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LEVERAGING BLUE ENERGY FOR SUSTAINABLE POWER GENERATION AT SEAPORTS

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ABSTRACT

Seaports are one of the crucial elements for global trade, performing as pivotal points for goods transportation and bridging countries to cross-border market connectivity. However, seaports leave a major ecological footprint due to the dependence on non-renewable energy for port operations, which lead to carbon emissions. By utilising the natural salinity gradient between the saltwater and freshwater, seaports can implement salinity gradient energy systems, like salinity gradient osmosis (SGO), to generate sustainable and renewable electricity. This is in accordance with the United Nations Sustainable Development Goals (SDGs), especially Goal 7: Affordable & Clean Energy; Goal 13: Climate Action, and Goal 14: Life Below Water. Adopting a blue energy system for port operation can significantly reduce dependence on conventional energy sources, lower CO^2 emissions and contribute to the port's sustainable initiatives. Harnessing the resources of saltwater and freshwater for the generation of electricity via a blue energy system strengthens energy reliability and enhances the seaport's progression towards a sustainable economic model and reinforces its commitments to environmental conservation.

Introduction

The sea and ocean are important environmental systems and are a significant component of world trade. Ports are vital components in maritime logistics, and can stimulate economic growth for communities and regional economic growth, as well as creating direct and indirect employment (Hossain, M, T, 2021). According to the Review of Maritime Transport 2024, Asia's ports are making significant strides in digital port management and are handling over 63% of global container port calls (UNCTAD, 2024). Malaysia's seaports are well positioned to take advantage of these developments. A prominent seaport is not only defined by its core capabilities and services, but also determined by external elements such as regional and global connectivity.

Accelerating global trade flows leads to the need to expand seaport infrastructure to facilitate goods movements, such as container terminals, storage facilities and connected transit facilities. Growing seaport development not only leads to social conflict but also environmental pressures that hinder the sustainability of seaports. Many researchers have found that port operations and seaport expansion lead to ecological issues. Industrialisation, and by extension globalisation, increases energy consumption. This increase in energy demand creates a conflict between economic growth and environmental quality, which is not easy to manage (Solomon, S, 2020). Port operations, such as berthing, movement of goods and storage facilities, require massive energy consumption. The maritime sector presently accounts for about 2.8% of all global greenhouse gases (GHG) emissions, mainly due to its rapid growth, its dependence on carbon-intensive bunkers and the sheer size of its business, as more than 80% of the world merchandise trade by volume is transported by sea (UNCTAD, 2022).

Multiple types of electrical instruments in seaports to facilitate cargo handling, shipping operations and other services lead to higher electrical consumption. As reported in a study of electric power consumption in Busan New Port, equipment electricity consumption accounted for over 60% of the annual electricity consumption. The electricity consumption of facilities, excluding equipment, increased by about 7.8 %, outpacing the increase of equipment. (Kin, S, 2023). A port's daily operation requires an uninterrupted electrical supply to ensure the port's performance efficiency, which facilitates logistics operations as well as strengthening economic stability. Moreover, the volume of electricity consumption is influenced by land capacity, available facilities and cargo operations. According to the World Nuclear Association, over 40% of energy-related CO_2 emissions are due to the burning of fossil fuels for electricity generation (WNA, 2024). The analysis demonstrates that the higher electricity consumption for various purposes, such as land clearing, automated infrastructure and vessel operations, triggers CO^2 emissions, necessitating the exploration of sustainable strategies to address carbon emissions.

The International Maritime Organisation (IMO) is tasked with enhancing global collaboration to ensure secure, safe, and efficient maritime operations and foster environmental stewardship in maritime practices. It introduced the 2023 IMO GHG Strategy, which is aimed at enhancing IMO's contribution to global efforts by addressing GHG emissions from international shipping. International efforts in addressing GHG emissions include the 2015 Paris Agreement and the United Nations 2030 Agenda for Sustainable Development and its SDG 13: "Take urgent action to combat climate change and its impacts" (MEPC, 2023).The IMO is committed to attaining net-zero GHG emissions contributed by international maritime operations by 2050. For instance, when a vessel berths at a port, it requires an uninterrupted electrical supply to operate core shipboard systems such as lighting, refrigeration and communications. If the port is unable to supply shore-to-ship power, also known as cold ironing, which connects a berthed vessel to a land-based electrical grid and powering down its auxiliary engines to reduce fuel consumption, the vessel will run its auxiliary diesel engines, which leads to carbon emissions. The implementation of sustainability solutions can enhance the sustainable capability of the port to address the dependence on fossil fuels to facilitate needed electrical support, which contributes to carbon emissions.

