greater energy density and extended cycle life, enhancing their appeal for maritime applications [266, 267, 268].

Another field of advancement is the incorporation of hybrid energy storage systems. By integrating supercapacitors or secondary energy sources with lithium-ion batteries, ships can meet peak power demands like rapid acceleration or guide without overloading the battery system. This method alleviates battery stress, boosts operational efficiency, and prolongs their lifespan. Furthermore, advancements in modular and scalable battery designs enable flexible installations across various types of ships from ferries and passenger vessels to offshore service ships while optimizing space use and weight distribution. Along with enhancements to onboard systems, charging strategies and energy management are crucial for reaping the full advantages of advanced batteries. Ports and vessels are progressively implementing smart charging systems that enhance charge cycles, avert overcharging, and minimize battery pack stress. By employing predictive algorithms and energy optimization software, battery usage can be made efficient and safe, even in the face of changing operational conditions like

variations in passenger loads or a sporadic renewable energy supply. progress in energy storage is vital for the success of electrified maritime transport. Advancements in battery energy density enable ships to cover longer distances and carry heavier loads, while developments in safety systems guarantee dependable and hazard-free functioning in challenging marine conditions. When combined with hybrid storage solutions, modular designs, and intelligent energy management, these advancements are laying the groundwork for a new era of cleaner, more efficient, and sustainable shipping. With the ongoing development of battery technologies, energy storage will continue to be a key facilitator of the worldwide shift to zero-emission maritime transport.

4.3 Energy Efficiency Technologies

One of the most essential methods for enhancing a vessel's energy efficiency is to optimize the hull design. The aim is to design the hull in a way that minimizes resistance as it moves through water. A hull that is well-designed lessens frictional drag, wave-making resistance, and enhances overall hydrodynamic performance. Hulls that are optimized for modern ships utilize streamlined shapes, facilitating smooth water flow along the ship's surfaces. To minimize wave generation, particularly around the bow, designers meticulously calibrate the hull's length, width, and curvature. To avoid turbulence and flow separation two major causes of energy loss a well-designed entrance shape, smoother transitions, and gently tapered stern sections are essential. The propulsion system can work at a significantly greater efficiency when water flows cleanly along the hull and exits smoothly behind the ship. The bulbous bows of the bow design are crafted to engage with the natural bow wave, receiving careful attention. The bulb can lessen wave resistance by redirecting water flow and partially cancelling the wave pattern when it is properly matched to the operational speed and loading conditions. In the same way, the shape of the stern is refined to ensure that water coming toward the propeller is distributed uniformly, which enhances the propeller's thrust production. Optimized hull forms can lead to considerable fuel savings frequently ranging from 5% to 15% by lessening the effort needed to propel the vessel through the water. The advantages increase even more when used in conjunction with advanced materials, smoother surface coatings, and low-fouling designs that maintain the hull's smoothness [269,270,271].

4.3.1 Air Lubrication Systems

Another significant energy saving technology is air lubrication, which aims to diminish the friction between the ship's hull and the water. This system modifies the hull water interaction by adding air beneath the vessel, rather than changing the shape of the hull. Air's density and viscosity are considerably lower than those of water. Therefore, the establishment of a partial air layer leads to a significant reduction in drag. In an air lubrication system, compressors deliver air to multiple outlets arranged along the smooth underside of the hull. As the vessel progresses, the air disperses into a thin layer of small bubbles or a film that adheres to the bottom of the ship. This air "cushion" minimizes the direct interaction between the hull plates and the surrounding seawater, thereby reducing hydrodynamic resistance. This effect is especially beneficial for large ships with broad bottoms, such as bulk carriers, tankers, and LNG carriers, due to their extensive wetted surface area. Typically, two approaches are employed: one uses micro bubbles that remain fixed to the hull surface, while the other generates a more continuous air film. While both methods can lower fuel consumption, air films are usually more effective when the hull is tailored to accommodate them. Depending on the type of ship, operating speed, and sea conditions, energy savings can vary from 5% to 15%. To operate the compressors, the system requires energy; thus, the net savings are contingent upon effective integration and upkeep. Performance can be diminished by elements like hull fouling, blockages in the nozzle, or turbulent sea conditions.

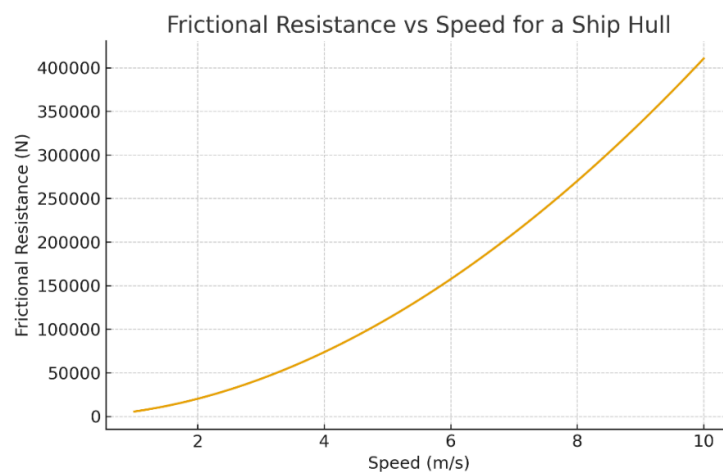


Figure 4-4 visual graph showing how frictional resistance increases with ship speed using the ITTC-1957 formula

Figure 4-6 visually demonstrates the non-linear, exponential increase in frictional resistance acting on a ship hull as speed increases, a relationship fundamentally governed by the ITTC-1957 correlation line formula. The curve shows that resistance

rises gradually at lower speeds but accelerates dramatically at higher speeds, as indicated by the values climbing from 50,000 N at 2 m/s to 400,000 N at 10 m/s. The propulsion power required (which directly overcomes this resistance) increases at a much greater rate than speed. Consequently, even modest speed reductions through optimized operation can yield substantial energy savings, directly enhancing the efficiency and range of battery-electric or hybrid propulsion systems.

4.3.2 Waste Heat Recovery

Waste heat recovery aboard ships is an essential technology aimed at harnessing and reusing the thermal energy generated by the ship's engines, especially from exhaust gases, to produce electricity onboard. Marine engines of considerable size, particularly diesel engines, function at elevated temperatures and generate substantial heat. This heat is usually dissipated into the environment via exhaust and cooling systems. This energy is essentially wasted without recovery. Waste heat recovery systems are engineered to capture this energy and convert it into usable power. This power can be used to provide electricity for various onboard systems, including lighting, air conditioning, and auxiliary machinery, thereby decreasing fuel reliance and enhancing overall energy efficiency. This procedure entails setting up heat recovery units like economizers or exhaust gas boilers that seize the thermal energy from the hot exhaust produced by the ship's auxiliary and main engines. These units convey heat to a working fluid typically water or thermal oil resulting in hot water or steam [272].

This produced steam can operate a steam turbine linked to a generator, creating electricity for the ship's electrical grid. Ships can realize considerable fuel savings through the integration of waste heat recovery, as the recovered energy supplements the output of conventional engines. This contributes to more eco-friendly maritime operations by not only lowering operational costs but also reducing greenhouse gas emissions and other pollutants. beyond energizing electrical systems, the heat that is recovered can be used for various other applications onboard, like heating fuel, water, or living quarters. This further improves the ship's energy efficiency. Depending on the type of engine, operational profile, and recovery system efficiency, modern vessels outfitted with sophisticated waste heat recovery systems can experience enhancements in overall engine efficiency of as much as 10 to 15 percent. With international regulations on fuel consumption and emissions tightening, especially those set by the (IMO), waste heat recovery technology is becoming crucial for designing energy-efficient vessels. Its implementation provides economic advantages and promotes sustainable shipping

practices by reducing fuel consumption and lowering the carbon footprint of maritime transport [273,274].

