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Renewable Energy Options for Seaport Cargo Terminals with application to mega port Singapore

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Structured Abstract

Purpose: This paper reviews and analyses renewable energy options, namely underground thermal, solar, wind, and marine wave energy, in seaport cargo terminal operations.
Design/methodology/approach: Four renewable energy options that are deployed or tested in different ports around the world are qualitatively examined on their overall implementation potential and characteristics, and their cost and benefits. An application to the port of Singapore is discussed.
Findings: Geophysical conditions are key criteria in assessing renewable energy options. In the case of Singapore, solar power is the only suitable renewable energy option.
Research limitations/implications: Being a capital-intensive establishment with high intensities of cargo operations, seaports usually involve a high level of energy consumption. The study of renewable energy options contributes to seaport sustainability.
Practical implications: A key recommendation is to implement a smart energy management system that enables the mixed use of renewable energy to match energy demand and supply optimally and achieve higher energy efficiency.
Originality/value: The use of renewable energy as an eco-friendlier energy source is underway in various ports. However, there is almost no literature that analyzes and compares various renewable energy options potentially suitable for cargo terminal operations in ports. This paper narrows the knowledge gaps.

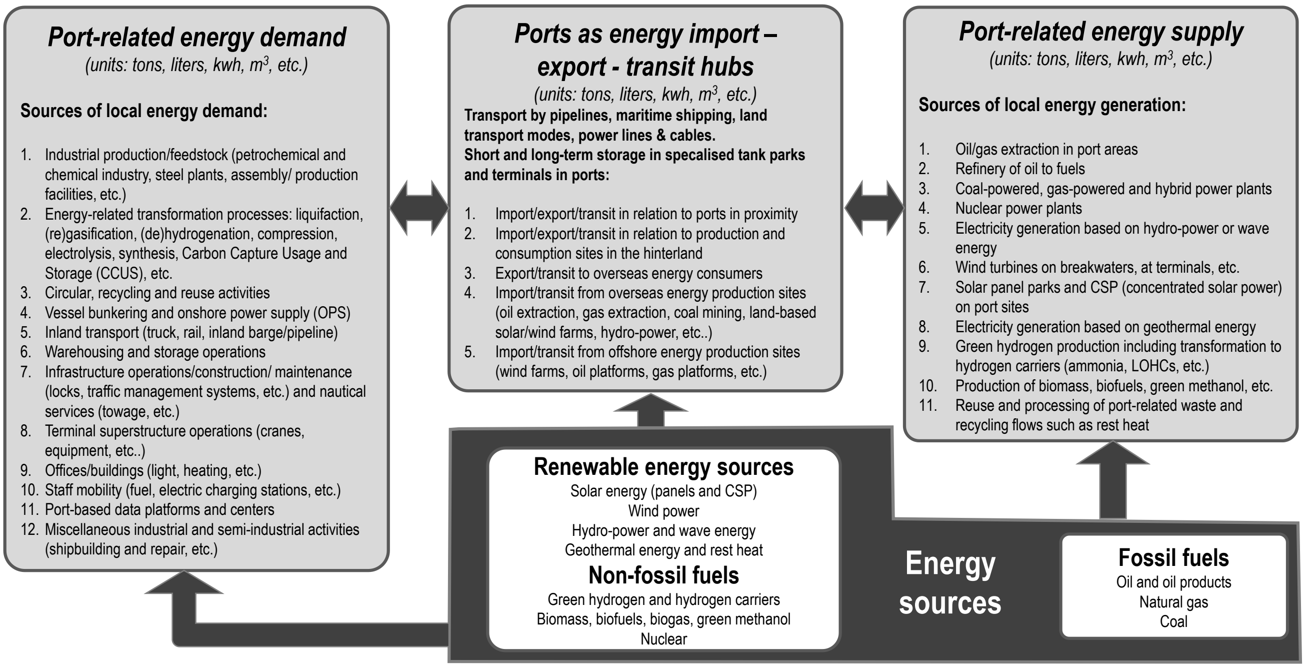
Keywords: Renewable Energy, Energy Management, Sustainable Development, Port, Terminal Operations, Singapore.

1. Introduction

Seaports are important coastal infrastructures for countries' national security and economic development. Being a capital-intensive establishment with high intensities of cargo, logistics, and industrial operations, ports usually involve high levels of energy consumption. Energy cost is an essential and substantial item in port operations expenditure (Elnajjar et al., 2021). As key port-related companies, terminal operators have attempted to use cost-efficient methods for terminal operations (Yap and Ho, 2023). Hence, energy management is a key topic in ports. At the same time, sustainable development has drawn increasing attention from regulators, governments, industry practitioners, and scientists around the world. Climate change concerns add to the need for ports to accelerate the implementation of ecological, low-emission, and carbon-neutral solutions (Yin and Lam, 2022). Large-scale conferences such as the United Nations Conference on Sustainable Development RIO 20+ (UNCSD, 2012), International Association of Ports and Harbors World Ports Conference (IAPH, 2022), and Terminal Operations Conference (TOC, 2023) were held to discuss planning in sustainable energy development to mitigate the emission of harmful gases and greenhouse gases (GHGs) into the atmosphere. Port cooperation and exchanges on these issues are stimulated through international and regional port and terminal associations and initiatives such as the Asia-Pacific Economic Cooperation (APEC) Port Services Network green port evaluation system, the World Port Sustainability Program (WPSP), and the Ecoports Foundation in Europe. Energy management affects not only the economic performance of a port but also the social and environmental aspects. For example, efficient energy management contributes to lower fuel consumption of cargo handling equipment and thereby air pollution. Therefore, sustainable energy management affects and contributes to the sustainable development of ports.