The term sustainable development first appeared in 1987. It is defined by the World Commission on Environment and Development (the Brundtland Commission) as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs". There has been extensive discussion of the concept and there is recognition of three essential aspects of sustainable development: Economic, social and environment (Smith, J., & Doe, A, 2020). Green port initiatives are considered as one of the major aspects of the environmental pillar. Green ports are ports with a healthy ecological environment, reasonable utilisation of resources, low energy consumption and minimal pollution (Chun *et al*., 2022). Green port initiatives present long-term strategies to address ecological degradation by minimising port operation-related pollution, such as air pollution, water pollution, and waste management, while maximising resource potential, which leads to environmental and economic efficiency. The further research and prompt execution of green port initiatives will diversify the strategic possibilities to attain sustainability in Malaysian ports.

Advances in global shipping have facilitated international trade, enabling consumers and countries to access and explore diverse goods and services. Globalisation has given rise to a new era of international competition that is reshaping global production and trade, thereby altering the organisation of industries (Gary, J, 2012). Apart from increasing global demand, technological advancements in production and logistics, and liberalised international trade and agreements have reduced trade restrictions and promoted global supply by international shipping. While large-scale shipping encouraged economic growth, it has also contributed to extensive energy consumption, which results in carbon footprints. When commodity demand increases, there will be a rise in the export and import of goods. This leads to higher cargo throughput at seaports that necessitates more energy for handling and logistics, which directly or indirectly contributes to carbon emissions output. The global ports and shipping sector is almost entirely powered by fossil fuels and generates around 2% to 3% of global emissions; around the same as global aviation emissions, and absolute emissions have risen around 12% since 2016 due to growth in global shipping transport (C40, 2025).

This paper focuses on the electrical generation methods to meet seaports' operational needs and reduce the dependence on non-renewable energy such as fossil fuels.. Lately, blue energy systems have received renewed attention compared to the electrochemical capacitor, which serves as an energy storage device, and several experimental techniques. This article provides an overview of this technology, identifies future opportunities and highlights the practical integration in a broader energy generation system by harnessing the blue energy system in seaports for environmental and economic efficiency.

Literature Review

Seaport Energy Demand

The escalation of global trade due to globalisation has accelerated seaport operations, which in turn has increased power demand. Seaport activities are important to the development and integration of world markets (Jouili. T, 2016) Higher cargo throughput leads to greater energy usage, thus, compromising environmental sustainability.

Policy Frameworks and Sustainable Strategies in Maritime Sector

International bodies have acknowledged these concerns, and many countries have enacted sustainability policies to reduce environmental emissions while maximising operation efficiency and resource utilisation. The 2030 GHG Strategy introduced by the IMO to cut maritime GHG emissions to attain net-zero emission by 2050 encourages seaports to implement sustainable energy strategies, such as renewable-energy integration, green port initiatives and also cold ironing.

Technological Solutions: Shore Power, Electrification, and Renewable Integration

Technological innovation has been widely studied as a solution to mitigate seaport emissions. Shore-to-ship power, also known as cold ironing, allows vessels to connect to onshore electricity grids while at berth, reducing reliance on auxiliary diesel engines. The electrification of short-trip port harbour vessels, including tugs, pilot boats, mooring tenders and maintenance craft could lead to port GHG emissions being reduced by as much as 25% (WRI, 2025). Despite proven environmental benefits, adoption has been limited due to costs and dependence on local energy sources, which may still rely on fossil fuels (WNA, 2024). Electrification of cargo handling equipment and automated port systems has shown promise in reducing fossil fuel consumption, though studies caution that overall energy demand may still rise due to urbanisation (Kin, 2023). Thus, integrating renewable energy generation within ports remains a critical research area.

