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Port Electrification: A Review of the Development of Electricity and New Renewable Energy Utilization

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Abstract: This study reviews the development of electricity utilization and renewable energy in port electrification. It highlights the need for more research on environmentally friendly renewable energy sources for ports. The study analyzes data from Scopus-indexed journals and finds that solar energy accounts for 29.11% of renewable energy sources, followed by wind energy at 27.85%, biomass, and wave energy at 10.13%, and geothermal, hydro, and others at 7.59%. Port electrification can reduce environmental impact and improve efficiency. By integrating electricity and renewable energy technologies, ports can contribute to a greener and more sustainable economy.

Keywords: electrification port; renewable energy; emissions reduction; qualitative case study

1. Introduction

The increase in greenhouse gas (GHG) emissions was thought to be the primary cause of climate change, which has now become a global concern[1)]. Indonesia, an archipelagic nation highly vulnerable to climate change and the world's fifth-largest emitter of greenhouse gases[2)], must cut emissions across the board, especially in the maritime industry. The global transportation sector experienced a 4% increase in emissions in 2022 and increased by 10% in Indonesia compared to 2021[3)], while the maritime sector accounted for 3% of the world's carbon emissions[4)]. The operation of ships and port activities using fossil fuels has led to an increase in GHG emissions[5)]. Port activities, such as shipping, cargo services, and other services, impact the environment around the port. To achieve an environmentally friendly port, known as a 'green port,' efforts are made to reduce carbon dioxide and greenhouse gas emissions[6)]. Operational efficiency is enhanced by digital solutions, waste management, and energy development.

Numerous studies have discussed the alarming effects of fuels, renewable energy, and climate change[7)]. The International Maritime Organization (IMO) is intensifying efforts to reduce emissions with the aim of achieving net-zero emissions in international shipping[8)]. This covers goals for the use of alternative fuels and energy sources, as well as goals for technological innovation. A variety of renewable energy sources include hydro energy, solar energy, wind energy, bioenergy, biofuels (such as biodiesel and bioethanol), and pure vegetable oil[7)]. Energy conservation has become extremely important due to the current global energy crisis[9)]. Indonesia is ambitious to achieve net-zero emissions by 2060 in response to climate change, focusing on energy efficiency and electrification. This priority reflects awareness of the energy sector's contribution to greenhouse gas emissions[10)]. Indonesia has a considerable geothermal capacity that is vital to be exploited for its renewable and sustainable qualities. As of 2021, the country has only utilized approximately 2,185.7 MW of its geothermal energy, despite having a potential of 23.7 GW[11)]. The 28th Conference of the Parties (COP-28) represents a tangible global action for limiting the rise in global temperatures. It also signifies Indonesia's concrete commitment to climate financing, primarily in pursuit of achieving the net-zero emissions target[12)]. Furthermore, Indonesia actively participates in the Asia Zero Emission Community (AZEC). This initiative aims to facilitate an energy transition alongside other Asian nations towards carbon neutrality and decarbonization[13)].

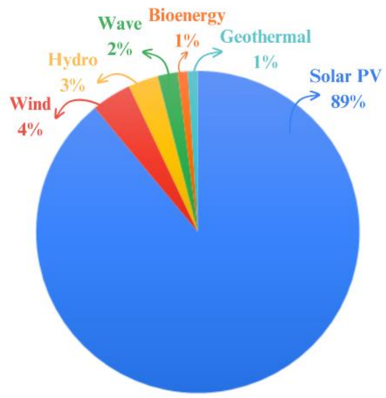

Fig. 1: Potential of New Renewable Energy in Indonesia[14].

Indonesia's renewable energy capacity reaches around 12.28% of Southeast Asia's total renewable energy capacity. Energy capacity in 2022 will come from 24.5% bioenergy, 18.72% geothermal, 2.48% solar energy, and 1.22% wind energy[15]. The potential for renewable energy for solar panels is on Kalimantan Island at 3077 (gigawatt) GW, for wind energy it is on Sulawesi Island with 8.92 GW, the most significant potential for hydro energy is on Papua Island with 1.58 GW, and biomass energy is on Sumatera Island with 18 GW[16]. The use of renewable energy for the electrification of ports contributes to increasing operational efficiency and minimizing environmental damage[17].