Being a clean and green port is also essential in the eyes of port policymakers and port communities as many ports are located near urban areas where population density is high (Lam and Yap, 2019). In practice, various solutions deploying more environmentally sustainable methods being applied to ports have emerged with technological advancement and innovations (Acciaro et al., 2018; Alamoush et al., 2020; Notteboom et al., 2020; Vanelslander et al., 2019). Various ports in different parts of the world find ways to optimize energy consumption in response to regulatory pushes in environmental matters, societal pressure, and opportunities to reduce costs. The use of renewable energy as an eco-friendlier energy source is also underway. Renewable energy is generated from natural resources that are self-replenished and non-fossil based (Darmani et al. 2014; Lund and Toth, 2020). Green fuels such as green hydrogen and green methanol are produced from renewable energy sources. Thus, a growing trend sees ports positioning themselves as green energy hubs (Notteboom and Haralambides, 2023; Prousalidis and D'Agostino, 2023). The energy hub function is multi-faceted combining port-related energy demand and local port-related energy production, with many ports also functioning as import, export, and or transit nodes as part of global and regional energy networks (Figure 1). Renewable energy adoption is becoming an ever more important aspect of this emerging energy landscape in ports. Ports are facilitating the development of large wind farms, solar parks, and other renewable energy installations in or near the port areas. Port-related companies active in terminal operations, logistics, and industrial activities are keen on developing and implementing cost-efficient projects focusing on the use of renewables. Cargo terminals are challenged to switch to green electricity sources, deploy hybrid or electric yard equipment (Forkin et al., 2023), and offer onshore power supply (OPS) solutions to ships visiting the terminals (Gutierrez-Romero et al., 2019; Bakar et al., 2023). The ongoing decarbonization in shipping is expected to boost the demand for bunkering activities of green methanol, green hydrogen, ammonia, and other green marine fuels.

Figure 1: The emerging multi-faceted energy landscape in seaports



Source: authors' compilation

In terms of academic research, energy studies in the port domain including those focusing on renewable energy are on the rise in recent years. However, renewable energy research concerning ports is still rather new. There is almost no research that analyzes and compares various renewable energy options potentially suitable for cargo terminal operations in ports.

Our study sets to contribute to this emerging topic and the field of sustainable ports in a broader sense. The paper aims to review and analyze renewable energy options in seaport cargo terminal operations. This research objective is met by examining four major renewable energy sources, i.e. underground thermal, solar, wind, and marine wave energy. Building further on a general literature-based discussion of the four renewable energy options in section 2, section 3 presents an in-depth analysis of the overall feasibility, cost and benefits, and payback period associated with (investment in) the four renewable energy options in ports. The paper ends with a case study following the principles of case study research (Yin 2009; Yin 1994). The case study is specifically aimed at empirically assessing the current state of the art concerning the feasibility and adoption of renewable energy options in cargo operations at the port of Singapore. Section 4 of the paper thus extends the discussion to provide recommendations on applicable renewable energy options in Singapore, to achieve sustainable energy management. The port of Singapore is chosen because of the very large cargo throughput and very high energy consumption in the port area. The port is active in enhancing its environmental performance and optimizing its energy management. Adopting renewable energy in cargo terminal operations is highly relevant in this case.

In this study, scientific literature and technical reports from professional organizations and equipment suppliers are reviewed to map renewable energy initiatives around the world. Data and information are collected, classified, and assessed. These inputs provide information about the costs and benefits of each renewable energy option. Implications will be drawn in the section recommending renewable energy options applicable to Singapore. The example of the port of Singapore shows the costs and benefits of these options within the expected lifespan of a typical mega container port.

2. Review of Renewable Energy Options in Ports

As mentioned in the introduction, there is an increasing interest in conducting renewable energy research for the port industry. However, knowledge gaps still exist. To date, a relatively small amount of literature can be found on renewable energy for ports, though more studies are available in related fields such as port microgrids (see e.g. Ahamad et al., 2018). Acciaro et al. (2014) deals with the overall topic of energy management in ports. While they examined the role of port authorities regarding two European ports as cases, our study takes a different focus by zooming in on port and terminal operations. In other words, Acciaro et al. (2014) focuses on a public authority's perspective and policies while our scope is at the port operations level. Moreover, Acciaro et al. (2014) have not particularly discussed renewable energy sources. Alamoush et al. (2020) provides an extensive review and categorization of ports' technical and operational measures to reduce greenhouse gas emissions and improve energy efficiency. While abatement potential, best practices, and key issues are discussed, Alamoush et al. (2020) does not provide an in-depth discussion on the cost and benefits of renewable energy options for cargo terminal operations. Actually, they call for further assessments of feasibility and effectiveness to identify the best combination of measures.

