Analyzing alternative energy solutions in container ports

Pavlović, Luka

UNIVERSITY OF RIJEKA
FACULTY OF MARITIME STUDIES

LUKA PAVLOVIĆ

ANALYZING ALTERNATIVE ENERGY SOLUTIONS IN CONTAINER PORTS

BACHELOR THESIS

Rijeka, 2024

UNIVERSITY OF RIJEKA
FACULTY OF MARITIME STUDIES

ANALYZING ALTERNATIVE ENERGY SOLUTIONS IN CONTAINER PORTS

ANALIZA ALTERNATIVNIH ENERGETSKIH RJEŠENJA U KONTEJNERSKIM LUKAMA

BACHELOR THESIS

ZAVRŠNI RAD

Course: Port and Terminal Technology

Mentor: Prof. Ines Kolanović, PhD

Student: Luka Pavlović

Study program: Logistics and Management in Maritime and Transport

JMBAG: 0112086030

Rijeka, July 2024

Student: Luka Pavlović

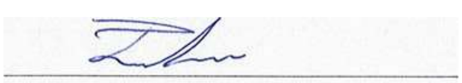
Study program: Logistics and Management in Maritime and Transport

JMBAG: 0112086030

DECLARATION OF INDEPENDENT PREPARATION OF THE BACHELOR’S THESIS

Whereby I declare that I have written the bachelor's thesis entitled Analyzing alternative energy solutions in container ports, have independently prepared under the supervision of Prof. Ines Kolanović, PhD. In my thesis I have applied the methodology of writing a professional/scientific paper and used the literature listed at the end of the thesis. The knowledge, attitudes, conclusions, theories and laws of other people that I have reproduced in the final work, directly or paraphrasing, have been cited in the usual way and linked with footnotes and bibliographic units, and no part of the work violates the copyrights of others. The work is written in the spirit of the English language.

Student



(signature)

Name and last name of the student

Luka Pavlović

Student: Luka Pavlović

Study program: Logistics and Management in Maritime and Transport

JMBAG: 0112086030

STATEMENT OF THE STUDENT – AUTHOR ON THE PUBLIC ANNOUNCEMENT OF THE DEFENDED BACHELOR'S THESIS

I declare that as a student – author of the bachelor's thesis, I allow the University of Rijeka, Faculty of Maritime Studies to permanently publish the theis publicly and make it available to the public free of charge in full text in the online digital repository of the Faculty of Maritime Studies.

For the purpose of supporting open access to final papers permanently published in the publicly accessible digital repository of the Faculty of Maritime Studies, I hereby grant a non-exclusive property right to use my bachlor thesis as an author's work without content, time, or spacial limitations under the terms of the Creative Commons license CC BY naming, as described at http://creativecommons.org/licenses/

Student – author

____

(signature)

SUMMARY

This thesis explores the significance of container ports in global trade and their role in energy consumption, highlighting the need for sustainable energy solutions to mitigate environmental impacts. Initially, the thesis provides an overview of container ports, detailing their operations and energy consumption patterns. It discusses the environmental impacts of traditional energy sources, focusing on greenhouse gas emissions and air pollution. The thesis evaluates the strengths and weaknesses of each technology to determine their feasibility and effectiveness. Implementation strategies are explored through a feasibility analysis, identifying challenges such as financial constraints, technological limitations, and regulatory hurdles. The economic and environmental implications are analyzed through a cost-benefit analysis, comparing the initial investments and long-term savings of alternative energy solutions. The conclusion summarizes the key findings, emphasizing the importance of alternative energy technologies in transforming container port operations.

Keywords: container terminal, alternative technologies, environmental impact, carbon footprint, long-term sustainability and resilience, challenges, transformation of port operations.

SAŽETAK

Ovaj rad istražuje značaj kontejnerskih luka u globalnoj trgovini i njihovu ulogu u potrošnji energije, ističući potrebu za održivim energetskim rješenjima kako bi se ublažili utjecaji na okoliš. U početku, rad pruža pregled kontejnerskih luka, detaljno opisuje njihove operacije i obrasce potrošnje energije. Raspravlja se o utjecajima tradicionalnih izvora energije na okoliš, s naglaskom na emisije stakleničkih plinova i zagađenje zraka. Rad ocjenjuje snage i slabosti svake tehnologije kako bi se utvrdila njihova izvedivost i učinkovitost. Strategije implementacije se istražuju kroz analizu izvedivosti, identificirajući izazove poput financijskih ograničenja, tehnoloških ograničenja i regulatornih prepreka. Ekonomski i okolišni učinci analiziraju se kroz analizu troškova i koristi, uspoređujući početna ulaganja i dugoročne uštede kroz alternativna energetska rješenja. Zaključak sadržava ključne nalaze, naglašavajući važnost alternativnih energetskih tehnologija u transformaciji operacija kontejnerskih luka.

Ključne riječi: kontejnerski terminal, alternativne tehnologije, utjecaj na okoliš, ugljični otisak, dugoročne održivosti i otpornosti, izazovi, transformacija lučkih operacija.

TABLE OF CONTENTS

1. INTRODUCTION

In the growing world of global trade, container ports stand as vital gateways through which goods travel across continents, connecting the entire trade market and amplifying economic growth. However, behind the scenes of this dynamic exchange lies a growing environmental challenge: the carbon footprint of traditional port operations. The past and current reliance on fossil fuels to power port activities has not only contributed to an increase in greenhouse gas emissions but also a decline in local air quality and public health. With the rising concerns of climate change on a global level, ports are beginning to implement long-term plans to become completely self-sustainable and environmentally acceptable.

This thesis delves into alternative energy solutions within container ports, exploring a broad spectrum of possibilities to reduce carbon emissions generated in ports and open the doors to a more sustainable future. Container ports hold immense potential as hubs for clean energy adoption. Depending on their geographical positioning, various ports will implement different alternative technologies to fully optimize their energy production. This will ensure ports are mitigating their impact on the environment while boosting operational efficiency and competitiveness in global trade.

In addition, the shift towards alternative energy solutions is part of broader sustainability initiatives and regulations aimed at potentially neutralizing carbon emissions and promoting renewable energy consumption in the maritime sector. These renewable energy technologies play a keen interest to not only minimize their environmental impact but also achieve cost savings and improve energy efficiency, leading to a prosperous economy and healthy planet.

Despite the benefits of these new technologies, integrating them into container ports brings numerous constraints, including technological limitations, high investment costs, and geographical challenges. Addressing these barriers requires careful planning for the integration of sustainable energy technologies in container ports.

This thesis aims to present an overview of the opportunities and challenges associated with alternative energy solutions in container ports. By synthesizing various literature, case studies, and online sources, this study steeks to offer valuable insights into the importance of moving toward a more sustainable and environmentally accountable future.

2. CONTAINER PORT OPERATIONS AND ENERGY CONSUMPTION

In the maritime industry, container ports serve as critical hubs for the movement of goods across continents. However, the increasing growth of container shipping and port operations has raised concerns about their environmental impact, specifically regarding energy consumption and emissions. The following subheadings detail about container ports and their current energy consumption. In this chapter, an overview of container ports and port operations will be given, and energy consumption patterns will be analyzed.