Overall reusing waste heat for electricity generation onboard turns a ship's wasted energy into a useful resource, enhances fuel efficiency, and mitigates environmental effects. By integrating such systems, modern engineering solutions can improve the sustainability of maritime operations without sacrificing reliability and efficiency. It constitutes a crucial advance in the direction of environmentally friendlier shipping and is consistent with worldwide endeavours aimed at cutting transportation-sector emissions.

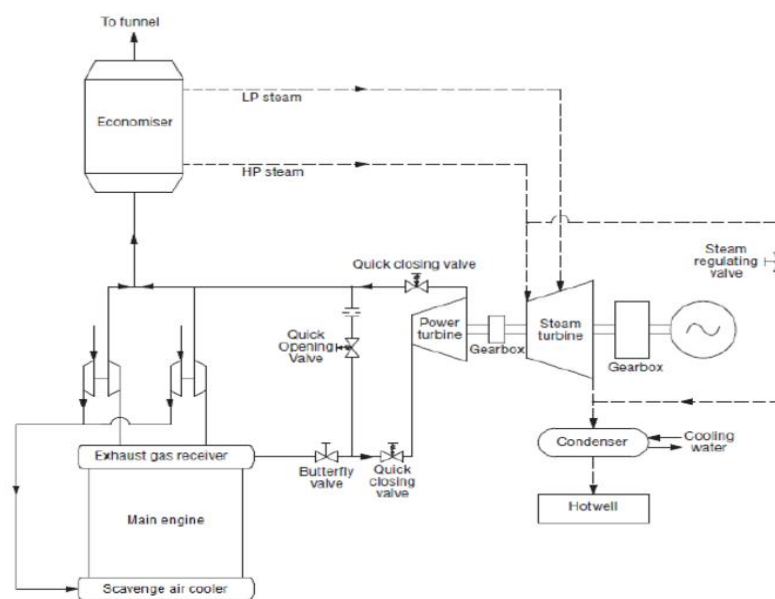


Figure 4-5 Heat recovery system image by goggle

Figure 4-7 describes the schematic of a Waste Heat Recovery System (WHRS) for a marine engine. The system captures thermal energy from the main engine's exhaust gases, using an exhaust gas receiver and an economizer to generate steam (both LP and HP). This steam then drives a steam turbine, which, through a gearbox, contributes power to the propulsion system or generators, thereby improving overall plant efficiency. Key safety and control components like quick-closing valves and a steam regulator valve are integral, ensuring safe operation. For your thesis, this visual represents a critical technology for reducing fuel consumption and emissions by converting waste heat into useful mechanical power.

4.3.3 Lightweight materials for ships

Lightweight materials have become increasingly important in modern ship design as the industry aims to enhance fuel efficiency, cut emissions, and improve overall vessel performance, lightweight materials have gained greater significance in contemporary ship design. Advanced composites and marine-grade aluminium are among the most used materials, both of which provide considerable benefits compared to conventional steel structures. These materials assist in reducing a vessel's fuel usage by decreasing its weight without sacrificing strength or durability, as lighter ships need less energy to move through the water. This subsequently results in decreased operational expenses and a diminished environmental impact elements that are increasingly vital as global maritime regulations become stricter. Lightweight construction enhances stability and payload capacity, providing ship operators with greater flexibility in transporting cargo and passengers.

Marine-grade aluminium is preferred due to its excellent strength-to-weight ratio, resistance to corrosion, and ease of fabrication. It is frequently utilized in high-speed craft, ferries, patrol boats, and areas of larger ships where minimizing weight is essential. With aluminium, shipbuilders can craft hulls and superstructures that are much lighter than those made of steel. This often leads to faster vessel speeds and enhanced flexibility. Even though aluminium can cost more than steel, the savings on fuel over time and the lowered need for maintenance frequently balance out the initial expense. Due to advancements in welding methods and alloy creation, aluminium is now more dependable in severe marine conditions, further encouraging its adoption. Composite materials, including fiber-reinforced polymers, carbon fiber composites, and glass-fiber laminates, provide significantly greater weight reductions compared to metal alternatives. These materials can be customized to a high degree, enabling designers to adapt their mechanical properties to components of the ship. Mixtures offer outstanding protection against corrosion, fatigue, and impact, all while necessitating very little upkeep during their lifespan. Because they can be shaped into complex forms, hydrodynamic designs can be improved to reduce drag and boost the efficiency of the entire vessel. Composites are being utilized more in smaller vessels, luxury yachts, naval ships, and elements such as deckhouses, masts, and interior frameworks. Thanks to developments in manufacturing methods such as vacuum infusion and automated fiber placement, composite production for marine applications has become more efficient and scalable [275, 276, 277].

Nevertheless, lightweight materials must be carefully engineered metals, composites, and conventional steel vary in thermal expansion, fire resistance, structural performance under heavy loads, and long-term durability, continuous investigation and progress in technology are tackling these difficulties, resulting in a greater reliability and prevalence of lightweight materials in shipbuilding. The maritime sector's efforts to adopt greener practices and improve energy efficiency have made the incorporation of aluminium and composite materials a vital approach for creating next-gen ships that fulfil performance requirements and lessen environmental effects.

4.4 Regulation and policy framework

4.4.1 IMO Regulations

MARPOL Annex VI serves as the international framework for preventing air pollution from ships, and it is how the International Maritime Organization (IMO) primarily regulates air emissions from global maritime transport. Annex VI establishes limits for emissions of Sulphur oxides (Sox), nitrogen oxides (NOx), particulate matter, and ozone-depleting substances. It also regulates the quality and Sulphur content of marine fuel oils. As of 2020, ships globally are required to utilize fuel with a Sulphur content that does not surpass 0.50% by mass. In designated Emission Control Areas, the limit is further reduced to 0.10%. The Annex contains provisions for regulating NOx emissions via a tiered approach (Tier I, II, and III) based on the age of the engine and whether the vessel operates within NOx Emission Control Areas. Ships are required to have certificates, and they must adhere to bunker fuel sampling, engine certification, and inspections as mandated by port state control. Over the years, Annex VI has broadened its scope to incorporate climate-related components, such as obligatory energy-efficiency standards, fuel consumption documentation, and greenhouse-gas mitigation strategies. The IMO implemented the Energy Efficiency Design Index (EEDI) under Annex VI to enhance the energy efficiency of new ships. By determining the maximum permitted CO₂ emissions per ton-mile for various types and sizes of ships, the EEDI sets minimum energy efficiency standards for new vessels. Every new ship must determine its "attained EEDI" and demonstrate that it meets or exceeds the "required EEDI," which tightens in phases every few years. Due to EEDI being performance-based rather than prescriptive, shipbuilders are required to optimize hull forms, engines, propulsion systems, and onboard technologies to achieve efficiency targets while having the freedom to select their methods. Since 2013, the EEDI has

been compulsory for most new ships exceeding 400 gross tonnages. It acts as a baseline technical standard aimed at enhancing ship design and innovation to achieve lower fuel consumption and diminished emissions [278, 279].