Renewable sources are naturally replenished and generate power to support a port's energy consumption. Different types of renewable energy are available in different places due to geographical characteristics (IEA, 2009). The analysis presented in this paper focuses on four renewable energy sources: (1) Underground thermal energy extraction; (2) Wave/hydro energy; (3) Wind energy; and (4) Solar energy. We provide port examples from various regions, but they are by no means exhaustive. Thus, this section provides an overview of current measures for renewable energy deployment in ports and related work in extant literature.

2.1. Underground thermal energy

Existing renewable energy generation techniques being used in ports could include underground thermal energy extraction. This involves the use of geothermal technologies to extract heat from the ground (or inject heat into the ground). Geothermal heat pumps can be used to transfer heat between the underground and a building, industrial facility, cargo terminal, or thermal energy storage system in the port area (Self et al., 2013; Gaur et al., 2021). Thermal energy can be used to heat and cool port buildings such as warehouses, to maintain the temperature of cold chain goods (such as fruit, meat, fish, etc.), or to provide additional energy or heat for industrial processes. By using a seawater source heat pump (SWHP) system, port activities can even rely on seawater as a heat source or sink for thermal energy systems (Cao et al., 2009).

2.2. Wave/hydro energy

Waves are generated by wind patterns and can provide a consistent and predictable source of renewable energy. Coastal seaports in principle offer opportunities for wave energy generation due to their proximity to the ocean. Port infrastructure such as breakwaters and piers can be equipped with wave energy devices, such as oscillating water columns (see Falcão et al., 2016 for a technical overview) to capture energy from waves.

2.3. Wind energy

Together with solar energy, wind energy is among the more popular sources of renewable energy being adopted in ports. A distinction can be made between onshore wind energy and offshore wind energy. Ports have a role to play in both types.

Onshore wind energy solutions have been applied in a large number of seaports such as the port of Bilbao (Ojanguren, 2013) and the port of Wismar (Philipp et al., 2021). Onshore wind turbines in port areas are mostly found on breakwaters and at cargo terminal sites.

Green energy production at offshore wind farms has seen a spectacular rise in the past decades and will see further strong increases in many parts of the world in the near future. The International Energy Agency (IEA, 2024) reports a global installed offshore wind capacity of 50.5 GW in the period 2017-2022 with expected growth to reach 154 GW in the period 2023-2028 in the 'main case' scenario, and 182 GW in the 'accelerated case' scenario. Northern Europe, and the North Sea in particular, is one of the main hotbeds for offshore wind power: The North Seas Energy Cooperation, a partnership between nine countries in the North Sea region and the European Commission, wants to realize 120 GW of offshore wind energy in the North Sea by 2030, and 300 GW by 2050. The green electricity generated by these parks is transported using large underwater power cables connecting the offshore wind farms to the mainland, with landfall locations often situated in or near seaports. For example, the Zeebrugge port area in Belgium is an important onshore landing point for electricity from offshore wind parks off the Belgian coast, through the projects Stevin and Nemo that have been implemented by transmission network administrator Elia. Given the strong rise of the offshore wind industry, quite a few ports have positioned themselves as major logistics hubs in the supply chains related to the production, assembly, installation, and maintenance of wind turbines offshore, see e.g., Gharehgozli et al. (2023) on the case of Texas, and Royal Haskoning (2023) on port infrastructure for the wind industry in the North Sea region.

2.4. Solar energy

Solar energy has been applied in Algeciras and Singapore (Esteve-Pérez and Gutiérrez-Romero, 2015; Iris and Lam, 2021), and both wind and solar energies in port of Antwerp-Bruges (Clemente et al., 2023), North Sea Port (North Sea Port, 2023), port of Rotterdam (2018), and Tianjin port (PRC, 2021). Port of New South Wales is in the middle of installing facilities for onshore power generated by solar and wind energies (Port Authority of New South Wales, 2023). Another good example is Khalifa Bin Salman Port in Bahrain. A major solar power project consisting of 20,000 solar photovoltaic panels will make the port fully solar energy-powered in the short term (APM Terminals, 2023). Ports generally have big flat spaces on the roofs of warehouses where solar panels can be installed. Port designs also take into account the placement of solar panels to provide shading for reefer cargoes (Matulka, Deshazo, & Callahan, 2013; Jiang, Chew, & Lee, 2015). This measure can reduce electricity demand by 50% and save up to USD$1.2 million for Port of Long Beach in the US (Matulka, DeShazo, & Callahan, 2013).