2.1. OVERVIEW OF CONTAINER PORTS

Container ports are intermodal nodes in the global supply chain, serving as connecting points for the transport of goods across extensive distances. They are specialized in handling cargo in standardized containers, enabling efficient loading, unloading, and transshipment activities. The implementation of standardized units brings the possibility of multimodal transportation, allowing containers to have an unlimited transport range.

Due to the exponential increase in the dimensions and carrying capacity of container ships, container ports are forced to adapt in terms of capacity and receiving possibilities. Located worldwide, container ports are equipped with various handling equipment used to load and unload containers onto trains, trucks, and other ships. Each container port has its own container yard where containers are constantly being reorganized for the upcoming arrival of ships. High-quality port management gives a port its global value and makes it a strong competitor against other ports.

It's important to remember the significance of container ports as not just points of transfer, but rather as economic engines, fostering trade, investment, and job creation all around the world. Facilitating the movement of raw materials, manufactured goods, and consumer products, container ports race against each other to secure their position as a leading port in global trade. In essence, container ports are not just gateways to the world but dynamic hubs of economic activity, innovation, and connectivity on a global scale. As English adventurer Sir Walter Raleigh wrote in 1829: "For whosoever commands the sea commands the trade; whosoever commands the trade of the world commands the riches of the world, and consequently the world itself."

2.1.1. ENERGY CONSUMPTION PATTERNS IN CONTAINER PORTS

Due to rising concerns associated with global climate change, the maritime sector is making ambitious plans to reduce carbon dioxide emissions. Specifically, the International Maritime

Organization (IMO) has committed to a strategy to reduce international shipping emissions by at least 50% by 2050. As the maritime sector continues to grow exponentially, the concept of "Green Ports" has emerged. Green ports are defined as ecologically friendly ports that efficiently manage their resources, energy consumption, and pollution levels [1]. With the implementation of new energy sources and smart technologies, green ports are emerging as the future of the maritime industry.

The types of energy consumed by port equipment can be represented by Figure 1.

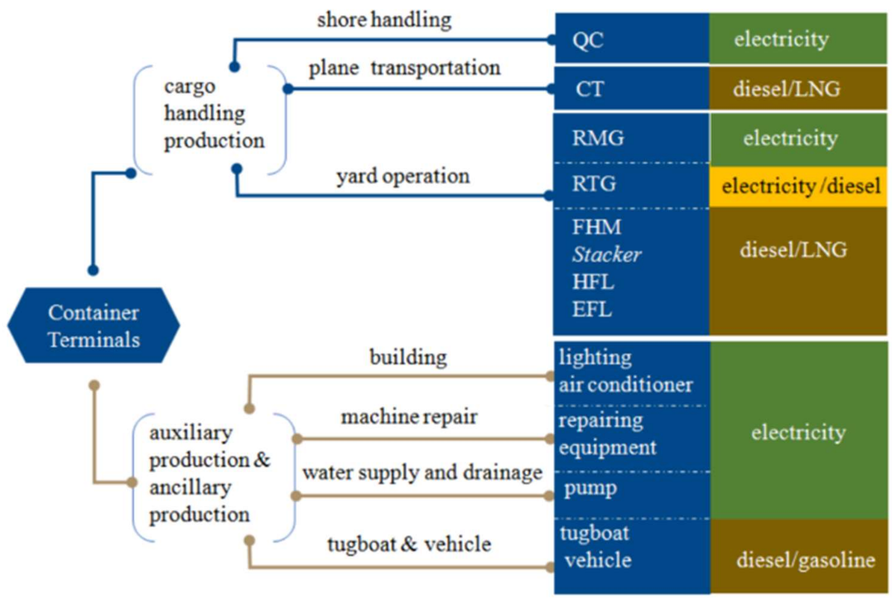


Figure 1. Types of energy consumed by equipment of container port. [1]

As seen in Figure 1, cargo handling equipment accounts for the greatest use of fossil fuels. Due to the large dimensions of the cargo handling equipment being used, enormous amounts of fuel are required to consistently optimize port operations. To correlate the types of energy consumed with real-time data, a statistical analysis of the amount of carbon dioxide released (in tons) is shown by Figure 2.

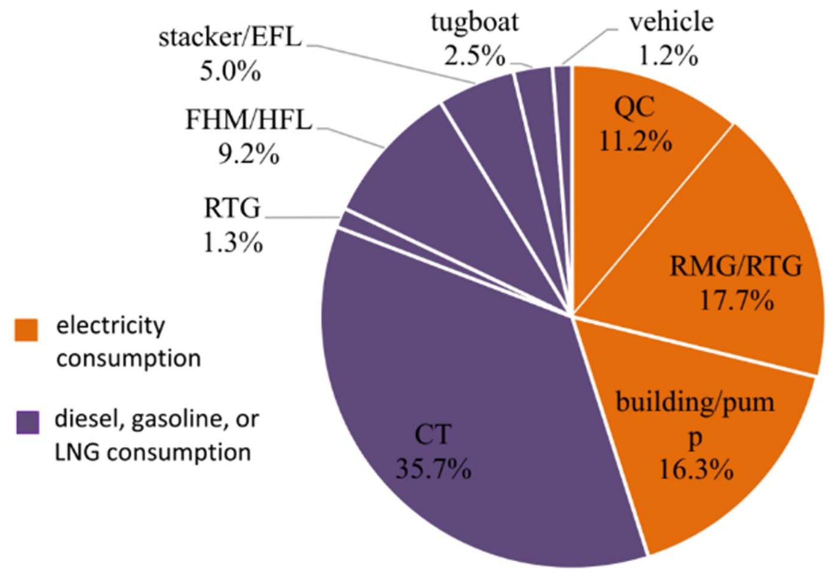


Figure 2. Energy consumption of China's container ports in 2020. [2]

As can be seen in both Figures 1 and 2, cargo handling procedures account for the highest amount of carbon emissions released into the atmosphere. To contextualize these numbers, China's container ports emitted 1.033 million tons of carbon dioxide in 2020 alone. More than 50% of this energy consumption was from diesel, gasoline, or LNG.

This figure represents the carbon emissions from just one country's container ports. Consider the cumulative emissions when accounting for all ports globally. This underscores why green ports are diligently working to significantly reduce carbon emissions in the maritime sector. By 2050, ports aim to meet the International Maritime Organization (IMO) standard of reducing shipping emissions by 50%.

2.1. ENVIRONMENTAL IMPACTS OF TRADITIONAL ENERGY SOURCES

Even though maritime transport is responsible for only about 2.5% of global greenhouse gas emissions, carbon emissions occur at all stages of port operations. From the berthing stages of a ship to the transport of containers in the container yard, carbon emissions are consistently significant. The environmental impacts of traditional sources include several other factors [2]:

1. air quality
2. climate change
3. noise pollution
4. port community health
5. surrounding land development.

These factors collectively highlight the broader environmental footprint of container ports and underscore the importance of transitioning to sustainable energy solutions. In terms of air quality and climate change, port operations contribute to a variety of atmospheric emissions that pose risks to the health of the port community. These emissions include nitrogen oxides, sulfur oxides, carbon monoxide, black carbon, nickel, and other harmful particles [3]. Importantly, the severity of health effects declines as the distance between a port and its community increases, although achieving this separation is often challenging due to the integration of port and hinterland infrastructures.