Renewable energy can positively impact achieving 75 targets (44.3%) of all Sustainable Development Goals (SDGs). However, focusing on the potential of renewable energy technology to reduce the environmental impact of port operational activities may hinder the achievement of 27 targets, accounting for 15.97% of all targets[18], this research can provide insights for port operators, policymakers, and researchers interested in improving sustainable development in the maritime sector[19].

In Indonesia, the shipping sector is adopting several strategies for emission reduction. These include the electrification of loading and unloading equipment, the use of solar cells for port facilities, and the application of renewable energy[20]. Electrical energy efficiency is being enhanced by New Renewable Energy (NRE)[6]. A critical aspect of these strategies is the electrification of transportation. This move aims to reduce the sector's dependence on fossil fuels. It encompasses the development of infrastructure for electric vehicles and integrating renewable energy into the transportation sector[10].

Indonesia is rich in geothermal resources but needs to be more utilized, developing most renewable energy projects requires a significant amount of time, with the exploration phase taking several years[21]. It is recorded that the installed capacity of geothermal energy is 8.3%, hydro energy is 6.2%, mini-hydro energy is 2.1%, solar energy is 0.1%, wind energy is 0.3%, and bioenergy is 0.1% of the total existing potential[22]. Therefore, mapping is needed to determine the progress of port electrification and its effectiveness.

This research is designed to conduct a Systematic Literature Review (SLR). Its goal is to analyze the potential of renewable energy, the use of technology, and the challenges and opportunities in implementing renewable energy to support port electrification. Additionally, it aims to provide recommendations for practitioners, researchers, and policymakers on steps to accelerate the adoption of port electrification and the use of NRE in ports.

The methodology employed is a literature review combined with a case study approach, analyzing data from journals indexed by Scopus. The research is structured into several parts: The first part introduces the research and its objectives. The second part details the scope of the literature review, encompassing the studies conducted and the procedures for identifying NRE. The third section presents the results of the literature review, based on an analysis of 30 articles. The final section summarizes the key findings from the literature and discusses their implications for both practice and research.

2. Methodology

This study utilizes a systematic literature review (SLR) method. An SLR is a comprehensive, explicit, reproducible, and systematic approach to identifying, evaluating, and synthesizing the findings of previous research studies, academic papers, and practitioner reports[23,24]. The primary objective of this scientific method is to evaluate and categorize vast amounts of information, assist in exploring the boundaries of research, and establish and expand fundamental knowledge[25]. The research process for the study titled 'Port Electrification: A Review of the Development of Electricity and NRE Utilization' includes three key stages: initial identification, article selection, and data analysis. The study's output will identify the potential advantages and obstacles to implementing renewable energy and technology in port electrification, as demonstrated in Fig. 2.