Some ports are exploring other solar energy configurations such as floating solar parks or vertical solar parks. For example, in the Summer of 2023, the Port Authority of Valencia announced it is carrying out studies for the creation of a large-scale vertical photovoltaic (PV) park. The test phase involves the use of PV panels on a strip of wall in the North Dock. In 2022, the port of Constanza in Romania started operations of a floating PV system that produces 15,000 kW annually to power one of the port's berths and several tugboats. A similar floating solution is applied in the port of Ostend in Belgium. Next to traditional PV panel parks on flat roofs or on vacant onshore or offshore port sites, alternative solar energy solutions based on Concentrated Solar Power (CSP) or Concentrated Solar Thermal energy (CST) are slowly starting to get adopted in ports. These technologies use mirror-based configurations to produce heat by solar irradiation concentrated on a small area (Zhang et al., 2013). For example, in 2019 the energy company Azteq installed a CST farm with 1,100 m² of parabolic reflectors on the site of the logistics company Adpo in the Antwerp port area.

3. Costs and benefits of renewable energy sources in ports

This section outlines the cost and benefits of the four renewable energy options (i.e., wind energy, solar energy, underground thermal energy and wave/hydro energy) that are deployed or tested in different ports around the world. Thus, we provide a discussion on extant literature dealing with the feasibility and relative competitiveness of the different renewable energy sources. The results are summarised in Table 1. The discussion draws connections to the three pillars of sustainable development, i.e., economic, social, and environmental sustainability (United Nations, 2005). Besides the general principles, local conditions are crucial for cost estimation and implementation of applicable energy options. Assessment incorporating elements within a port context to evaluate possibilities, costs and benefits of using renewable energy is not found in the literature. Therefore, these are the identified knowledge gaps and motivations for conducting this research. We will first discuss the overall costs and benefits common to these renewable energies.

Table 1. Analysis of Renewable Energy Options with Port Examples

RENEWABLE ENERGY SOURCE	DISTINCTIVE BENEFITS	COSTS (GENERAL)	COSTS	CURRENT PORT EXAMPLE
Underground Thermal Energy	• Stable and reliable, unaffected by climate or weather • Able to work at full capacity continuously	• Relatively high capital costs, especially on infrastructure • Extensive network of energy distribution and storage to ensure the utility rate. • Most renewable energy is available in remote areas, transmission of energy generated is costly. • Deployment of renewable energy in large scale should consider local environmental factors which are related to economic performance. • Lifecycle management: cost and operational challenges related to the recycling of (older) installations. • In some regions, high cost and lengthy permitting procedures for the installation of high-voltage electricity grid extensions.	The payback time for a ground source system with 300% more effective than a conventional system is about 12 years.	Rhine River Ports
Solar Energy	• PV technology is easily adopted • Flexible application on port buildings and equipment • New land-saving applications such as floating and vertical solar parks • Potential for Concentrated Solar Power (CSP) in ports still largely untapped		A 6083 square meter solar panel system from REC with PV module from Singapore which produces 1000 kW per hour output requires an initial investment of USD830,000. Traditional high-capacity PV parks on land require large surfaces.	• Algeciras Port (Spain) • Antwerp-Bruges (Belgium) • North Sea Port (Belgium/the Netherlands) • Port of Rotterdam (Netherlands) • Port of Singapore (Singapore) • Tianjin Port (China)
Wind Energy	• Technology is mature with economies of scale achieved through ever larger wind turbines • Wind can be exploited in most places		Enerpower, a famous UK and Italian industrial wind turbine company's 1.5MW system with an average 6.5m/s wind speed with USD0.17 per kWh requires 3.3 years payback. Wind parks require large space offshore or onshore, including potential incompatibility with other (nearby) spatial functions such as navigation channels or industrial production of dangerous substances (SEVESO rules).	• Antwerp-Bruges (Belgium) • Port of Bilbao (Spain) • Port of Hamburg • (Germany) • North Sea Port (Belgium/the Netherlands) • Port of Rotterdam (Netherlands) • Tianjin Port (China) • Port of Wismar (Germany)

Wave Energy	• Wave offers a huge energy potential, high power density		25 GWh generators are tested around coastline of Canada with 25 years of life cycle. A 10 years' payback period requires an electricity fee of at least USD0.089 per kWh.	Baltic Sea region

Source: Authors with reference from sources in the text

3.1. General assessment of costs and benefits

Several research methods such as mathematical models have been used to compare and combine alternative energy sources. Ahamad et al. (2018) designed and examined a renewable energy-based microgrid with wind and solar as the sources. A cost-effective solution is found in the case study of the Port of Copenhagen. Molavi et al. (2020) employed a stochastic programming approach to examine the benefits of applying microgrids with renewable energy sources. The case study of Barbours Cut Terminal shows that the application of microgrids enhances the port's environmental performance and productivity at the same time. Elnajjar et al. (2021) presented an experimental setup and results of wind and solar energy applications in the Port of Jebel Ali. Aided by a simulation model, their paper demonstrates that a lower total cost can be achieved. Another paper by Iris and Lam (2021) also found the benefit of lower cost. They developed a mixed integer linear programming model to integrate operations planning and energy management for seaports with a smart grid to harness renewable energy. In the case of Singapore using solar energy, a smart grid can achieve significant savings on total cost. The study by Baker et al. (2022) is also on seaport microgrids. They design a hybrid system with an onshore power supply and a renewable energy storage system from wind and solar sources. The case study of Port of Aalborg showed that the majority of electricity can be generated from renewable energy sources, hence the system significantly lowers both cost and emissions. Tawfik et al. (2023) analyzed the effectiveness of solar and wind energies in Alexandria port by an optimization model and simulation. An energy management plan to optimize the generated powers from the two types of renewable energy is then derived. Zhang et al. (2023) used optimization and meta-heuristic algorithms to evaluate the performance of a marine microgrid system. The microgrid incorporates several renewable energy sources, namely wind turbines, sea waves, and solar heat. In the work of Clemente et al. (2023), together with the smart port concept, multiple port examples from various parts of the world are presented to show the adoption of marine wave, wind and solar as renewable energy sources.