The EEDI is applicable solely to newly constructed vessels, but the IMO also governs existing ships with the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII). Analogous to the EEDI, the EEXI is applied retroactively to vessels in service, mandating that they achieve a minimum level of technical efficiency. This requirement frequently compels operators to implement adjustments like limiting engine power, enhancing the hull, or upgrading the propeller. In contrast, the CII assesses the annual operational carbon intensity of ships over 5,000 gross tons by determining the grams of CO₂ emitted per cargo-carrying capacity and nautical mile. Every ship is assigned an annual performance rating ranging from A (excellent) to E (poor). A ship that has received a D rating for three consecutive years or an E rating in any one year is required to submit and execute a corrective action plan aimed at regaining compliance. Through optimized passage planning, reduced speeds, fuel management, hull maintenance, and the use of alternative or low-carbon fuels, this system encourages operators to enhance real-world efficiency.

MARPOL Annex VI, the EEDI, EEXI, and CII collectively create a thorough regulatory framework that deals with the technical design and operational performance of ships. Annex VI regulates air pollutants and sets up the framework for greenhouse-gas measures; the EEDI guarantees that each new generation of ships is more energy-efficient than its predecessor, while the EEXI and CII promote reductions in fuel consumption and CO₂ emissions during operation for the current global fleet. The collective aim of these regulations is to reduce shipping's environmental impact and bring the maritime industry into alignment with international climate objectives, while fostering technological advancement, improved operational methods, and a gradual shift toward cleaner fuels [280, 281].

4.4.2 EU and Regional Policies

The Fuel EU Maritime Regulation represents one of the European Union's key strategies aimed at cutting greenhouse-gas emissions from vessels that dock at EU ports. It necessitates that large vessels typically those above 5,000 gross tons progressively diminish the greenhouse-gas intensity of the energy they utilize on board. The regulation sets a limit on emissions intensity that will decline starting in 2025 and continuing until 2050. This aims to promote the transition from fossil marine fuels to

renewable and low-carbon alternatives like advanced biofuels, e-fuels, green methanol, ammonia, and other sustainable options. Fuel EU Maritime also mandates that the majority of container and passenger vessels connect to an onshore power supply while docked, which greatly reduces emissions in the port. Operators are required to monitor and report on the energy consumption and greenhouse-gas performance of their vessels, as well as to maintain a valid compliance certificate. All ships visiting EU ports are subject to regulation, irrespective of their flag state, thereby guaranteeing a level playing field for global operators. Fuel EU Maritime promotes the EU's wider objectives for climate neutrality and speeds up the decarbonization of maritime transport in Europe by encouraging demand for cleaner marine fuels.

The Fit for 55 package is the European Union's comprehensive climate and energy legislative framework designed to achieve a 55% reduction in net greenhouse-gas emissions by 2030. It forms a core part of the European Green Deal and covers nearly every major economic sector, including transport. For shipping, fit for 55 introduces several transformative measures: the extension of the EU Emissions Trading System to maritime transport, the creation of the Fuel EU Maritime Regulation, and new rules supporting alternative fuels and energy infrastructure, such as enhanced renewable-energy requirements and expanded shore-side electricity capabilities [282,283].

The European Union's Fit for 55 package serves as a comprehensive climate and energy legislative framework aimed at achieving a 55% reduction in net greenhouse-gas emissions by the year 2030. As a key element of the European Green Deal, it encompasses almost all major economic sectors, transport included. In the shipping sector, fit for 55 brings in various groundbreaking initiatives: extending the EU Emissions Trading System to cover maritime transport, establishing the Fuel EU Maritime Regulation, and implementing new provisions that promote alternative fuels and energy systems, including stricter renewable-energy mandates and increased shore-side electricity options. Europe's main carbon-pricing mechanism, the EU Emissions Trading System (EU ETS), has been reformed to include maritime transport. The ETS limits the overall greenhouse gas emissions from sectors that take part in it, and it mandates that businesses possess emission allowances for each ton of CO₂ emitted. The EU has established a direct carbon price for maritime carriers that operate to, from, or within EU ports by including shipping in the ETS. Each year, ship operators are required to calculate their emissions and surrender allowances based on the proportion of their voyages that fall under EU jurisdiction. During the phase-in period, the

percentage of maritime emissions covered increases gradually, ending in a requirement for full compliance after several initial years. The financial incentive to reduce emissions via operational measures such as speed optimization, improved routing, hull and propeller maintenance, and investments in cleaner fuels and technologies is created by the cost of purchasing allowances. As such, the ETS serves as an economic catalyst that complements Fuel EU Maritime's technical and fuel-based requirements.

Fuel EU Maritime, fit for 55, and the EU ETS work together as a coordinated policy system addressing maritime emissions from various perspectives. Fuel EU Maritime targets the greenhouse-gas intensity of energy consumption onboard, promoting cleaner fuels and port electrification for ships. Fit for 55 offers a comprehensive climate framework and integrates maritime policies into a cohesive strategy. With the introduction of carbon pricing through the EU ETS, reducing emissions becomes financially beneficial.

Ship operators must now navigate compliance that encompasses not just reporting and certification, but also strategic choices regarding fuel selection, ship design, operational efficiency, and cost management within a carbon-regulated framework. With these policies combined, the EU is positioned as a leader in maritime decarbonization, with a considerable impact on global shipping practices [284, 285].

4.4.3 Carbon Pricing

Carbon pricing for ships includes the economic mechanisms and policies that impose a monetary charge on greenhouse-gas emissions from maritime transport. This approach aims to make pollution financially detrimental and incentivize shipowners to invest in cleaner technologies and more efficient practices. The main concept is that carbon emissions are regarded as an economic externality one that has not been assigned a price and thus is exploited excessively, and that carbon pricing serves to internalize this cost, making sure that those who pollute cover the costs of the environmental consequences of their actions. In the maritime sector, carbon pricing is emerging as a key catalyst for decarbonization due to the industry's historical dependence on low-cost, high-carbon fuels such as heavy fuel oil, where cost incentives serve as potent signals in an industry sensitive to costs [286, 287].

There are two major forms of carbon pricing applied to shipping: carbon taxes and emissions trading systems (ETS). With a carbon tax, the price per tonne of emitted CO₂ is predetermined. This allows ship operators to know exactly what their emissions will cost and to plan their budgets for investments in cleaner fuel over the long term. In

contrast, an ETS limits total emissions and lets the market determine the carbon price through allowance trading. Shipowners are required to hand over allowances that match their emissions, with the price varying based on supply and demand dynamics. This method incentivizes businesses that can lower emissions at a reduced cost since they can save or sell surplus allowances and punishes those that do not adapt [288].

Carbon prices under an ETS impose a direct financial penalty for inefficiency. Operational costs increase for a vessel that produces more emissions and requires more allowances due to higher fuel consumption per voyage. This motivates companies to implement actions like optimizing route planning, cutting sailing speed (slow steaming), improving hull maintenance, and equipping ships with energy-efficient technologies, the incentive to adopt low-carbon strategies increases with the carbon price. As fuel already constitutes the greatest operational expense for most vessels, incorporating a carbon cost intensifies the incentive to utilize cleaner fuels such as LNG, biofuels, e-methanol, ammonia, hydrogen, or forthcoming synthetic fuels with reduced carbon intensity. [289,290]

From an economic perspective, carbon pricing contributes to rectifying the competitive inequity between fossil fuels and cleaner options, despite emitting significantly more CO₂, traditional heavy fuel oil is still cheaper per energy unit than many sustainable marine fuels. Carbon pricing makes low-carbon fuels more financially appealing and promotes investment in fuel production, bunkering infrastructure, and new ship designs by placing a cost on carbon emissions and thereby narrowing the price gap. This price signal can assist in reshaping the global maritime fuel market over time by redirecting demand toward renewable and zero-carbon energy sources.