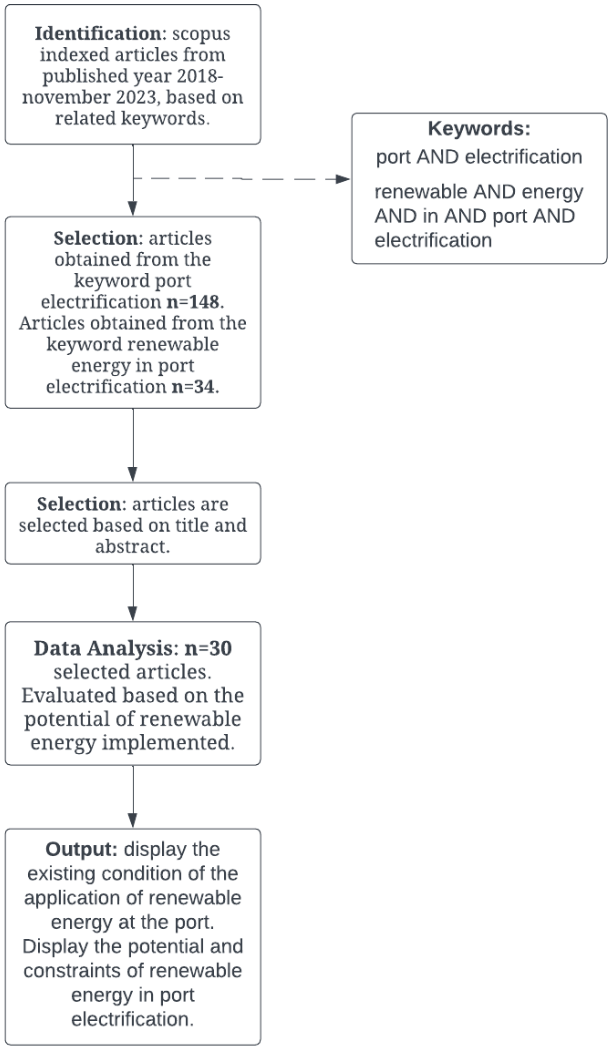

Fig. 2: Research flow.

The first stage is identifying the literature to be analyzed. Literature was collected through the Scopus database for 2018-2023. The reason for choosing the Scopus database is that it covers a wide range of international articles that can be accessed and reviewed. We searched for relevant articles using the keywords "port AND electrification" and "renewable AND energy AND in AND port AND electrification" to gain an understanding of the development of the application of NRE in port electrification from previous research. The criteria for reviewing the articles are shown in Table 1.

Table 1. Criteria of the reviewed article.

Criteria	Content Criteria
Type of publication	Scopus indexed articles
Language	English
Year of publication	2018- November 2023
Databases	Scopus
Keywords	port AND electrification, renewable AND energy AND in AND port AND electrification.

In the next stage, 148 articles were obtained from the keywords port AND electrification and 34 from the keywords renewable AND energy AND in AND port AND electrification. The articles were selected based on the title and abstract in the next step. After the literature was selected, 30 articles were analyzed. The 30 articles were evaluated based on the potential for NRE applied to ports. Of the 30 articles, the distribution of years of publication of the most significant articles is in 2023, with 11 articles, as shown in Fig. 3.

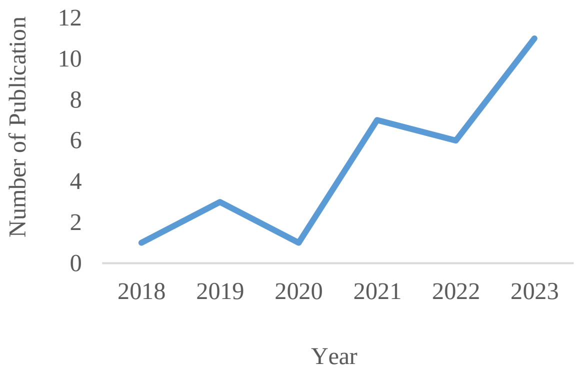

Fig. 3: Profile of relevant publications.

The case studies or research locations of the 30 articles are dominated by Indonesia at 24% and Egypt at 16%, which can be seen in Fig. 4.

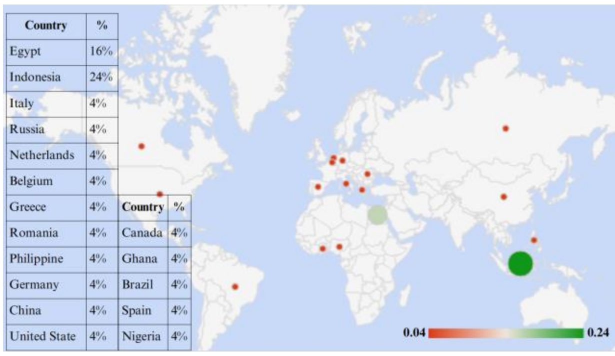

Fig. 4: Publication distribution map.

3. Result and Discussion

The research explores the current state of electrification in port operations and the use of NRE. It also examines renewable energy sources that have the potential to be developed. Indonesia has taken steps to improve port environmental protection by renewing ships, implementing solar-powered navigation beacons, reporting ship fuel consumption, electrifying port facilities, and digitizing services[26].