Modern ports are increasingly transitioning to more sustainable energy sources to mitigate these impacts. Epidemiological studies have consistently linked pollutants from berthed ships and port operations to negative health effects such as lung cancer, asthma, premature mortality, and cardiovascular diseases [4, 5].

Noise pollution in container ports encompasses noise from container handling, cranes, vehicles, and auxiliary equipment. Noise levels can be measured using various databases that track decibel levels generated by movement. Equipment powered by traditional fossil fuel engines typically produces higher noise levels compared to those powered by electricity, like the comparison with electrified cars which mainly produce tire-road traction noise.

Assessing noise pollution in ports also involves considering the materials used in port infrastructure. Thicker materials tend to absorb more noise from vehicle tires. Implementing alternative energy technologies in container ports can mitigate negative impacts across all environmental factors. By transitioning to sustainable energies, container ports can transform from being perceived as polluting hubs of water transport to environmentally responsible hubs.

2.2. ALTERNATIVE ENERGY TECHNOLOGIES FOR CONTAINER PORTS

As container ports strive for sustainable energy consumption, they are increasingly implementing alternative energies based on their geographic location. Certain energy sources are more favorable in specific regions due to their higher efficiency in energy production. Figure 3 illustrates the various types of alternative energies used in ports.

Figure 3. Alternative energies in green ports. [3]

2.2.1. OVERVIEW OF EACH ALTERNATIVE TECHNOLOGY

The first of many alternative energy technologies is offshore wind turbines. There are different types of offshore wind turbines, depending on the water depth. There are three types of wind turbines which can be defined as the following [6]:

1. Vertical axis wind turbines: Having a low center of gravity, these turbines are constructed with a vertical axis, making them more suitable for use in marine facilities. Since these turbines can be constructed in the sea, they can be constructed on a larger scale in comparison to their horizontal counterparts with an increased capacity of 20 MW.
2. Floating wind turbines: For areas with a depth deeper than 60-80 m, fixed axis turbines are impractical due to the decreased stability of the turbines base. For this reason, the wind turbines float on a platform and are anchored to the ocean bed.
3. Fixed-foundation wind turbine: All offshore wind turbines have fixed platforms except for a few experiments. These fixed foundations are installed at depths of 50-60 m. The pillars with which the platform is connected can be single-pillars, triple-pillars, gravity

foundation, and box foundation. The deeper the water, the more complex the system is required.

Offshore wind energy has experienced exponential growth since the year 2009. Over the years, the capacity in megawatts shows a dramatic climb, especially between the years 2020-2021. The following figure shows the scope of the exponential growth.

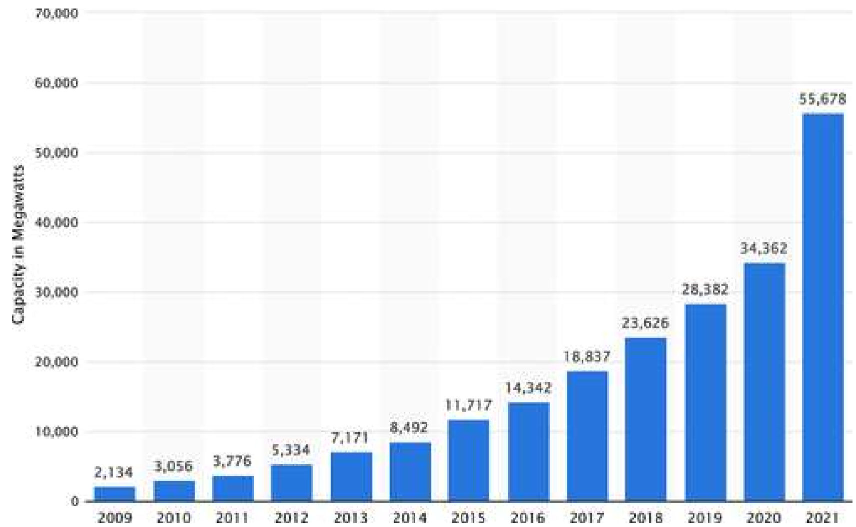


Figure 4. Worldwide wind energy capacity. [4]

The Global Wind Energy Council (GWEC) has identified offshore wind energy to be one of the most rapidly developing energy alternatives across the world. The overall capacity of wind energy has grown by about 75 times over the past two decades. Specifically, increasing the capacity from 7.5 GW in 1997 to about 823 GW in 2021 [7]. With the current represented trend, offshore wind energy will continue to grow rapidly by 2050.

The second type of alternative energy that is gaining popularity is the floating solar plant. As its name suggests, these solar panels are fixed to a floating frame near the shoreline. The following image shows the vast scale the solar plant covers.


Figure 5. Floating solar plant. [5]

Photovoltaic systems like these are one of the most sustainable and environmentally friendly technologies for harnessing energy [8]. The greatest strength of floating solar plants has been the need for freeing up new space on land to support the large scale of solar panels. This brings good use of large ~~bodies~~ areas of water while also keeping land areas free for other infrastructure uses. Unlike its onshore counterpart, the floating solar plant offers additional advantages. These advantages include zero greenhouse gas emissions, unlimited energy, ease of accessibility, and low maintenance.

Though it's still in its growing stages of development, ocean energy can be described as the production of energy with the ocean's natural resources. These resources are known as tides, waves, currents, and thermal hot spots. Since the ocean covers 70% of the globe's surface, global usage of ocean energy has logical sense. The following figure shows a visual representation of how the generators for tidal energy would look like.

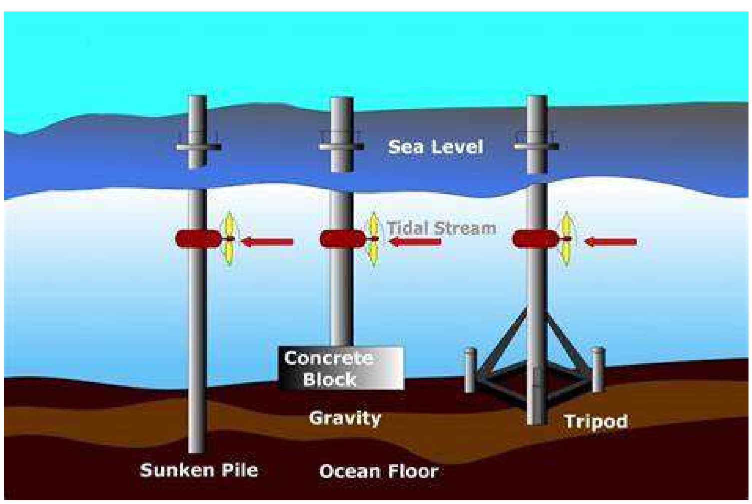


Figure 6. Tidal energy generators. [6]

An alternative to tidal energy generators are ocean current generators, which operate similarly but are positioned at greater depths in the ocean. Unlike tidal generators, ocean current generators harness strong kinetic energy from ocean currents [9]. These generators must be anchored to the seabed at significant depths, presenting challenges in construction and maintenance. However, they can adjust their position autonomously to optimize energy capture based on changing ocean conditions. Ocean current generators are particularly suitable for container ports located near areas with strong water currents. This technology leverages aggressive water movement to generate renewable energy efficiently.