Long-term choices regarding shipbuilding and fleet renewal are also affected by carbon pricing mechanisms. When planning newbuild vessels, shipowners must consider the accumulation of carbon costs over a ship's 20-to-30-year lifespan.

A vessel that relies on fossil fuels or has unsatisfactory energy efficiency could encounter carbon costs that are substantial and escalating, thereby diminishing its profits. Consequently, shipowners are more motivated to place orders for ships that can use alternative fuels, incorporate energy-efficient propulsion systems and optimized hull designs, and include digital performance-monitoring tools. Thus, carbon pricing speeds up long-term investments in technologies that align with climate goals. [291,292].

Ultimately, carbon pricing promotes wider behavioural and cultural changes in the maritime sector, businesses start to incorporate sustainability into financial planning, procurement strategies, chartering agreements, and corporate reporting, charterers might prefer vessels that produce fewer emissions to reduce their own carbon liabilities, whereas financiers and insurers are increasingly considering carbon exposure in their assessments of shipping investments. Thus, carbon pricing goes beyond simply penalizing emissions; it transforms the whole economic ecosystem of maritime transport, making environmental performance a key component of business competitiveness.

4.4.4 Green certification

Green certification for ships relates to voluntary or obligatory initiatives that acknowledge vessels for their eco-friendly practices. Eco-labels and certifications indicate that a ship complies with stringent criteria regarding energy efficiency, emissions reduction, waste management, and overall environmental performance. Common instances include ISO 14001, a global benchmark for environmental management systems that aid ship operators in systematically observing, controlling, and diminishing environmental effects, other green labels might certify low fuel use, lower greenhouse-gas emissions, or adherence to sustainable operational practices. These certifications motivate shipping companies to embrace cleaner technologies, enhance operational efficiency, and show environmental accountability to regulators, customers, and charterers. Acquiring acknowledged green certifications allows ships to enhance their sustainability and secure a competitive edge in markets that are becoming more aware of environmental issues [293,294].

4.5 Economic and Social Aspects

Green shipping requires balancing the higher initial costs of energy-efficient ships, alternative-fuel technologies, and retrofitting existing vessels against the long-term advantages of reduced operational costs, decreased fuel consumption, and observance to increasingly strict environmental regulations. Capital expenditures for the initial phase can be considerable, particularly for ships that use low-carbon fuels like LNG, ammonia, hydrogen, or advanced biofuels, as well as vessels that feature hybrid or electric propulsion systems, energy-efficient hull designs, and onboard energy management solutions. However, during the operational lifespan of a vessel, these investments are frequently balanced out by savings derived from better fuel efficiency,

lower maintenance needs, evasion of carbon taxes, and improved access to green ports that offer incentives or reduced fees. Green financing mechanisms are essential for facilitating this transition, providing subsidies, grants, low-interest loans, and green bonds that reduce economic barriers, speed up the adoption of sustainable practices, and promote innovation in vessel design, alternative fuel use, and emission-reduction technologies [295,296].

Equally significant is the social aspect of green shipping as cleaner technologies are adopted, there arises a need for a skilled maritime workforce adept at managing alternative fuels, operating energy-efficient propulsion systems, and monitoring and reporting on environmental performance. This motivates investment in training, certification programs, and professional development, guaranteeing that crew members, engineers, and technical staff possess the necessary expertise to safely and efficiently operate modern sustainable vessels. In addition, green shipping stimulates economic activity in associated sectors such as renewable fuel production, ship retrofitting, port electrification, and the creation of energy-efficient components. This results in new job opportunities and aids regional economic development.

Even with these opportunities, the transition encounters various obstacles, including the significant initial capital investment required for low-emission vessels, the restricted availability and infrastructure for alternative fuels on a global scale, regulatory complexities across different jurisdictions, and uncertainties regarding technologies linked to new solutions. Despite these challenges, there are significant opportunities for innovation in areas such as ship design, fuel switching, hybrid propulsion systems, digital optimization for fuel efficiency, and operational strategies like slow steaming and route optimization [297,298].

By investing early in green technologies, shipowners can achieve a competitive edge through reduced lifetime operating costs, improved adherence to environmental regulations, access to preferential chartering contracts, an enhanced reputation among environmentally conscious clients, and alignment with global climate objectives. Green shipping bolsters the long-term sustainability and resilience of the maritime sector while minimizing its environmental impact by merging economic planning, financing strategies, workforce development, and technological innovation [299,300].

4.6 Chapter Summary

Green transportation modes for ships focus on reducing emissions, improving energy efficiency, and minimizing environmental impact within the maritime sector. Key approaches include the adoption of alternative fuels such as LNG, biofuels, hydrogen, and ammonia, along with the integration of electric and hybrid propulsion systems. Innovations like wind-assisted propulsion, solar power, and hull-optimization technologies further enhance sustainability. Together, these solutions aim to reduce greenhouse gas emissions, comply with international regulations, and support the transition toward a cleaner, more environmentally responsible global shipping industry.

Chapter 5 . Cold Ironing (Shore-to-Ship Power)

5.1 Introduction

Cold ironing is also known as shore-to-ship power or substitute maritime power has become one of the most significant technological solutions for reducing environmental impacts in port areas. This term denotes the method of supplying ships with electrical power directly from the shore while they are docked, enabling ships to switch off their auxiliary engines that typically operate on diesel fuel. These auxiliary engines are crucial for sustaining onboard functions like illumination, climate control, cargo handling apparatus, safety mechanisms, and communication systems. However, when they run on fossil fuels, they release considerable quantities of nitrogen oxides, sulphur oxides, particulate matter, and carbon dioxide, cold ironing replaces onboard power generation with cleaner electricity from the port's grid, thus eliminating these emissions, this electricity is often produced from renewable or low-emission sources, enhancing the environmental benefits. The expression “cold ironing” originates from the time of steamships, in the early days of maritime transport, ships were driven by large iron engines and coal fired boilers, when a ship docked and its engines were turned off, the machinery would cool down entirely, and the iron parts would become “cold,” signalling that the ship’s power systems were inactive. [301, 302].

With the advent of contemporary environmental issues, the idea was reintroduced with a new significance permitting ships to turn off their engines while docked, thus effectively reverting the equipment to a “cold” state. Initially, the shift from the historical model to modern cold ironing technology was gradual, However, by the early 2000s, ports started to develop dependable electrical infrastructure to facilitate this transition, the ports of Long Beach and Los Angeles in the U.S. were early innovators, motivated by stringent local air-quality laws and community demands for a decrease in pollution, by adopting it early on, they opened the door for global expansion and international standards. The primary aim of cold ironing is to greatly diminish ship emissions during the berthing period, which can extend for several hours or even days depending on cargo operations, even at rest, ships need significant energy. This energy has traditionally been supplied by diesel generators onboard ships that run continuously emitting harmful pollutants and contributing to the poor air quality in port cities. These

emissions pose a particular challenge for densely populated coastal areas, where residents and port workers face exposure to intensified levels of exhaust gases. Cold ironing provides an immediate and highly effective method for eliminating these pollutants at their source by allowing ships to switch to shore power, another significant benefit is the reduction of noise pollution, as shutting down diesel engines results in a quieter and more pleasant environment around the port, the enhancement of environmental conditions has made cold ironing a crucial focus in numerous national and regional strategies aimed at reducing emissions.