In existing practice in the port sector, cargo handling equipment using conventional fossil fuels such as diesel emits exhaust pollutants and GHG, such as carbon dioxide, nitrogen oxide, and sulphur dioxide. Alternative sustainable energy options from renewable energy and power generation have the benefit of reducing the emission level. When the energy production approach including both infrastructure and process is ecologically sustainable, zero or almost zero emissions can be achieved (Sifakis et al., 2021). This is a remarkable difference between renewable and non-renewable energies. The use of these renewable energies is also safe. Hence, renewable energy adoption contributes to the social and environmental performances of a port, benefiting human well-being and protecting the environment at the same time.

Another key benefit is diversifying a country's energy sources and reducing the dependency on using and importing conventional fuels, thus contributing to the energy security of the nation. This benefit has become more important than before as countries are paying more attention to diversifying energy sources due to geopolitical tensions and wars in recent years (Notteboom and Haralambides, 2023).

Concerning costs, renewable energy adoption affects the economic and financial performance of a port at least in the short term. The barrier to implementing renewable energy is the high capital costs especially for building infrastructure and facilities (EPA, 2018) with vague cost estimation (IRENA, 2015). For example, the payback period for an underground thermal source system with 300% more effectiveness than a conventional system is about 12 years (Midttømme et al, 2008).

A very large space is usually required for the infrastructure and facilities associated with renewable energy adoption, which in turn adds to the cost of development. The space requirement may even hinder the use of renewable energy for those ports with severe space constraints.

Also, an extensive network of energy distribution and storage should be established to ensure the utility rate. On top of the infrastructure, a comprehensive energy storage system is required to manage power flow and output fluctuations (Das et al., 2019).

Another cost consideration is associated with the fact that most renewable energy is available in remote areas, e.g., deep underground for thermal heat and offshore locations for strong wind. This characteristic makes the transmission of the renewable energy generated for port usage costly.

Also, the availability of renewable energy is subject to environmental constraints of a particular location. The deployment of renewable energy on a large scale should consider local environmental factors to see if the energy generation is sufficiently cost-effective, and how it affects cash flow and profitability (EPA, 2018).

Large amounts of electricity generated by wind, solar, wave and or thermal sources require transmission investment in the capacity of the electricity grid so that energy generation locations are well connected to the final energy consumers. As many countries have liberalized their electricity markets, coordination problems between investments in the regulated electricity grid and investments into new power generation might occur more frequently. Wagner (2019) demonstrated that inefficiencies arise if transmission investment follows wind power investment. Indeed, in some regions, the electric grid development has difficulties in keeping up with the rise of renewable energy production. For example, several countries in Europe have reported mounting capacity issues in their high-voltage grid. Complex planning and licensing procedures result in lengthy trajectories from inception to realization. This can hamper the energy transition trajectory. Moreover, the growing ESG (Environmental, Social and Governance) requirements imposed on companies imply no shortcuts can be considered in dealing with stakeholders and the social aspects of large infrastructure projects in the energy sector. As a result, large infrastructure works in electricity networks can take up to 10 or even 15 years to realize while the actual construction time only covers a few years.

3.2. Distinctive costs and benefits of each renewable energy option

Underground thermal energy resources in seaports can help to reduce energy costs and emissions, contributing to more sustainable port operations. Still, there are only a few examples of the actual large-scale application of underground thermal energy use in ports, such as in Rhine River ports (Puttke, 2013). Referring to Table 1, the distinctive benefit of thermal energy is stable and reliable performance, unaffected by climate or weather conditions. The source is from the Earth's heat which is long-lasting. The energy generation can work at full capacity continuously, basically 24/7. For the other three forms of renewable energy, they are all affected by climate or weather conditions, so energy input is relatively irregular. Quite a few obstacles to the implementation of thermal energy systems in ports exist such as unfavourable geological or geographical conditions, potential saltwater corrosion of equipment used in thermal energy systems, heavy regulatory requirements and environmental assessments, and high initial capital investment. Furthermore, underground thermal energy installations typically lack the scale and size to take up a significant share in the total energy mix of a port area. For a port to adopt thermal energy, the geographical location is a major determinant or hindrance simply because a nearby thermal energy source or power plant may not be available. According to the International Geothermal Energy Association's estimation, only 6.9% of the global potential thermal energy is exploited (IGA, 2023).