There is another ocean technology that is slightly different than the rest. Thermal energy converters are another sustainable possibility, as they produce their energy based on the difference between colder temperatures at the ocean depth and warmer temperatures near the surface. Below is a representation of a thermal energy converter and how it operates.

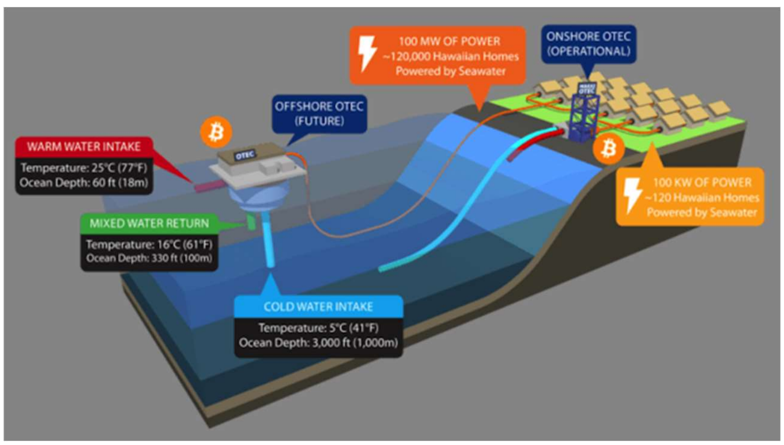


Figure 7. Thermal energy converter. [7]

For electrical energy to be produced, steam must be generated. For steam to be generated there must be three checkpoints where different temperatures of water will travel. This water will be pumped up by a tube, collecting the coldest water near the ocean floor and the warmest water near the surface. In between these two checkpoints is the mixed water temperature that is a result of the coldest water and warmest water mixing in a joined tube. As the water temperatures mix, the heat exchanger condenses the combined water, resulting in steam. The steam is then pumped into a turbine that is directly connected to a generator. This generator has a power cable connected to it that directly transmits the energy to an onshore structure. The energy produced by the thermal converter is not stored, meaning there is a constant production of energy ready for on-the-spot usage.

The final alternative energy technology that will be mentioned is the fuel cell. Fuel cells use the chemical energy of hydrogen ammonia to produce electricity. The hydrogen is supplied in the form of ammonia because of its liquid state. This allows for greater quantities of fuel to be stored. The reasoning behind the conversion into a liquid state is because liquids fill in more space than gases. LNG/LPG carriers use the same practice when transporting gases in the shipping industry. These fuel cells are capable of powering large utility buildings, making them a promising source of energy for green ports. Fuel cells can be defined as batteries, except they don't need to be recharged. If the fuel cell is consistently supplied with fuel, ammonia or hydrogen, the fuel cell will continuously produce electricity. Referencing the U.S. Department of Energy, fuel cells have several benefits over conventional combustion-based technologies with possibility of operating at higher efficiencies than combustion engines and can convert the chemical energy in the fuel directly to electrical energy with efficiencies capable of exceeding 60% [10].

Below can be seen a figure of a fuel cell and the process that takes place ~~I~~ in order to convert bio fuels into electrical energy.

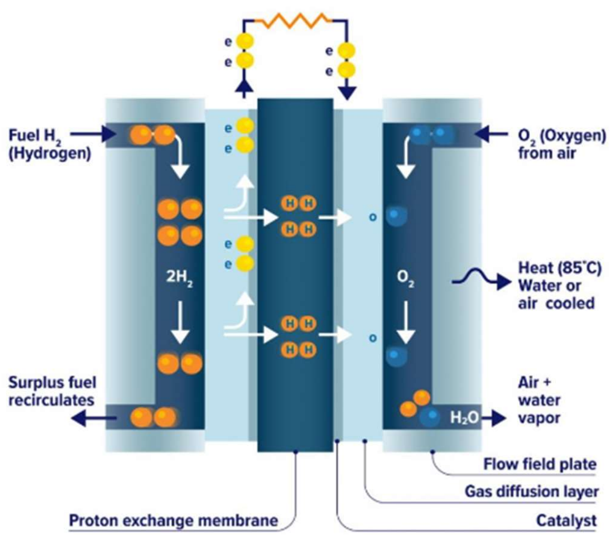


Figure 8. Fuel cell. [8]

A fuel cell consists of two electrodes, an anode, and a cathode separated by an electrolyte membrane. In this configuration, hydrogen serves as the fuel source, supplied to the anode, while air is fed to the cathode. Energy is generated as hydrogen molecules are split into protons and electrons. The separated electrons flow through an external circuit, generating electrical energy. Meanwhile, the protons migrate to the cathode, where they combine with oxygen to produce water vapor.

Fuel cells are highly versatile for electricity generation in container ports. They can serve as a reliable power source for all port operations due to their broad applicability within the port's energy grid. With a continuous supply of sustainable fuels like hydrogen and ammonia, a port could potentially become self-sufficient in energy, reducing reliance on other energy resources.

2.2.2. STRENGTHS AND WEAKNESSES

In order for a port to succesfuly choose the most reliable altnernative twchnology, advantages and disadvantages must be taken into consideration. Even though some of the technologies will come out to be more favorable for application, ports across the globe will need to consider which technology best suits their surroundings because some technologies will be more efficient in areas where their usage will be optimized at the highest level. The following bullets show the advantages (+) and disadvantages (-) for each alternative technology [11]:

Offshore wind power plant

+ high efficiency due to more speed and consistency of wind
+ high energy generation due to positioning in areas with higher wind speeds
+ miniscule environmental impact
+ large sea surface allows for vast wind farms to be constructed
- complex infrastructure
- high installation cost
- challenging maintenance and repair due to far location
- negative impact on marine life
- negative impact on birds

Offshore solar power plant

+ high performance due to cooling effect of surrounding water
+ large-scale of solar panels decreases algae blooms due to reduced water evaporation
+ large sea surface allows for vast solar farms to be constructed
+ land space is not needed due to floating capability
- high installation cost
- not profitable in a small-scale
- disruption to aquatic life
- high maintenance costs
- must be constructed in calm waters

Ocean thermal energy converter

+ reliable
+ environmentally friendly
+ low maintenance
+ independent of weather conditions
+ high energy efficiency
- high initial cost
- large-size turbines require expensive components
- energy conversion occurs at sporadic intervals

Tidal energy

+ predictable energy generation
+ high power output
+ consistently efficient
+ low maintenance
- limited installation sites
- high installation costs
- negative environmental impact on marine life
- inability to construct supply for high demand

Ocean current energy

+ high efficiency
+ predictable energy generation
- negative environmental effects
- high installation cost
- must be located at deeper depths, unlike tidal energy
- complex energy transportation to land

Fuel cell

+ readily available
+ high efficiency
+ zero noise pollution
+ zero carbon emissions
+ not dependent on weather conditions
+ very reliable
+ low maintenance
+ low cost

+ adaptable
- need for hydrogen extraction
- need for raw materials
- need for hydrogen storage unit
- highly flammable potential

Considering all proposed alternatives for generating sustainable and clean energy, solar power, wind power, and fuel cells stand out as the most promising options. These technologies offer high output and versatile adaptability to various applications. Fuel cells have the capability to continuously supply a port with clean and efficient energy. While ports will require storage units for hydrogen and ammonia, the ability to access readily available energy without adverse effects on the environment, marine life, and surrounding land makes them highly advantageous. Having defined the advantages and disadvantages of each alternative energy technology, and identified a preferred technology, the next critical step is to strategize for successful implementation. This analysis will address common challenges and barriers, alongside examples of successful implementations.