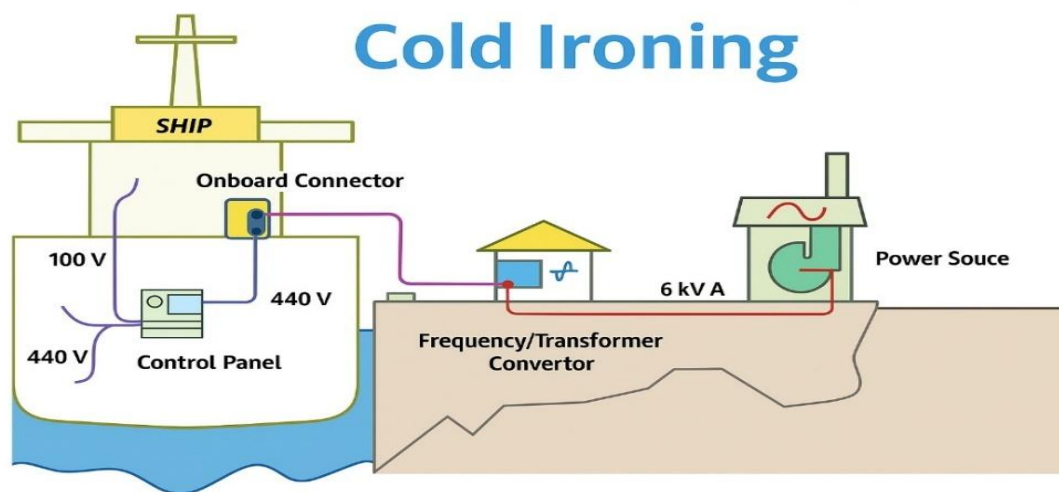


Figure 5-1 Fundamental principle of Cold Ironing image by Google

Figure 5-1 illustrates the fundamental principle of "Cold Ironing" or Shore Power Connection, a key technology for reducing emissions in ports the shore power typically at a different voltage and frequency, is conditioned by a Frequency/Transformer Converter on the ship, this converted power is then distributed through the ship's Control Panel to feed the vessel's electrical loads (e.g., lighting, cooling, and auxiliary systems) at standard voltages like 440V and 100V. By allowing the ship to shut down its auxiliary engines while at berth, cold ironing eliminates all associated local air pollutants (SO_x, NO_x, PM) and noise, representing a crucial strategy for sustainable port operations and a vital topic for a thesis on green shipping.

Cold ironing has gradually become significant in the context of global green port initiatives aimed at reducing carbon emissions in the maritime industry, many ports worldwide now consider the implementation of shore power systems a necessary investment to align with the changing expectations of regulators, shipping companies, and local communities. International organizations like the International Maritime

Organization (IMO) and the European Union have implemented progressively strict regulations regarding port emissions, prompting ports to embrace cleaner technologies [303,304].

Cold ironing is commonly emphasized as one of the most effective and results driven solutions, as it directly lowers emissions without necessitating significant changes to port operations. Simultaneously, technology has progressed to the point that systems have become more standardized and cheaper to produce especially regarding international standards for high voltage connections, frequency conversion, and safety requirements. With the ongoing integration of renewable energy sources into electrical grids, the environmental advantages of cold ironing are expanding, further solidifying its significance in sustainable port development. Cold ironing is quickly becoming a vital part of contemporary maritime infrastructure, moving from being an optional environmental measure to a necessity that aids ports in shifting to operations that are greener, quieter, and more energy efficient.

The Port of Genoa in Italy has become one of the prominent Mediterranean ports promoting the implementation of cold ironing as a component of its long-term sustainability strategy. Genoa, being one of the busiest commercial and passenger ports in Europe, accommodates a large volume of container ships, ferries, and cruise ships. These vessels contribute to considerable energy demand and potential emissions while docked, the Port Authority has made substantial investments to modernize its electrical infrastructure and facilitate shore-to-ship power connections, acknowledging the environmental challenges posed by the densely populated urban area surrounding the port. With the backing of national initiatives, EU funding, and Italy's overall decarbonization objectives, Genoa has started to implement cold ironing systems at major terminals, especially those catering to cruise and ferry traffic, where the advantages are most direct, the port's "Green Port" vision encompasses these initiatives, aiming to incorporate renewable energy sources, enhance energy efficiency, and lessen local air pollution. Consequently, Genoa is establishing itself as both a key logistical centre and an exemplar of sustainable port development within the Mediterranean area [305,306].

5.2 Why cold ironing is needed

Ships at berth emit pollutants that pose a significant challenge to public health and the environment. Even at rest, ships need to run auxiliary diesel generators to provide

energy for vital onboard systems, and these engines produce significant quantities of CO₂, NO_x, SO_x, and particulate matter (PM). Numerous studies have demonstrated that pollutant concentrations in port areas often exceed urban background levels due to these at berth emissions. NO_x plays a role in the development of ground level ozone and respiratory irritation, SO_x is responsible for sulphate aerosols and acidification, PM (notably PM_{2.5} and ultrafine particles) infiltrates the lungs and bloodstream, heightening asthma rates, cardiovascular diseases, and premature deaths. In addition, these emissions take place near coastal areas with high population density, thereby worsening health effects. Ports across Europe, North America, and Asia regularly indicate that a significant portion of their local air pollution originates from berthed ships rather than vessels in motion, this is due to the fact that engines operate under low load conditions an inefficient state that generates higher emissions for each energy unit produced, the levels of SO₂ and heavy metal particulates (such as vanadium and nickel from marine fuels) are frequently several times greater near berths compared to those in the surrounding urban areas. In large ports with significant container or cruise-ship traffic, the cumulative effect results in chronic pollution hotspots that impact port workers and nearby residential areas.

5.2.1 Regulatory pressures

Regulatory pressures are mounting across global, regional, and national domains, transforming the reduction of at-berth emissions from an optional measure into a compliance requirement. The IMO's MARPOL Annex VI establishes increasingly strict limits on the sulphur content of marine fuels and NO_x emission tiers, driving ports and shipowners to implement methods that reduce atmospheric pollutants, alongside, the IMO's Greenhouse Gas Strategy mandates a decrease in overall carbon intensity, which makes it ever more crucial for operators aiming to achieve long-term climate targets to reduce CO₂ emissions at berth [307,308].

Within the European Union, the Fuel EU Maritime and AFIR regulations require that shore-power infrastructure be established in core TEN-T ports and mandate that container and passenger ships connect to available onshore power beginning in 2030, with an expansion to nearly all EU ports by 2035. These regulations make it a legal requirement to berth without emissions, likewise, organizations like the California Air Resources Board (CARB) in the U.S. implement some of the strictest at-berth emission reduction regulations worldwide, mandating that certain types of ships use zero-emission technologies while docked.