3.1 Electrification in Ports

The use of electricity in port operations raises several benefits and challenges that require regulations that are in line with technological developments[27]. Several benefits and challenges need to be considered when it comes to the development of port electrification. It is essential to consider various aspects of the development of port electrification. Important to understand the benefits and challenges of developing port electrification. One of the main benefits is the reduction of carbon emissions from fossil fuels, such as diesel, which are commonly used to power ports[28)]. Electrification can replace these fuels with more environmentally friendly options[29)]. Additionally, port electrification can increase energy efficiency and reduce operational costs[29)].

However, there are also challenges to consider. Developing port electrification requires a significant investment to support existing infrastructure and technology[30)]. Limited electricity networks can also pose a challenge to electrification efforts[30)]. Finally, the cost of using electricity in ports can be a significant obstacle for port entrepreneurs[29)].

Despite these challenges, developing port electrification is an essential step in achieving environmentally friendly port activities, increasing energy efficiency, and reducing carbon emissions[31)].

3.2 Use of NRE at Ports

3.2.1 Distribution of NRE Use

The topic of NRE is centered on its ability to reduce carbon emissions from fossil fuel engines[32)]. This section specifically covers the types of NRE that are utilized in ports. Through analyzing 30 research articles, we were able to classify them based on the type of NRE used, as presented in Table 2.

Table 2. Types of renewable energy.

Energy	Source
Solar	Alsnosy Balbaa & Noha Hany El-Amary[33)]; Giovanna Attanasio, et al.[34)]; Seyedhahid Vakili and Aykut I. Olcer[35)]; Nugroho Agung Pambudi, et al.[11)]; Daniel Clemente, et al.[36)]; I Wayan Ngarayana, et al.[37)]; Robert Philipp, et al.[38)]; Lizica Simona Paraschiv and Spiru Paraschiv[39)]; MR Arsalan, et al.[40)]; Magdy Tawfik, et al.[41)]; Ika Wahyu Setya Andani, et al.[42)]; David Firnando Silalahi, et al.[43)]; Hon Chung Lau[44)]; Nikolas Sifakis, et al.[45)]; Mohammad Parhamfar, et al.[19)]; Cagatay iris, et al.[46)]; D. Pivetta a, et al.[47)];Elif Demir, et al.[48)]; Chidozie Ezekwem & Suresh Muthusamy[49)]; N. Nikitakos, et al.[50)]; E. Czermanski[51)]; NNA Burn[52)]; Magdy Tawfik, et al.[41)]; D. Bosich[53)]; Guangd Li[54)].
Wind	Ibrahim Sadek & Mogamed Elgohary[55)]; Ibrahim S. Seddiek[56)]; Raul Cascajo[57)]; Giovanna Attanasio, et al.[34)]; Seyedhahid Vakili and Aykut I. Olcer[35)]; Nugroho Agung Pambudi, et al.[11)]; Daniel Clemente, et al.[36)]; I Wayan Ngarayana, et al.[37)]; Robert Philipp, et al.[38)]; Lizica Simona Paraschiv and Spiru Paraschiv[39)]; Magdy Tawfik, et al.[41)]; Ika Wahyu Setya Andani, et al.[42)]; Hon Chung Lau[44)]; Nikolas Sifakis, et al.[45)]; Mohammad Parhamfar, et al.[19)]; Cagatay iris, et al.[46)]; Elif Demir, et al.[48)]; C. Ezekwem, et al.[49)]; N. Nikitakos, et al.[50)] ;E. Czermanski[51)]; NNA Burn[52)]; Guangd Li[54)].
Bioenergy/ Biomass	Alsnosy Balbaa & Noha Hany El-Amary[33)]; Giovanna Attanasio, et al.[34)]; Nugroho Agung Pambudi, et al.[11)]; I Wayan Ngarayana, et al.[37)]; Lizica Simona Paraschiv and Spiru Paraschiv[39)]; Ika Wahyu Setya Andani, et al.[42)]; Hon Chung Lau[44)]; D. Pivetta a, et al.[47)]; N. Nikitakos, et al.[50)].
Geothermal	Nugroho Agung Pambudi, et al.[11)]; I Wayan Ngarayana, et al.[37)]; Ika Wahyu Setya Andani, et al.[42)]; Hon Chung Lau[44)]; N. Nikitakos, et al.[50)].
Waves	Raul Cascajo[57)]; Daniel Clemente, et al.[36)]; AM Rizal, NS Ningsih[58)]; Mohammad Parhamfar, et al.[19)]; Simone Bonamano[59)]; Elif Demir, et al.[48)]; N. Nikitakos, et al.[50)]; E. Czermanski[51)].
Hydro	Nugroho Agung Pambudi, et al.[11)]; I Wayan Ngarayana, et al.[37)]; Lizica Simona Paraschiv and Spiru Paraschiv[39)]; Ika Wahyu Setya Andani, et al.[42)]; Hon Chung Lau[44)]; N. Nikitakos, et al.[50)].
Other	Seyedhahid Vakili and Aykut I. Olcer[35)]; Nugroho Agung Pambudi et al.[11)]; Ika Wahyu Setya Andani et al.[42)]; Hon Chung Lau[44)]; D. Pivetta a, et al.[47)]; Hossam A. Gabbar[60)].