3. IMPLEMENTATION STRATEGIES

In order for the previously mentioned technologies to become implemented as reliable energy solutions, important aspects must be taken into consideration. Firstly a feasibility analysis must be done to see if the realization of these technologies is even practical. Within this analysis, challenges and barriers will be inspected to show what are some of the most concerning and problematic challenges ports will need to adapt to for successful implementation. Once the challenges are presented, current examples of successful implementation are important to reference.

3.1. FEASIBILITY ANALYSIS OF ALTERNATIVE ENERGY SOLUTIONS

Alternative energy solutions are increasingly gaining traction among green ports, heralding the future of sustainable energy. However, before these solutions can be adopted, a comprehensive analysis of their practicality, viability, and economic aspects is essential. Practicality considerations encompass a range of factors that influence the feasibility of implementing specific energy solutions in diverse regions. Geographic location plays a crucial role, affecting the efficiency of different energy options. Therefore, ports need to evaluate local climate conditions, oceanography, topography, and hydrography to determine the most suitable energy alternatives. Armed with this analysis, ports can then proceed with planning their implementation strategies.

Looking at offshore wind farms, the average cost of installations began at 2,300 €/kW in the early 2000s, peaking at 5,000 €/kW fifteen years later. By 2018, costs had decreased to 4,000 €/kW [12, 13, 14]. Projections for 2030 estimate further reductions to around 2,300 €/kW [15]. This significant cost decline underscores offshore wind energy as a leading sustainable energy option. Offshore solar farms are also gaining traction among investors due to their minimal impact on marine life and high energy production capabilities. In the United States, photovoltaic system capacity grew from 218 MW in 2005 to approximately 51,000 MW by 2017 [16]. Similar efforts are underway in Europe, where investments in offshore PV systems are aimed at achieving carbon neutrality by 2050 [17]. Additionally, floating solar plants contribute to efficiency gains by leveraging the cooling effect of water, thereby increasing irradiance on solar arrays [18].

Among the handful of alternative technologies, fuel cells show promising feasibility when integrated into container ports, akin to offshore wind and solar farms. Unlike traditional combustion engines, fuel cells have no moving parts; their components are solid and fixed within the cell. This simplifies both manufacturing and maintenance [19]. In 2018, the fuel cell market saw an 8% increase in power installations compared to 2017. By 2023, installations were expected to rise by 13%, with a further estimated increase of 14.9% by 2026 [20]. Given these trends, we can anticipate continued growth in fuel cell energy installations.

However, despite the apparent simplicity, one significant challenge stands out: the economic aspect of implementation, particularly the initial investment required for constructing energy solutions and establishing storage facilities. This paragraph will also showcase several case studies of successful implementations and highlight the challenges and barriers encountered alongside these successes.

3.2. CHALLENGES AND BARRIERS TO ADOPTION

The primary barrier hindering the adoption of sustainable energy solutions is the initial investment, as mentioned earlier. While the concept of sustainable energies may be intuitive to some investors, the high startup costs often pose a significant deterrent. Understanding why investors are cautious about these new technologies is crucial. To do so, it's essential to comprehend the organizational structures and operations of ports. Ports can generally be categorized into four types: Public Service Ports, Tool Ports, Landlord Ports, and Private Service Ports. Each type has its own organizational structure and operational framework. Among these, the Private Service Port model is often considered the most favorable for implementing new innovative technologies into port infrastructure. This model consolidates infrastructure, superstructure, human resources, and regulatory oversight under a single private governance entity. This unified approach allows ports to secure adequate funding for large investments from the private sector.

Another significant barrier faced by alternative technologies is their environmental impact despite their potential for clean energy production. The construction and deployment of these technologies, especially those placed in the ocean, can have adverse effects on the surrounding environment. Particularly concerning are ocean current generators, offshore wind farms, and tidal generators, which can disrupt marine life habitats. Species most affected by these technologies, due to noise levels emitted by generators, include larger predatory animals such as turtles, sea lions, seals, whales, dolphins, and others. Vibrations from these generators produce frequencies that interfere with essential activities such as mating, hunting, communication, and migration patterns [21].

3.3. CURRENT EXAMPLES OF SUCCESSFUL IMPLEMENTATION

As mentioned earlier, container ports worldwide are adopting various technologies based on their geographical advantages and energy needs. For example, the Port of Rotterdam in the Netherlands utilizes wind turbines and solar panels to generate renewable energy within its confines. In contrast, the Port of Yokohama in Japan has embraced fuel cell technologies, leveraging its local expertise and infrastructure. Copenhagen, Denmark, benefits from strong coastal winds, making offshore wind farms a viable renewable energy source for the port. Meanwhile, China leads the global photovoltaic market, rapidly deploying solar power plants with capacities ranging from tens to hundreds of megawatts, despite starting later than other countries [22].

These are just a few of the many ports that have adopted the use of alternative energy systems, showcasing the potential the maritime industry has for lowering their carbon footprint. Although many ports have adopted alternative energies, they haven't become fully sustainable. The main reason for this is that the entire agenda for decarbonizing the maritime sector is relatively new and is continuously being researched for flaws and upcoming potentials for its extensive use.

The integration of sustainable energy sources in container ports, like any large-scale investment, comes with unique challenges and barriers that ports must carefully navigate. Each port's organizational structure plays a crucial role in determining its ability to innovate and implement these technologies effectively.

4. ECONOMIC AND ENVIRONMENTAL IMPLICATIONS

In oder to conclude whether or not alternative energy technologies truly are worth the investment, an economic and environmental analysis needs to be done. An economic analysis will give insight to the initial investment costs, revenue generation opportunities, and the competitive advantage of transitioning toward sustainable practices. In terms of environmental implications, an analysis on the environment will be done to reveal if alternative energy technologies truly are environmentally friendly or appear too good to be true.

4.1. COST AND BENEFIT ANALYSIS OF ALTERNATIVE ENERGY SOLUTIONS

Throughout this thesis, various alternative energy solutions were discussed. Each of these technologies showed to be highly feasible when put into practice. Even though the alternative technologies show high feasibility, the cost of installing these technologies can make or break a ports plan to integrate these solutions as reliable sources of energy. A detailed analysis will be done of each technologies initial cost, and how the costs have changed over the past years and how the prices are expected to look in the future.

By 2018, the cost of installing offshore wind turbines had decreased by 30%, specifically to $78/MWh [23]. This rapid decrease outpaced other technologies, leading to its popularity among investors. The cost reduction did not stop there. In 2022, the Offshore Wind Market report noted a further 13% decrease in commercial offshore wind projects in the US, averaging $61/MWh. Continuous reductions are projected to average $60/MWh by 2030 [24]. Another model, Forecasting Offshore Wind Reductions in Cost of Energy (FORCE), estimates that the cost of offshore wind farms could drop significantly to $53/MWh by 2035 [25]. Unlike onshore wind farms, offshore farms are not constrained by land availability. This allows the industry to install larger turbines, thereby reducing installation and integration costs per unit of energy generated.