Emerging Research on Blue Energy for Seaports

Recent literature has shifted attention toward innovative renewable energy technologies, including blue energy, which harnesses the salinity gradient between seawater and freshwater to generate electricity. Blue energy is regarded as a promising carbon-free source of power, particularly relevant for coastal infrastructures such as seaports. Experimental approaches, including Pressure-Retarded Osmosis (PRO) and Reverse Electrodialysis (RED), have been tested with encouraging results (Chun, 2022). Scholars argue that seaports are uniquely positioned to benefit from blue energy, given their access to seawater and proximity to urban demand centres (Gary, 2012). While current research primarily focuses on laboratory-scale efficiency and energy storage mechanisms, there is growing recognition of blue energy's potential integration into broader renewable port energy systems (C40, 2025).

Theoretical Framework

The maritime sector is the foundation of global commerce, with more than 80% of goods shipped via sea routes (WBG, 2025). According to the UN Trade and Development (UNCTAD) Data Hub, around 46.1% of global maritime trade was from developed countries, and more than 53% of total maritime trade was from developing countries in 2023, which is comparatively greater than previous years. (UNCTADstat, 2025). The continual progression of international maritime trade directly influences energy demand by seaports for efficient operations. Every shipped cargo requires handling, storage and cargo transportation within the seaport, which requires an uninterrupted energy supply. However, extensive energy usage also leads to ecological damage, such as GHG emissions, which are causing climate change (Budiyanto, 2025). This scenario compelled seaports to undertake efficient and sustainable strategies to address both energy demand and carbon emissions. Implementation of a blue energy system to generate electricity for the operations at seaports will bring a significant change to the maritime industry. Blue energy is a renewable and ecologically friendly energy extracted from the biophysical process in oceans and other aquatic bodies to produce electricity. The concept of blue energy, otherwise known as osmotic power, was developed upon the realisation that through electrochemistry, a concentration cell with both saltwater and freshwater can be formed (ECS, 2016).

Harvesting clean energy from the environment to satisfy growing energy demand is of great importance for the survival and sustainable development of the human civilisation (Zhijun, 2014). In recent times, renewable energy systems (RES) capitalise on regenerative ecological resources such as solar, wind and hydro energy to produce clean energy to mitigate reliance on fossil fuels and promote sustainability. According to the 7th SDG, access to affordable, reliable, sustainable and modern energy should be assured. A well-established renewable energy system supports all sectors to make impressive gains. Exploitation of freshwater and saltwater would serve as a strategic instrument to attain this goal. The salinity gradient power (Osmotic Power) is generated from the interaction of freshwater, such from rivers and lakes, and seawater to produce clean energy for efficient port operations. Nearly over 97% of the Earth's water is in the oceans. A significant portion is either frozen in glaciers and ice caps (approximately 68.7%) or locked away as groundwater (approximately 30.1%). This leaves only a small fraction – roughly 1.2% of all fresh water and only 0.007% of all water on Earth – as surface water (rivers, lakes, swamps, and soil moisture) that easily accessible for human use (IERE, 2025) Most international ports are situated at transition zones where major rivers integrate with saltwater. (ISPI, 2021).

Technological advancement enhances the techniques to extract blue energy, such as the pressure retarded osmosis (PRO) method. The PRO method fundamentally drives its operating mechanism on the natural process of osmosis. After World War II, the energy demand surged due to rapid economic growth, increased suburbanization, and the spread of modern technological innovations in automobiles and electrification. In the 1950s, researchers discovered that the osmotic pressure difference between saltwater and freshwater could theoretically generate power. The theoretical feasibility of electricity generated by mixing fresh and salt water was proposed in the 1950s, and the PRO process was suggested in the 1970s. However, at the beginning of the PRO process, studies revealed that the PRO membrane was insufficient to produce water to operate a hydro turbine because the porous support substrate of the PRO membrane had a higher internal resistance against the solute transport within its inside and subsequently resulted in severe internal concentration polarisation (ICP) (Kim, 2013). The first application of the PRO process goes back to 1973 by Sidney Loeb, who suggested using the concept of osmotic energy for power generation (Altiee, 2014). In principle, two solutions with uneven concentrations divided by a semipermeable barrier. The higher solute concentration solution, under pressure, facilitates the water from the low concentration solution through the membrane driven by the osmotic pressure gradient, which causes the high concentration solution to undergo dilution. Once diluted, the high concentration solution is routed to pressure reduction through a turbine system to produce clean energy.