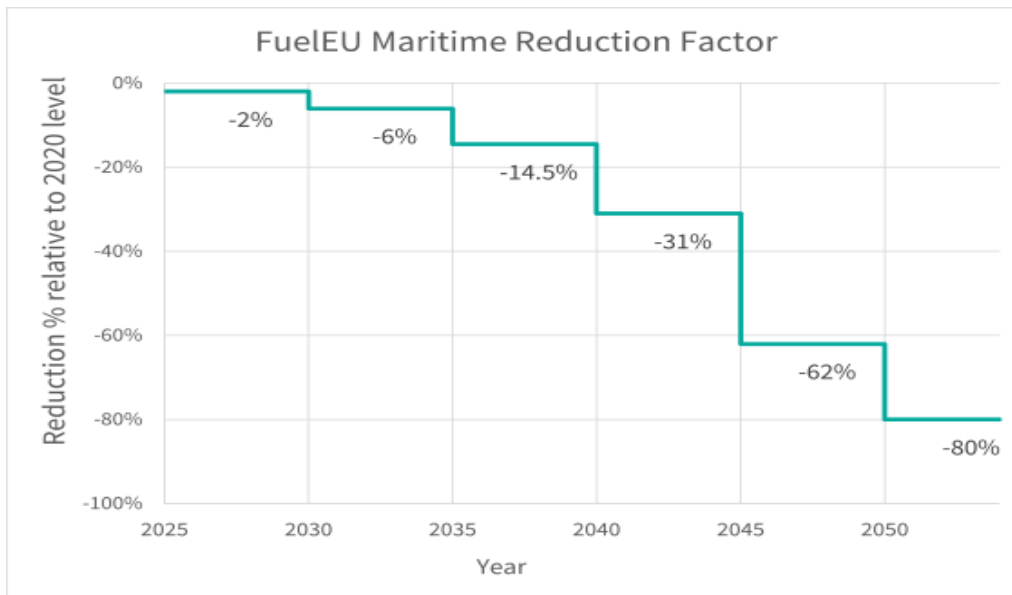


Figure 5-2 Reduction in GHG intensity of energy image by Google

Figure 5-2 illustrates the increasing regulatory pressure of the Fuel EU Maritime initiative, mandating a progressive reduction in the greenhouse gas intensity of energy used on board ships. The required reduction factor escalates sharply from 2% in 2025 to a full 80% by 2050. By switching to shore-side electricity, which is increasingly sourced from a cleaner grid, a ship can dramatically lower its annual GHG intensity, providing a direct and compliant pathway to meet these stringent mid-terms long-term (80% by 2050 targets, thus making cold ironing a strategic necessity for regulatory compliance.

To accelerate the transition, many national governments and port authorities offer financial incentives or impose penalties, as a result, operators who fail to obey encounter increased costs, restricted access, or regulatory sanctions, in addition to environmental and regulatory drivers there are significant economic motivations, keeping auxiliary engines running while in port uses considerable amounts of low-sulphur fuel oil or marine gas oil both of which are among the highest fuels utilized in shipping. By utilizing electricity from shore sources, fuel use is diminished, and this can lead to significant financial savings when averaged across a vessel's operational year, as supplementary engines run constantly while the ship is docked, cutting down on these hours can decrease mechanical wear and tear, lubrication-oil consumption, vibration stresses, and the need for unscheduled maintenance, thereby extending the lifespan of costly engine components. As the maintenance and overhaul cycles for auxiliary engines are directly linked to operating hours, decreasing those hours results

in a reduction of lifecycle costs. In numerous ports, ships that utilize shore power are granted reduced port fees or environmental rebates, enhancing their economic competitiveness.

Cold ironing improves the port's environmental reputation and supports green-corridor initiatives, thereby making it more appealing to shipping lines aiming for ESG targets. Moreover, investing in shore power reduces the risk of incurring future compliance costs as regulations become stricter, thus protecting operators from costly last-minute retrofits or operational limitations, with the integration of larger proportions of renewable energy into electrical grids, the lifecycle carbon footprint associated with shore power use keeps diminishing, thereby amplifying its economic and climate advantages [309,310].

5.3 How cold ironing works

5.3.1 Ships connect to on shore power supply

Upon arrival at port, a ship navigates into its berth and positions itself with the assigned shore power connection points. Specialized cables and connectors that meet international standards (like IEC/ISO/IEEE standards) are then employed to physically link the ship to the onshore electricity supply. The connection guarantees that the ship can receive power in a safe and dependable manner, without causing disruptions to either the port's grid or the ship's electrical systems.

5.3.2 On board generators shut down

When the link to shore power is verified and stable, the ship progressively turns off its onboard diesel generators. Normally, ships depend on these generators for propulsion and to provide electricity for onboard activities such as lighting, heating, air conditioning, and operating equipment. Ships can lower fuel use and reduce greenhouse gas and pollutant emissions, especially in busy ports where air quality is a concern, by transitioning to onshore supply.

5.3.3 Power Delivered Through Standardized Cables and Connectors

Using high-voltage cables and standardized connectors, electricity is transmitted from the shore grid to the ship, ensuring compatibility and safety. The power supplied can vary from low-voltage systems for small ships to medium- or high-voltage systems for large vessels, sometimes reaching several megawatts. On ships, transformers and switchgear are used to adjust the incoming voltage to suitable levels for their internal systems [311,312].

5.3.4 Onboard Systems Run from Shore Power

Once linked, all essential shipboard systems lighting, HVAC, galley equipment, navigation systems, and even some auxiliary propulsion function using electricity from the shore. This enables the ship to keep up its regular operations while docked, without having to run its engines.

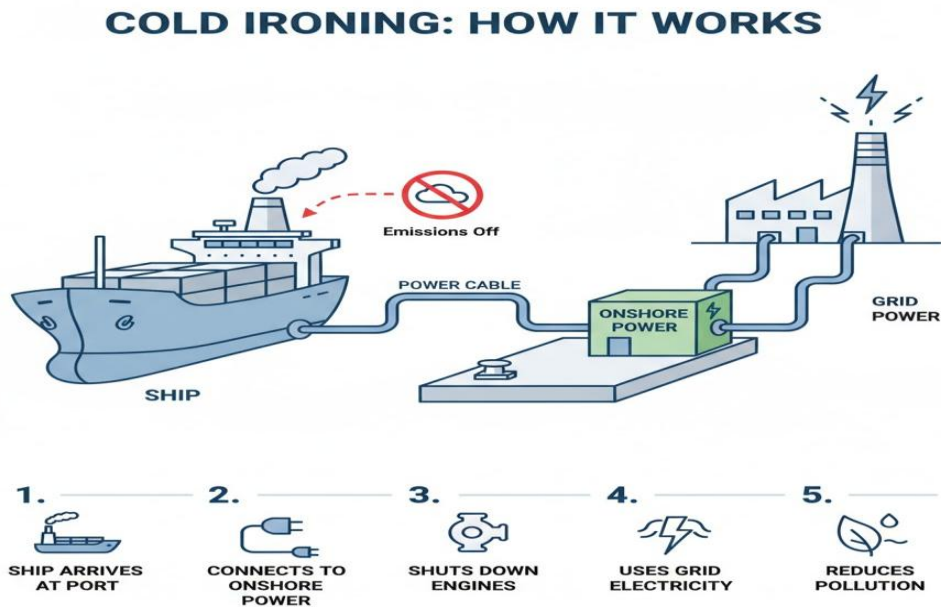


Figure 5-3 Working principles of cold ironing image generated by AI

Figure 5-3 shows the working principle of cold ironing, or shore-side electricity, the process begins when a ship arrives at port and connects its electrical system to the onshore power grid via a power cable. The ship then shuts down its auxiliary engines, turning its emissions off by disconnecting from its own fossil-fuel-powered generators and using grid electricity for all its at-berth needs, the ship significantly reduces local air pollution and noise in the port area. The Figure effectively captures the core operational sequence that makes cold ironing a critical technology for decarbonizing port cities and complying with strict environmental regulations.

5.3.5 Disconnection process

The ship guarantees that all systems onboard are prepared to revert to generator power before leaving. Shore power is turned off following appropriate safety protocols, the cables are stored, and the onboard generators are rebooted. This changeover is managed to avert electrical spikes or disruptions.

Key Benefits of Cold Ironing:

- Decreases air pollution and CO₂ emissions in port areas.

-
- Reductions fuel costs by avoiding generator operation while docked.
 - Minimizes noise pollution in ports, improving working conditions for port staff and nearby communities [313].

5.4 Main system components of Cold ironing

5.4.1 Shore side infrastructure

The shore side infrastructure includes all the equipment and systems necessary to transfer

electrical energy from the local utility grid to the ship's connection point.