In terms of floating solar plants, prices differ when comparing offshore and onshore installations. Reference [26] notes that labor for ground-based solar plants is $40 per hour, whereas it increases to $60 per hour for floating solar plants. However, because floating solar plants do not require land, these higher labor costs might be offset. Reference [27] provides a breakdown of construction costs for floating solar plants, with PV modules costing $0.25 per watt, electrical components such as cables and inverters costing $0.12 per watt, galvanized steel priced at $2.20 per kilogram, and heavy-duty polyethylene (HDPE) at $2.40 per kilogram. In 2018, the Levelized Cost of Energy (LCOE) for floating solar plants was €53 per MWh, higher than the €35 to €40 per MWh for ground-mounted plants [28]. A 2021 NREL report shows the LCOE for floating solar plants at $57 per MWh without the Investment Tax Credit (ITC) and $38 per MWh with the ITC, while ground-mounted plants are $47 per MWh without the ITC and $32 per MWh with it [29]. Looking ahead, based on current and past trends, integration costs are expected to decrease further. For inland ports with large bodies of calm waters, this energy source can be considered ideal.

Ocean thermal converters are among the most expensive energy technologies in terms of investment costs. Due to these high infrastructure and implementation expenses, 100 MW plants are considered the most profitable for developed ports [30]. Regarding the Levelized Cost of Electricity (LCOE), in 2015 the calculated LCOE was 18 US$ cents/kWh for a 100 MW thermal plant, a figure that remained unchanged in 2018 [31]. When comparing thermal energy converters to offshore solar and wind farms mentioned earlier, the costs are significantly higher. Specifically, estimated electricity costs for solar and wind farms range from 3.2 to 5.4 cents/kWh [32]. This highlights how thermal energy converters tend to be positioned at the higher end of cost economics.

Turning to ocean tidal and current energy, it's important to note the scarcity of available data on current energy due to the high complexity associated with installing generators. Tidal energy has the potential to generate significant amounts of electricity. For example, the Meygen tidal project, which began in 2018, saw its initial four turbines produce over 35 GWh of electricity by the end of 2020, with a Levelized Cost of Energy (LCOE) averaging $280 per MWh [33]. By 2021, the LCOE for this technology had increased to an average of $584 per MWh [34]. Another recently published case study shows an ocean current turbine achieving a competitive LCOE of $564.3 per MWh [35]. Ocean current turbines, despite their limited application, exhibit higher LCOE compared to tidal energy turbines, making them among the less favorable alternative technologies for implementation.

The economy of fuel cells demonstrates that higher production volumes lead to lower production costs. In 2021, a case study analyzed the cost differences based on scale of production for fuel cells. To illustrate this numerically, the cost per kilowatt (kW) for 1 stack of 1000 units averaged $1052.34 USD. Scaling up production to 50,000 units reduced the cost by over 50%, averaging a promising $460.09 USD/kW. To fully grasp the significant cost difference between these two scales of production, we must examine the cost per unit. To produce 1000 units, the cost per unit is $1.05 USD/kW. In contrast, for 50,000 units, the cost per unit drops to $0.009 USD/kW [36]. This calculation simply divides the total costs of

$1052.34 USD/kW and $460.09 USD/kW by their respective production scales. The potential for high-scale production of fuel cells is of great interest to global ports, as increased demand could further drive down production costs.

4.2. ENVIRONMENTAL IMPACT

The primary focus of implementing alternative technologies in container ports is to mitigate and eventually eliminate the negative effects that traditional energy sources have on the surrounding environment. While the adoption of sustainable energy sources appears to offer greater advantages than traditional sources, it also brings certain implications. Each alternative energy mentioned earlier impacts the environment differently, with some technologies having minimal to no negative effects. For instance, offshore solar farms provide environmental benefits. Unlike onshore solar farms, they eliminate the need for deforestation. Additionally, floating solar panels reduce water evaporation, which is beneficial for regions prone to droughts. One of the major environmental benefits of offshore solar farms is the reduction of algae blooms. Algae blooms occur when excessive sunlight hits nutrient-rich water bodies. The solar panels provide shading, preventing direct sunlight from reaching the water surface.

As for offshore wind farms, both positive and negative environmental impacts have been recorded. Starting with the negative impacts, offshore wind farms have shown to interfere with birds, marine mammals, and ecosystem structure. The following figure represents which areas are affected the most:

Figure 9. Most frequently reported environmental impacts of wind energy. [9]

It is evident that birds and marine mammals are significantly affected by offshore wind farms. The noise emitted by wind turbines disrupts the migration patterns of these animals. Despite these negative impacts, it is important to highlight the positive effects as well. Several case studies have shown that offshore wind farms contribute positively to the environment through the creation and enhancement of artificial reefs. The structures deployed and their moorings attract diverse marine life to areas with low biodiversity [37]. Additionally, these wind farms act as natural barriers to commercial fishing vessels that use large-scale nets, thereby helping to preserve the seabed.

While ocean generators, including both tidal and current types, do not produce emissions, they come with several drawbacks that directly impact the environment and its inhabitants. The most significant concerns associated with these underwater turbines are noise pollution and the risk of marine animals colliding with them, potentially causing harm to both the animals and the energy structures. Although collisions are possible, they are highly unlikely; most animals near the turbines are merely curious of the structure and not at significant risk for collision [38]. However, noise pollution has been observed to affect certain animals. This impact is illustrated in the following figure:

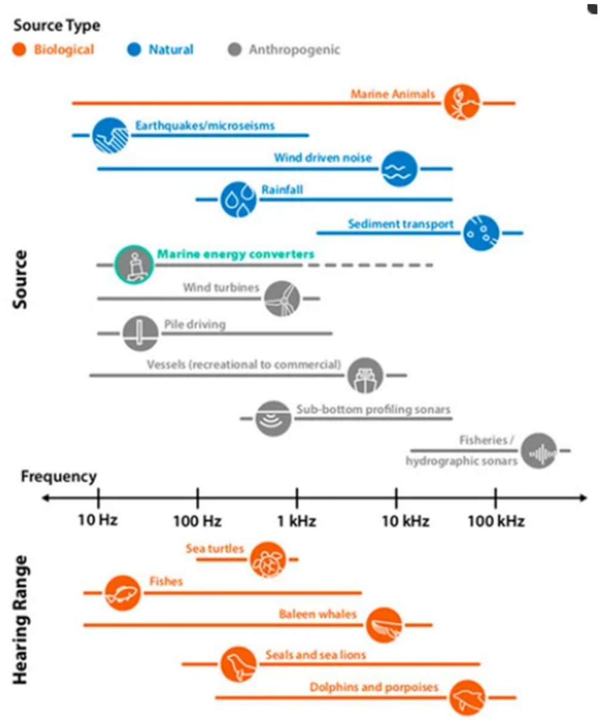


Figure 10. Frequency overview of noises in marine environments. [10]

When considering the frequency of noise produced by marine energy converters, it's noteworthy that they emit noise at frequencies similar to those used by many marine animals. The dashed line in the figure represents the unknown limit of the emitted frequency, indicating that energy converters have not been recorded emitting at higher frequencies. From the figure above, it is evident that other noise sources such as commercial vessels and sonars emit much higher levels of noise, which could potentially impact the behavior and lifestyle of marine animals.