Marine wave energy taps into the advantage of a coastal location. When compared to the other three types of renewable energy, waves offer a huge energy potential. Its power density is higher than thermal heat, wind, and solar energy (Ilyas et al., 2014). Wave energy and thermal energy can potentially be integrated with solar and wind energy to contribute to the creation of a smart grid of renewable energy. However, for the time being, conventional power plants remain the main source of system flexibility, supported by new interconnections, storage and demand-side response. Cascajo et al. (2019) investigated the feasibility of installing wave energy converters in the Port of Valencia. Advantages such as lowering maintenance costs and facilitating energy extraction are shown. While wave energy technology has advanced in recent years, there are still technical challenges to overcome, such as device reliability and durability to withstand harsh marine environments, and cost-effectiveness. The economic viability of wave power energy projects in seaports often depends on government incentives and the availability of financing. Despite these challenges, marine wave power generation is already applied in the Baltic Sea region (Blažauskas, 2013) and the port of Sakata in Japan (Clemente et al., 2023).

The adoption of *wind energy* is fast. The technology is mature and stable. Wind is usually abundant and can be exploited in most places. Wind turbines can be installed on port breakwaters, on marine sites near the port's entrance channels (not obstructing navigation) or integrated at the terminal and other port sites. Due to the coastal or estuarine location of many ports, offshore wind is a natural candidate as a renewable energy source when wind consistency is sufficient. Sadek and Elgohary (2020) used economic analysis to assess the cost effectiveness of switching from national grid electricity to wind energy in Alexandria Port. Their finding shows a profitable solution. However, the rise of wind power (and also solar power) gives unprecedented importance to the flexible operation of power systems to secure enough energy at all times. The cost of battery storage declines fast, and batteries increasingly compete with gas-fired peaking plants to manage short-run fluctuations in supply and demand. When produced at times when solar and wind energy resources are abundantly available, green hydrogen can also support the electricity sector, providing long-term and large-scale storage and improving the flexibility of energy systems by balancing out supply and demand (Notteboom and Haralambides, 2023).

Among the four options, *solar energy* could be the easiest to adopt for ports. Solar photovoltaics (PV) technology is advanced and mature. The PV panels can be installed at many locations, such as port buildings and equipment, thus making solar energy highly flexible. This explains why the development of solar energy is growing rapidly, both within and outside the port industry. Floating and vertical solar parks, as well as Concentrated Solar Power (CSP) or Concentrated Solar Thermal energy (CST), have widened the application possibilities of solar energy, while at the same time solving some of the land availability issues in ports. Fossile et al. (2020) performed a multicriteria decision analysis for choosing the most suitable renewable energy among wave, wind, and solar as the production source for Brazilian ports. Based on twenty criteria, solar energy is considered the most viable option.

3.3. Payback period

Since high cost is a major obstacle, we compare the payback period of the renewable energy infrastructure projects to further understand the differences among the four renewable energies. There are many conditions and parameters for a fair assessment, such as project scale, pricing, energy input, energy output, and technology advancement level. It is almost impossible to set the same parameters for different renewable energy infrastructure projects. However, based on the available data and information, the deployment of underground thermal and wave energies tends to have longer payback periods than solar and wind energies. Taking an example of Enerpower, a famous UK and Italian industrial wind turbine company's 1.5MW system with an average of 6.5m wind speed with USD0.17 per kWh, it takes 3.3 years for payback. Such a short payback period is unattainable by underground thermal and wave energy projects. In addition to other factors, a long payback period would be a major reason for a relatively lower adoption rate of underground thermal and wave energies by ports.

The payback period of a project is not the only aspect that needs to be considered. A holistic approach to renewable energy projects should also consider lifecycle management (up to the recycling of older installations) and the investment needed to connect renewable energy production sites to the electric grid and to upgrade the grid's capacity where needed. For example, as the first-generation wind farms are reaching the end of their lifecycle, wind turbine recycling solutions have become a major issue. Most components of a wind turbine such as the foundation, tower, gearbox and generator are already recyclable. However, wind turbine blades are made of glass fiber-reinforced plastics (GFRP) composites and pose bigger challenges in a circular economy context (Jensen et al. 2018).

4. Case study: Renewable Energy Options for the port of Singapore

The port of Singapore is the world's busiest port in terms of shipping tonnage, having an average of 140,000 ship calls per year. It is also the largest transhipment hub which handled a container throughput of over 39 million TEUs in 2023, making it the world's second largest container port in volume terms after the port of Shanghai. The two cargo terminal operators Jurong Port and PSA place energy transition and the terminals' environmental performance high in their corporate agenda. Both operators have policies and projects to reduce the consumption of fossil fuels and increase the adoption of green energy.

Considering profitability as well as social and environmental aspects of terminal operations, recommendations are made based on Singapore's local context. Table 2 provides a qualitative assessment of the suitability of the four renewable energy options in the context of Singapore Port.

Solar power is evaluated as the most suitable renewable energy option for Singapore due to the city state's geophysical conditions. Located one degree north of the equator, Singapore has abundant sunlight throughout the year and sunlight duration is rather stable in different months. The average hours of sunshine per day are 5.6 (Statista, 2024). The port sector has started tapping on this natural resource in the middle of the last decade. Since 2016, Jurong Port in Singapore has installed thousands of square meters of solar panels on the roof of warehouses in the terminal storage yard areas at a cost of S$ 30 million (Jurong Port, 2018). The facility, capable of generating over 12 million kWh per year, is the largest port-based solar facility in the world. PSA, another terminal operator in Singapore, also installed a 4MW peak solar system in Pasir Panjang Terminal in 2018 (Straits Times, 2018).