Major functions are:

- Gaining energy from the municipal grid
- Modifying and conditioning energy to fit the ship's needs
- Guaranteeing safe distribution and oversight
- Offering interfaces for linking and unlinking

Typical components installed on the shore side include switchgear, protection devices (such as circuit breakers and relays), control and monitoring systems, and communication interfaces.

5.4.2 Substation

The cold ironing supply system is centered around the shore substation; its primary function is to draw electricity from the public grid and adapt it for use by ships.

The substation serves the following functions:

a. Voltage transformation

- Ships frequently need various voltage levels from the utility grid.
- To achieve the appropriate voltage, the substation utilizes either step-down or step-up transformers.
- As per IEC/ISO/IEEE 80005 standards, the standard voltages for ships include:
 - 6,6 kV
 - 11 kV
- Low-voltage systems can be utilized for smaller vessels (such as ferries and yachts).

b. Protection and safety

Inside the substation are:

- Overcurrent safeguarding
- Protection against earth faults

-
- Isolation switchgear
 - Synchronization gear (if necessary)
 - This guarantees the protection of both the port electrical network and the ship.

c. Monitoring and control

SCADA or digital control systems are included in advanced substations to:

- Supervise power quality
- Manage the load
- Coordinate the beginning/ending of the supply
- Guarantee adherence to standard procedures.

5.4.3 Frequency voltage converter

Ships can function with electrical specifications that differ from those of the local utility grid.

As an illustration:

- A lot of ships operate at a frequency of 60 Hz
- Grids in Europe usually provide 50 Hz

To resolve this discrepancy, the system employs shore power converters that consist of:

a. Frequency converter

- Transform the electrical frequency (for instance, 50 Hz to 60 Hz)
- Guarantee stable output that is controlled for harmonics
- Can be either rotary converters or, more commonly, static converters (derived from power electronics)

b. Voltage converters/Transformers

- Set the voltage to match the level needed by the vessel.
- Guarantee stable output despite fluctuating load conditions
- Power quality management

c. Converters control:

- Stability of voltage
- Harmonics (THD)
- Phase balancing

They guarantee that the vessel gets a clean and dependable power supply comparable to that of its onboard generators [314,315,316,317].

5.4.4 Cable management system

This system offers the physical means to transfer electrical power from the shore connection point to the ship. It is intended to be safe, flexible, and easy to operate.

a. Cable handling mechanism

Depending on the design of the port, CMS can be:

- Cable reels installed on the quay
- Cable cranes or gantry systems
- Vehicles for mobile cable handling
- Cable connection systems that are automated

These systems ensure the safe management of heavy, high-voltage cables.

b. Cable types

Cold ironing cables are usually:

- High-voltage, flexible, rubber-encased
- Protected for use in marine environments
- Engineered to endure mechanical stress, saltwater exposure, and recurring bending

c. Connectors / plugs

Must adhere to IEC/ISO/IEEE 80005-1 standards:

- Marine connectors for high voltage with multiple pins
- Corrosion-resistant and weatherproof
- Fast locking mechanisms for secure docking

d. Safety and interlocks

Systems for managing cables includes:

- Functions for emergency stop
- Monitoring of cable tension
- Electrical interlocks to ensure connection only occurs when safely aligned

This guarantees a trustworthy and secure transfer of power from ship to shore and vice versa [318,319,320].

5.5 Ship side components of seaside

5.5.1 Shore connection panel ship side

The main interface through which the ship receives power from the port is the shore connection panel, it guarantees that shore power is both compatible with and safely integrated into the ship's electrical system.

a. Main function

- Gets high-voltage or low-voltage power from land.
- Verifies voltage, frequency, and phase sequence of incoming signals.
- Houses the circuit breaker for the main shore connection.

-
- Offers measurement of voltage, current, frequency, and phase rotation.
 - Contains interlocks to avert unsafe connection or disconnection.
 - Exchanges information with shore systems (pilot contacts, readiness signals).
 - Guarantees proper equipotential bonding prior to energization.

b. Key points

- HV/LV circuit breaker
- Monitoring tools
- Pilot contact arrangement within the plug/socket
- interface for earthing and bonding
- Emergency stop and alarm signal

5.5.2 Ship side transformers

When the voltage/frequency of the ship's internal power system differs from that of the shore supply, transformers can be utilized.

a. Purpose

- Voltage compatibility (e.g., shore provides 11 kV, vessel uses 6.6 kV).
- Electrical isolation for grounding compatibility between ship and shore.
- Enhancement of power quality through the reduction of harmonics.
- Improvement of safety while preserving the ship's internal grounding philosophy.

b. Design points

- Approved for ongoing ship load ("hotel load").
- Cooling and insulation of marine quality.
- Short-circuit and overload protection are synchronized with the ship's switchboard.
- To ensure optimal integration, it should be installed close to the main switchboard [320,321].

5.5.3 Safety and protection Devices (Ship side)

Safety devices guarantee the security of both crew and gear during a ship's connection to an external high-voltage source.

a. Main protection function

- Detection of earth faults prior to and while establishing a connection.
- Protection against short circuits and overloads (using breakers, relays).
- Monitoring of voltage and frequency to guarantee that shore power is within the

specified limits.

- Interlocks to avoid connecting/disconnecting while loaded.
- Emergency shutdown if there is cable tension, a bonding failure, or unsafe conditions.

b. Typical devices

- High-voltage circuit interrupter and protective relays
- Grounding switches
- Phase-sequence and voltage checkers
- Overcurrent/earth fault relays
- Push buttons for emergency stop
- Alarm and communication system (vessel–shore)

5.6 Benefits of Cold ironing

5.6.1 Significant reduction of air emissions

Cold ironing enables ships to depend completely on electricity from the shore while moored, thus allowing them to turn off their auxiliary diesel engines [322,324]

This leads to significant decreases in detrimental emissions, including:

- Carbon dioxide (CO₂) – plays a role in the increase of global temperatures
- Sulphur oxides (SO_x) – lead to acid rain and breathing problems
- Nitrogen oxides (NO_x) – play a role in the development of smog
- Particulate matter (PM) – presents significant health hazards

In bustling ports, where vessels have long been accustomed to running their engines for extended durations, this diminishment aids in the advancement of worldwide decarbonization initiatives and climate objectives.

5.6.2 Improved air quality and port environment

Cold ironing greatly enhances air quality in port areas and nearby neighbourhoods by removing the need for engines to be used while docked.

Benefits include:

- Port workers' working environment becomes more healthy
- Diminished exposure to environmental toxins for adjacent communities
- Reduced noise pollution, as diesel generators are not operating anymore
- Improved sustainability and liveability of the port as a whole

This holds particular significance for port cities with high population density, as emissions from maritime activities are a key source of local pollution.

a. Lower operational costs for ship operators

Although an initial investment in onboard compatibility may be necessary, ships frequently benefit from:

- Reduced energy expenses, given that grid electricity is generally less costly than marine diesel oil
- Lower fuel consumption, resulting in savings
- Reduced engine wear and maintenance, as auxiliary engines run for fewer hours
- Enhanced operational efficiency in the long run
- Ports frequently provide additional incentives, such as reduced port fees for ships that utilize shore power, enhancing the economic advantages [325,326,327].

b. Enhanced compliance with environmental regulations

There is a growing demand from international, regional, and local regulations for reduced emissions in port areas.

Cold ironing assists ships in adhering to:

- EU rules regarding port emissions, particularly within Emission Control Areas (ECAs)
- environmental standards set by the IMO (International Maritime Organization)
- Laws at the national level are designed to decrease greenhouse gases and airborne contaminants

Using shore power diminishes the chances of incurring penalties for non-compliance and enhances a company’s environmental reputation and sustainability credentials.