Thermal energy converters have minimal impact on the environment as they generate energy from temperature differences in water. Their quiet design ensures they do not affect marine animals. However, the main drawback of this technology is its high cost. Hydrogen fuel cells convert hydrogen and oxygen into electricity and water, emitting no pollutants that affect the environment directly. However, pollution can occur during the production phase, depending on the source of hydrogen and the production method. Leakage during transportation and storage of hydrogen is a particular concern [39]. When hydrogen leaks, it can contribute to climate change by increasing the prevalence of other greenhouse gases such as methane, ozone, and water vapor [40].

Despite some technologies having proven negative effects on the environment and its inhabitants, the advantages they offer for both the economy and the pressing issue of climate change far outweigh the benefits of traditional energy sources. The goal is to reduce the carbon footprint in container ports.

In addition to renewable energy adoption, optimizing logistics and port operations plays a significant role in reducing carbon emissions. Implementing smart technologies and digital solutions helps streamline processes, minimizing idle times for vessels and trucks, and optimizing cargo handling efficiency. Replacing traditional handling equipment fueled by fossil fuels with automated and electrified container handling equipment reduces diesel consumption and emissions while enhancing overall port logistics... Furthermore, enhancing shore power infrastructure enables vessels to connect to grid electricity while docked, eliminating the need for onboard diesel generators and reducing emissions from ship operations. This is where the offshore energy technologies would have the greatest advantage.

Moreover, green ports are focusing on enhancing environmental management practices and promoting sustainable practices throughout their supply chains. This includes implementing green procurement policies, reducing waste generation through recycling and reuse programs, and adopting eco-friendly terminal designs that incorporate natural lighting, green spaces, and sustainable building materials. Collaborating with stakeholders such as shipping lines, freight forwarders, and local communities is also essential to foster a better approach to sustainability in port operations. By integrating these strategies, container ports that are going “green” are not only reducing their carbon footprint but also setting benchmarks for sustainable development in the maritime sector, contributing to global efforts towards mitigating climate change and preserving marine ecosystems.

5. CONCLUSION

Throughout this thesis, various alternative energy resources have demonstrated their value in enhancing environmental sustainability, improving port operations efficiency, reducing dependence on fossil fuels, and fostering innovation. As we progress towards a more sustainable future, container ports in the maritime industry must embrace these practices. By doing so, we can create a greener and more prosperous world for future generations. Technologies such as offshore solar farms, offshore wind farms, ocean generators, thermal generators, and fuel cell technologies, as discussed, not only reduce a port's carbon footprint but also set a precedent for other transportation sectors to prioritize sustainability.

For ports, alternative energy solutions are not just about environmental benefits; they are also financially astute. Initially, the installation costs of alternative energies may appear high, but the focus should be on the long-term benefits. These technologies promise significantly lower electricity costs compared to continuing with traditional sources. Achieving energy self-sufficiency reduces reliance on external electricity suppliers, shielding ports from volatile energy prices and future regulatory uncertainties. As efforts to slash carbon emissions in the maritime sector evolve, ports equipped with alternative energy technologies will adapt more swiftly to regulatory changes. Moreover, sustainability enhances a port's reputation among investors, customers, and stakeholders, positioning it favorably for current and future business relationships.

REFERENCES

[1] Kenan, N.; Jebali, A.; Diabat, A. The integrated quay crane assignment and scheduling problems with carbon emissions considerations. Comput. Ind. Eng. 2022, 165, 107734. [Google Scholar] [CrossRef].

[2] Fridell, E. Emissions and fuel use in the shipping sector. In Green Ports; Bergqvist, R., Monios, J., Eds.; Elsevier: Amsterdam, The Ntherlands, 2019; pp. 19-21, Chapter 2. [Google Scholar]

[3] Fridell, E. Emissions and fuel use in the shipping sector. In Green Ports; Bergqvist, R., Monios, J., Eds.; Elsevier: Amsterdam, The Ntherlands, 2019; pp. 22-33, Chapter 2. [Google Scholar]

[4] Andersson, C.; Bergstrom, R.; Johansson, C. Population exposure and mortality due to regional background PM in Europe-long-term simulations of source region and shipping contributions. Atmos. Envion. 2009, 43, 3614-3620. [Google Scholar] [CrossRef]

[5] Broome, R.A.; Cope, M.E.; Goldsworthy, B.; Goldsworthy, L.; Emmerson, K.; Jegasothy, E.; Morgan, G.G. The mortality effect of ship-related fine particulate matter in the Sydney greater metropolitan region of NSW, Australia. Environ. Int. 2016, 87, 85-93. [Google Scholar] [CrossRef]

[6] Sun, X., Huang, D., Wu, G.: The current state of offshore wind energy technology development. *Energy* **41**(1), 298–312 (2012)

[7] Shliomenzon, Y.: Mapping policy and legal framework for the offshore wind energy development. https://www.spglobal.com/commodityinsights/en/ci/research-analysis/policy-and-legal-framework-for-the-offshore-wind-energy.html (2022)

[8] Rahman, M., Hasanuzzaman, M., Rahim, N.: Effects of various parameters on PV-module power and efficiency. *Energy Convers. Manage.* **103**, 348–358 (2015)

[9] Bahaj, A.S.: Marine current energy conversion: the dawn of a new era in electricity production. *Philos. Trans. R. Soc. A: Math., Phys. Eng. Sci.* **371**(1985), 20120500 (2013)

[10] U.S. Department of Energy. (n.d.). *Fuel Cells*. Office of Energy Efficiency & Renewable Energy. Retrieved from https://www.energy.gov/eere/fuelcells/fuel-cells

[11] Wiley. (2023). IET Renewable Power generation. *Mohammad Parhamfar, Iman Sadeghkani, Amir Mohammad Adeli*. Retrieved June 29, 2024, from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/rpg2.12811

[12] International Renewable Energy Agency (2019a) Future of wind. deployment, investment, technology, grid integration and socio–economic aspects. Tech. rept. Abu Dhabi

[13] International Renewable Energy Agency (2019b) Renewable power generation costs in 2018. Tech. rept, Abu Dhabi

[14] Shouman ERM (2020) Global prediction of wind energy market strategy for electricity generation. In: Modeling, simulation and optimization of wind farms and hybrid systems. IntechOpen

[15] Crago, C.L.; Koegler, E. Drivers of growth in commercial-scale solar PV capacity. *Energy Policy* **2018**, *120*, 481–491.

[16] Garanovic, A. *EU Targets 40 GW of Ocean Energy and Other Emerging Technologies by 2050*; Offshore Energy: Rotterdam, The Netherlands, 2020

[17] Deshmukh, M. K., & Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews, 12*(1), 235-249. https://doi.org/10.1016/j.rser.2006.07.011

[18] Cigolotti V, Genovese M, Fragiacomo P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. *Energies*. 2021; 14(16):4963. https://doi.org/10.3390/en14164963

[19] Stationary fuel cells market, 2019–2030—Global market projected to reach $5.1 bn by 2030. *Focus Catal.* **2020**, *2020*, 2.