After technological progress in the 2000s, a Norwegian renewable energy company, Statkraft, introduced the first osmotic power prototype plant in Tofte, Norway, in 2009. The plant operates on a process called pressure-retarded osmosis (PRO), which basically involves pumping seawater at 60% to 85% of the osmotic pressure against one side of semipermeable membranes, whose other side is exposed freshwater (Patel, 2010). The modern type facilitates the membrane plate to separate both low salinity (freshwater) and high salinity (saltwater) that allows water molecules to pass through while preventing salt ion movement and equalising the salt concentrations from both freshwater and saltwater through the osmotic pressure gradient method that allows increasing the volume and pressure on the seawater section by the inflow of freshwater. The elevated hydrostatic pressure on the saltwater stream is employed to operate the turbine linked to a generator and converts the pressure into mechanical energy that facilitates the generator to produce electricity for operations. Unlike wind energy and solar power, blue energy through pressure-retarded osmosis (PRO) can operate without interruption. Most major seaports are strategically situated along river estuaries, where freshwater merges with seawater, presenting an ideal environment for a PRO plant to produce an uninterrupted energy supply, which can supply power for port operations, such as cranes, storage, lighting and monitoring systems. The port of Shanghai for example is strategically located near the coastal outlet of the Yangtze River. The Perai River near Penang Port, which is one of the major seaports in Malaysia, serves as a strategic location to implement a blue energy system to generate clean energy and reduce the dependency on fossil fuels, which can contribute to reducing GHG and advance the green port initiative in line with IMO sustainability goals.

Discussion

The application of a blue energy system via pressure-retarded osmosis (PRO) in ports has great potential for the maritime industry's green transformation and carbon emissions mitigation push. According to the World Trade Organisation (WTO), trade volume growth in 2025 would stand at 2.4%, up sharply from a previous estimate of 0.9% (CNBC, 2025). As global trade increases, the associated acceleration in port energy demand amplifies the necessity for renewable energy and an uninterrupted power supply for efficient port operations. The integration of blue energy systems through the Pressure-Retarded Osmosis (PRO) method at seaports represents a progressive stand in seaports energy independence, mitigates carbon emissions and advances international frameworks such as the IMOs carbon reduction and green port initiatives. The Pressure-Retarded Osmosis (PRO) system could provide seaports a stable energy supply due to the availability of saltwater and freshwater, unlike other renewable energy systems such as solar system and wind energy.

However, a blue energy system will have technological and operational challenges. The major limitation is the durability of the semipermeable membrane, which is a primary part of generating power. The internal concentration polarization refers to the accumulation of solutes near the membrane surface. It slows down the FO process by decreasing the osmotic pressure and thus reducing the efficiency of the system (Rufuss, 2022). Even though technological advancement has optimised membrane design, the higher cost for maintenance and production needs to be addressed. Moreover, implementation of a blue energy system into current port infrastructure necessitates strategic planning and high capital investment, and comply with the environmental regulations and the geographic structure of the seaports, such as pollution issues and land capacity. In addition, regular ecological monitoring and inspections must be applied, as the discharge of desalinated water into the sea can lead to marine environment damage due to unstable salinity gradients. The implementation of a blue energy system offers multiple advantages and specific limitations compared to other renewable technologies. Even though wind energy and solar power systems are widely applied in industries, their operational limitations and dependency on weather conditions require a consistent energy supply. Furthermore, hydropower plants require higher construction capital, and cause ecological and social issues. Nevertheless, the blue energy system has potential to provide continuous energy supply for seaports with minimal environmental damage.

Conclusions

The advancement of international trade and marine industries significantly leads to higher energy demand. This drives the necessity for a transition to renewable and sustainable energy. This study highlights the potential of blue energy systems through Pressure-Retarded Osmosis (PRO) method as a sustainable and innovative alternative for clean energy generation to reduce the ecological impact of power generation systems. A blue energy system can be independent from weather conditions and provide an uninterrupted power supply for multiple port operations such as cold-ironing, storage and crane operations. However, the building of blue energy systems into existing port infrastructure also presents capital, technological and environmental challenges. These limitations need efficient capital optimisation, research and development (R&D), and continuous environmental monitoring. Moreover, implementation of smart energy management techniques, such as power storage and distribution according to the operational demand, along with international collaboration to draw an effective framework, will ensure sustainability in the long-term.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Author Contributions Statement

The author confirms contribution to the paper as follows: The author reviewed the results and approved the final version of the manuscript.

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