However, solar energy is an intermittent energy source, that is, energy outputs from the sun are irregular and not continuously available to generate power supply. In the context of Singapore, due to a tropical climate, cloud cover and rain particularly affect the variation of solar energy. Therefore, an energy storage system is required to manage the intermittency issue. A recommendation is to implement a smart energy management system to match energy demand and supply optimally, leading to higher energy efficiency and sustainability. For instance, solar energy can be stored to offset peak energy consumption when a terminal encounters the highest volume of cargo operations.

Furthermore, the increased use of electric-powered cargo handling equipment with charging from solar energy outputs is considered a key element for decarbonization in the port of Singapore. The extensive electrification of terminal operations combined with an ambition for net zero carbon emissions increases the demand for green electricity. For example, PSA began operations of the first phase of the massive 65 million TEU capacity Tuas Port extension project in 2022. Three more phases are expected to be completed over the next 20 years. Port equipment such as quay cranes, rail-mounted gantry (RMG) cranes and horizontal movers are automated and run on electricity to increase productivity and reduce carbon footprints. Moreover, the adoption of full automation implies that Tuas Port will no longer need to use flood lighting at night, which can greatly save energy. While the high capital cost of solar energy is a concern, the advancement of technology would be able to produce more economically viable options that have a shorter payback period. From a national perspective, increasing the use of renewable energy in the port industry will reduce the reliance on electricity consumption from the national power grid. This is a strategic energy transition pathway for net energy-importing countries including Singapore. Hence, the adoption of solar energy at the cargo terminals of Jurong Port and PSA is beneficial for the port sector as well as the country's long-term interest.

The other renewable energy sources are far less suitable and feasible in the context of Singapore. Underground thermal energy is not available for power generation in Singapore at present. Although an exploratory study is underway for assessing geothermal energy's potential (CNA, 2023), the site of a probable source is very distant from the seaport terminals. Wind and wave energies usually require large pieces of land or large areas of territorial sea water to generate the power. The total land area of Singapore is only 734.3 square kilometres, and its territorial sea extends 3 nautical miles from its coastline (Government Technology Agency of Singapore, 2023), making Singapore one of the smallest countries in the world. Small countries like Singapore are not able to provide a large piece of land or sea space for typical wind farms (Yap and Loh, 2019; URA, 2023). Furthermore, the constraint of low average wind speed of 2 meters per second in Singapore (Meteorological Service Singapore, 2024a) restricts the viability of operating wind turbines effectively. Existing SEVESO rules also restrict the possibility of installing wind turbines near chemical plants producing and or handling dangerous substances, such as on Jurong Island. Over 80% of Singapore's territorial sea is used for maritime activities. The sea space is filled with navigation channels and anchorages (see Figure 2) which is not suitable for wave power deployment or offshore wind farm installation due to the potential blockage of the navigation channel and anchorages. Also, the low average wave height of less than 1 meter means that it is infeasible to generate wave energy (Meteorological Service Singapore, 2024b). Considering the limitations, therefore, these are not viable energy options for Singapore.

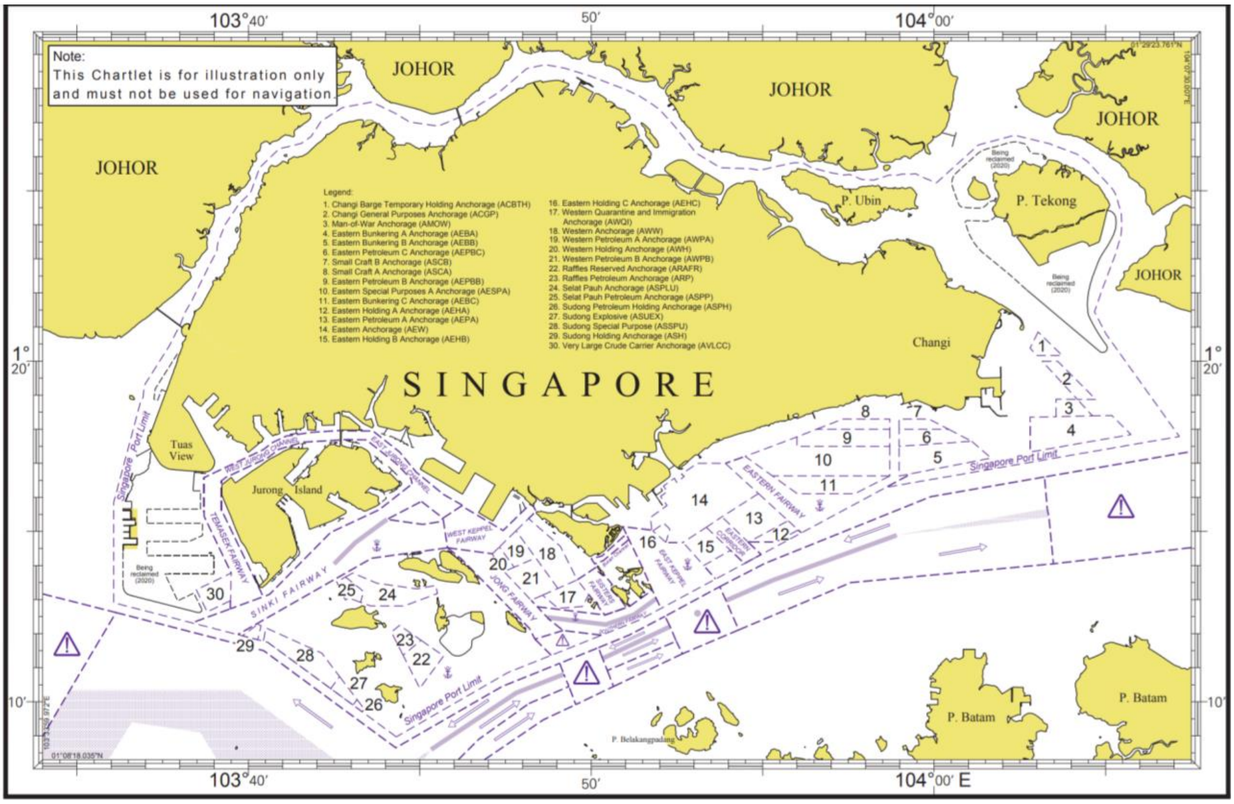
Overall, port operators and port authorities or port managing bodies are recommended to select those energy options that can bring benefits that outweigh the costs, with the consideration of local conditions which include the natural environment and government policies.