[20] Vo, T.T.E.; Ko, H.; Huh, J.; Park, N. Overview of Possibilities of Solar Floating Photovoltaic Systems in Siddharth Suhas Kulkarni, David John Edwards,

[21] A bibliometric review on the implications of renewable offshore marine energy development on marine species, Aquaculture and Fisheries, Volume 7, Issue 2, 2022, Pages 211-222, the OffShore Industry. *Energies* **2021**, *14*, 6988. https://tinyurl.com/2p9d9k3c

[22] Lee, A.: Offshore wind power price plunges by a third in a year. https://www.rechargenews.com/transition/offshore-wind-power-price-plunges-by-a-third-in-a-year-bnef/2-1-692944 (2019)

[23] Offshore wind market report: 2022 edition. https://www.energy.gov/sites/default/files/2022-09/offshore-wind-market-report-2022-v2.pdf (2022)

[24] A driving force for projecting offshore wind energy costs. https://www.energy.gov/eere/wind/articles/driving-force-projecting-offshore-wind-energy-costs (2022)

[25] Martins, B.P.: Techno-economic evaluation of a floating PV system for a wastewater treatment facility. Master's Thesis. KTH School of Industrial Engineering and Management Energy Technology (2019)

[26] Rosa-Clot, M., Tina, G.M.: Chapter 10 - levelized cost of energy (LCOE) analysis. In: M. Rosa-Clot, G. Marco Tina, (eds.), *Floating PV Plants*, pp. 119–127. Academic Press, San Diego, CA (2020)

[27] Oliveira-Pinto, S., Stokkermans, J.: Assessment of the potential of different floating solar technologies – Overview and analysis of different case studies. *Energy Convers. Manage.* **211**, 112747 (2020)

[28] Ramasamy, V., Margolis, R.: Floating photovoltaic system cost benchmark: Q1 2021 installations on artificial water bodies. https://www.nrel.gov/docs/fy22osti/80695.pdf (2021)

[29] Chen, Y.; Li, Y.R.; Hsieh, P.F.; Lee, C.S. Strategies of Developing Deep Ocean Water Industry-Cluster and Value Network Views. In Proceedings of the PICMET'07-2007 Portland International Conference on Management of Engineering &Technology, Portland, OR, USA, 5–9 August 2007; pp. 351–357

[30] Langer, J., Quist, J., Blok, K.: Recent progress in the economics of ocean thermal energy conversion: critical review and research agenda. *Renewable Sustainable Energy Rev.* **130**, 109960 (2020)

[31] Lazard's levelized cost of energy. **https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf** (2021)

[32] International levelised cost of energy for ocean energy technologies. **https://www.ocean-energy-systems.org/oes-projects/levelised-cost-of-energy-assessment-for-wave-tidal-and-otec-at-an-international-level** (2015)

[33] Yang, Z., Ren, Z., Li, Z., Xu, Y., Li, H., Li, W., Hu, X.: A comprehensive analysis method for levelized cost of energy in tidal current power generation farms. *Renewable Energy* **182**, 982–991 (2022)

[34] Bárcenas Graniel JF, Fontes JVH, Garcia HFG, Silva R. Assessing Hydrokinetic Energy in the Mexican Caribbean: A Case Study in the Cozumel Channel. *Energies*. 2021; 14(15):4411. https://doi.org/10.3390/en14154411

[35] Cigolotti V, Genovese M, Fragiacomo P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. *Energies*. 2021; 14(16):4963. https://doi.org/10.3390/en14164963

[36] Hall, R., João, E. & Knapp, C. W. Environmental impacts of decommissioning: Onshore versus offshore wind farms. *Environ. Impact Assess. Rev.* **83**, 106404 (2020).

[37] Copping AE, Hemery LG, Overhus DM, Garavelli L, Freeman MC, Whiting JM, Gorton AM, Farr HK, Rose DJ, Tugade LG. Potential Environmental Effects of Marine Renewable Energy Development—The State of the Science. *Journal of Marine Science and Engineering*. 2020; 8(11):879. https://doi.org/10.3390/jmse8110879

[38] Isaksson, N.; Masden, E.; Williamson, B.; Costagliola-Ray, M.; Slingsby, J.; Houghton, J.; Wilson, J. Assessing the effects of tidal stream marine renewable energy on seabirds: A conceptual framework. *Mar. Pollut. Bull.* **2020**, *157*, 111314.

[39] 2022 AMR Plenary Session (pdf) (9.9 MB, June 2022); Hydrogen and Fuel Cell Technologies Office; U.S. Department of Energy

[40] Ocko, Ilissa, and Steven Hamburg. "For Hydrogen to Be a Climate Solution, Leaks Must Be Tackled." Environmental Defense Fund, 7 Mar. 2022, www.edf.org/blog/2022/03/07/hydrogen-climate-solution-leaks-must-be-tackled.

LIST OF ABBREVIATIONS

RMG – Rail Mounted Gantry crane

RTG – Rubber Tyred Gantry crane

LNG – Liquified Natural Gas

IMO – International Maritime Organization

GWEC – The Global Wind Energy Counsil

LPG – Liquified Petrolium Gas

PV Systems – Photovoltaic Systems

ITC – Investment Tax Credit

LCOE – Levelized Cost of Electricity

LIST OF FIGURES

(1) Q Y Li. Carbon emission status and carbon reduction path analysis of waterway transport in China [J]. Transport Energy Conservation & Environmental Protection, 2021, 17 (2): 1-4 (in Chinese).

(2) Q Y Wang. 2019 China energy statistics [M]. Beijing: IGDP, 2019 (in Chinese).

(3) Gutierrez-Romero, J.E., Esteve-Pérez, J., Zamora, B.: Implementing onshore power supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* **255**, 113883 (2019)

(4) Statista, Offshore wind energy capacity worldwide from 2009 to 2021. https://www.statista.com/statistics/476327/global-capacity-of-offshore-wind-energy

(5) Casa Vogue. (2017, June). China inaugura maior usina de energia solar flutuante do mundo [China inaugurates the world's largest floating solar power plant]. Casa Vogue.

(6) Linquip. (n.d.). Tidal energy diagram: Story of tidal power. Linquip. Retrieved June 29, 2024, from https://www.linquip.com/blog/tidal-energy-diagram-story-of-tidal-power/

(7) Makai Ocean Engineering. (n.d.). Ocean Thermal Energy Conversion (OTEC). Makai Ocean Engineering. Retrieved June 29, 2024, from https://www.makai.com/renewable-energy/otec/

(8) ClimateBiz. (n.d.). How do hydrogen fuel cells work? ClimateBiz. Retrieved June 29, 2024, from https://climatebiz.com/how-do-hydrogen-fuel-cells-work/

(9) Galparsoro, I., Menchaca, I., Garmendia, J.M. *et al.* Reviewing the ecological impacts of offshore wind farms. *npj Ocean Sustain* **1**, 1 (2022). https://doi.org/10.1038/s44183-022-00003-5

(10) Copping AE, Hemery LG, Overhus DM, Garavelli L, Freeman MC, Whiting JM, Gorton AM, Farr HK, Rose DJ, Tugade LG. Potential Environmental Effects of Marine Renewable Energy Development—The State of the Science. *Journal of Marine Science and Engineering*. 2020; 8(11):879. https://doi.org/10.3390/jmse8110879