Category	Cold Ironing (Shore Power)	Traditional Engine Use at Berth
Energy Source	Electricity from shore	Ship’s diesel generators
Emissions	Very low/no CO ₂ , NO _x , SO _x , PM	High emissions of pollutants
Air Quality	Clean, improved air	Polluted air in port areas
Noise	Very low noise	High noise from engines
Operational Cost	Lower (cheaper electricity, less fuel)	Higher (continuous fuel use)
Maintenance	Reduced engine wear	Increased engine wear

Regulatory Compliance	Easily meets environmental rules	Higher risk of non-compliance
Infrastructure Needs	Requires shore power setup	No special infrastructure needed
Environmental Impact	Positive, supports sustainability	Negative, contributes to pollution

Table 5-1 Comparison Table: cold ironing vs traditional engine use

Table 5-2 highlights cold ironing's pivotal role in sustainable port management by contrasting its attributes with traditional engine use. While the conventional method relies on polluting diesel generators, resulting in high emissions noise and operational costs cold ironing utilizes shore-based electricity to virtually eliminate at-berth pollutants and noise this shift not only improves local air quality and reduces engine maintenance but also ensures compliance with narrowing environmental regulations. Although it demands initial infrastructure investment, cold ironing presents a lower long-term operational cost and a significantly reduced environmental footprint, establishing it as an essential technological intervention for decarbonizing maritime operations and advancing the goals of green shipping corridors.

5.7 Challenges for cold ironing

High Installation cost

- **Port Infrastructure:** The implementation of cold ironing necessitates considerable investments in transformers, switchgear, cabling, and shore-side connection points that can manage high-voltage electricity.
- **Ship Retrofitting:** To ensure compatibility with shore power, existing vessels often require modifications to their electrical systems, which incurs additional costs.
- **Economic Justification:** For ports with low traffic or ships that have short stays, the return on investment may be slow.

5.7.1 Compatibly between ports and ships

Electrical Standards Variations: Voltage and frequency standards (e.g., 60 Hz vs. 50 Hz) vary across countries and ports, complicating universal plug compatibility for ships.

Connector Types: The absence of standardized connectors often necessitates the use of extra adapters or conversion equipment.

Operational Complexity: It is crucial for crew and port operators to establish the correct connection to avert harm to the electrical systems of the ship or port.

High Power Demand: While docked, ships need substantial electricity to operate engines, HVAC, and onboard systems. Big ships can require tens of megawatts.

Local Grid Enhancements: The local grids of numerous ports cannot manage this extra load without fortification, which entails additional expenses and planning.

Energy Management: To prevent blackouts or transformer overloads, the simultaneous connection of multiple ships necessitates meticulous load balancing.

5.7.2 Weather and operational constraints

Weather Impact: Storms, heavy winds, or ice can pose risks for connecting and disconnecting cables, damage equipment, or necessitate shutdowns.

Docking schedules: To ensure a continuous power supply, it is necessary to synchronize with docking and departure times; delays may complicate operations.

Safety Concerns: Without proper management, high-voltage connections can lead to electrical shocks, fires, or equipment malfunctions, particularly in adverse conditions [327,328].

5.8 Summary

Cold ironing has emerged as a fundamental approach to decreasing air pollution and greenhouse gas emissions in port regions. Ports can greatly reduce emissions of nitrogen oxides, Sulphur oxides, and particulate matter by enabling vessels to turn off their onboard engines while at dock and use shore power. This helps enhance local air quality and supports global climate objectives. Cold ironing is being adopted globally, pushed by the dual forces of tightening environmental regulations and the shipping industry's dedication to sustainability and corporate responsibility. With ports investing in the required infrastructure and technologies, cold ironing is set to become a key element in changing maritime operations to be greener and more energy-efficient, thereby aiding the larger shift to a low-carbon economy.

Chapter 6 . Conclusion and Future Work

6.1 Conclusion

Environmental sustainability has emerged as a crucial framework for guiding the future development and functioning of seaports around the globe. Ports, as vital junctions in worldwide logistics networks, are under mounting pressure to reconcile economic performance with responsible environmental stewardship. The cumulative effects of port activities such as air and water pollution, habitat disruption, noise emissions, and greenhouse gas contributions necessitate a transition to more integrated and scientifically grounded sustainability strategies. Consequently, modern ports are implementing various solutions such as transitioning to shore-side electricity (cold ironing), using electrified or hybrid cargo-handling equipment, generating renewable energy, employing advanced systems for wastewater and ballast water treatment, and utilizing digital tools to optimize vessel traffic and minimize operational inefficiencies. At the same time, seaport environmental sustainability encompasses more than just technological improvements. This encompasses coordinated governance, engagement of stakeholders, more stringent environmental regulations, and ongoing monitoring of ecological indicators, these actions safeguard marine biodiversity and coastal communities while bolstering the resilience of ports against climate threats like rising sea levels, storm surges, and shifting weather patterns. It is crucial to note that sustainable port practices help ensure long-term economic stability by lowering operational costs, boosting adherence to international standards, and improving the global competitiveness of port operations.

To sum up, attaining environmental sustainability in seaports is not just a voluntary endeavour; it is a strategic imperative. Seaports can transform into cleaner, more efficient, and climate-resilient hubs by incorporating environmental considerations into all aspects of port planning and daily operations. This transformation guarantees that ports will keep facilitating global trade while protecting the ecosystems and communities reliant on them, thereby fostering a more sustainable maritime industry for future generations.

6.2 Future Work

Future efforts to advance environmental sustainability in seaports will need a combination of technological innovation, policy development, and collaborative governance, one of the major areas for future work is the wider adoption of next-generation green technologies, such as entirely electric cargo handling systems, hydrogen powered equipment, and autonomous, low emission vessels. Constant research is needed to assess the safety, feasibility, and cost effectiveness of these technologies, as well as their potential to decrease overall carbon footprints. Furthermore, integrating smart port systems including AI-driven traffic management, digital twins, and real-time environmental monitoring will help optimize operations, minimize congestion, and predict environmental risks more accurately.

Another significant direction for future work involves climate adaptation planning. As ports are especially vulnerable to tremendous weather events, sea level rise, and coastal erosion, future research should focus on developing strong port infrastructure. This may include nature-based solutions such as wetland restoration living shorelines, and eco-engineered breakwaters, which can offer both safety and ecological benefits. Long term climate modelling will also be necessary to anticipate risks and inform adaptive strategies.

Strengthening policy frameworks and international cooperation will be vital. Future work should explore consistent environmental regulations for waste, emissions, and biodiversity protection across worldwide ports to ensure consistency and equality. Collaboration between governments port authorities, shipping companies, and environmental organizations will help accelerate development and share best practices. Public private partnerships, especially in developing regions, will be crucial for financing sustainable advancements and capacity building.

Finally, future research should expand on the social dimensions of port sustainability, including the health impacts of port operations on nearby communities and the role of workforce training in operating greener port technologies. Understanding community concerns, increasing transparency, and involving local stakeholders in planning will help ensure that sustainability initiatives are both effective and socially equitable.

To sum up, attaining environmental sustainability in seaports is not just a voluntary endeavour, it is a strategic imperative, seaports can transform into cleaner, more efficient, and climate resilient hubs by incorporating environmental considerations into

all aspects of port planning and daily operations. This transformation guarantees that ports will keep facilitating global trade while protecting the ecosystems and communities reliant on them, thereby fostering a more sustainable maritime industry for future generations.

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