Table 2. A qualitative assessment of the suitability of Renewable Energy Options in the Singapore port's context

RENEWABLE ENERGY SOURCE	**LOCAL FAVOURABLE CONDITIONS**	**LOCAL UNFAVOURABLE CONDITIONS**	**OPPORTUNITIES TO BE FURTHER EXAMINED**	**CONCRETE PROJECTS AND REALIZATIONS IN SINGAPORE**
Underground Thermal Energy	Not available for power generation at present	No facilities available in Singapore	None, not available for seaport terminals	None
Solar Energy	Abundant sunlight throughout the year. Extensive local sustainable finance ecosystem. Ambitions of Singapore government in terms of green energy.	Variation of solar energy (cloud cover and rain). Land availability issues for ground-level solar parks and Concentrated Solar Power (CSP). Potential competing uses of solar energy generation in port (e.g. green mobility).	Need for an energy storage system and smart energy management system to manage the intermittency issue. Potential for new land-saving applications such as floating and vertical solar parks. Use more electric-powered cargo handling equipment with charging from solar energy outputs.	Since 2016: solar panels on top of warehouses in Jurong Port Since 2018: solar system in Pasir Panjang Terminal Since 2022: solar energy for electric port equipment and administrative buildings at Tuas Port
Wind Energy	Extensive coastline for a small island state.	Low average wind speed. A territorial sea full of navigation channels and anchorages. High urbanisation and industrialisation of available land. Incompatibility with nearby SEVESO plants and airport activity.	Very limited	None
Wave Energy	Not present	Limited wave dynamics in Singapore waters. Water surface availability issues in territorial sea.	Very limited	None

Source: Authors

Figure 2: Anchorages and fairways in Singapore



Source: MPA (2021)

5. Conclusions

This research addressed an emerging topic in port studies, i.e. renewable energy options for cargo terminal operations. Four renewable energy sources, namely underground thermal, solar, wind, and marine wave energy, and their applications in ports are reviewed. Based on academic literature, technical reports, and real-life port cases from around the world, the current practices and prospects for these four renewable energy options were presented.

To take an example in practice, the review findings were applied to the port of Singapore to present a set of recommendations for the further implementation of renewable energy sources in cargo terminal operations. The challenges in this respect for the port are significant given Singapore's ambition for net zero carbon emissions coupled with increasing demand for green electricity linked to the extensive electrification of terminal operations. The analysis shows that among the four renewable energy options, only solar power is suitable for Singapore due to the city state's geophysical conditions. A stronger focus on renewable energy production and use in the port can help to reduce electricity consumption from the national power grid. In line with the above, it is recommended that the relevant stakeholders in Singapore implement a smart energy management system that enables the use of renewable energy to match energy demand and supply optimally and achieve higher energy efficiency.

Regarding the analysis, port decision-makers in Singapore and other countries can consider the costs and benefits of various renewable energy options to be adopted. The triple aspects of economic, social and environmental performance should be considered for long-term sustainable development. As for researchers, renewable energy deployment in ports and terminals is an interesting area for further research. For example, the performance of energy storage systems for renewable energy supply can be investigated. Also, changing energy consumption patterns after adopting a new renewable energy source can be analyzed when relevant data are collected. Prediction of future energy needs based on the current and expected port utilization would be an interesting area for future research. Models with multiple scenario planning and comparisons will be useful to support decision making. We recommend future research efforts in developing renewable energy decision support tools to benefit environmental sustainability in seaports.

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