According to Table 2, solar energy is the most dominant form of energy, with a percentage of 29.11%, followed by wind energy with 27.85%. Bioenergy and wave energy come in third with 10.13%, while geothermal energy, hydro energy, and others make up 7.59%. Solar energy is the most popular form of energy due to its sustainability advantages and non-emission of greenhouse gases during production[38)]. Photovoltaic (PV) panels are being utilized to generate 430 MWh per day in 1/5 of the Portland area[32)]. Solar energy infrastructure is being deployed on land and in water according to the conditions of Indonesia, which is an archipelagic country with a tropical climate[11)]. The generation costs for solar energy range from $5.90 to $18.65/kWh, and capital costs are expected to decline over the long term[41)]. Although numerous sources of green energy exist, solar energy is the most common and is available almost all year round, especially during the summer months from March to September[40)].

3.2.2 NRE Technology

Numerous ports worldwide have adopted solar PV systems[19)], including both onshore and offshore solar panels, solar power generation technology, and On-Grid and Off-Grid technology[54)]. The implementation of on-grid solar cells has the potential to power port facilities in Indonesia, including land-based connections, which could reduce the reliance on traditional fossil fuel power plants [40]. Moreover, solar PV cell technology has been used to produce energy throughout the year[35]. The application of PV Cells has already been successfully implemented at various ports worldwide, including the Philippines[35], Egypt[33], ASEAN countries[44], Port of Brestova, Porozina[53], and Jurong Port of Singapore[61].

However, using solar photovoltaic energy necessitates continual efforts to develop suitable infrastructure, supportive policies, and financial incentives mechanisms[39]. Additionally, DC electric power systems require better coordination in the distribution network[52].

Floating solar power plants have numerous advantages, including land use, increased efficiency due to reduced water evaporation, the inhibition of weed growth such as water hyacinth, and suppression by photovoltaic panels that form a cooling system for the electricity produced[11].

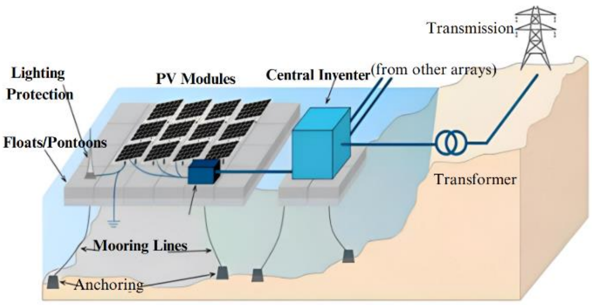

Fig. 5: Floating solar power plant components[11].

Intermediate wind technology is applied both onshore[45,51] and offshore[19,45,52,56–58]. Onshore turbines are used in places like The Kaliningrad Sea fishery port where the average wind speed is 7-8 m/sec[49]. Offshore wind power generation involves turbines located offshore where wind speeds over the ocean are higher than on land[19]. However, constructing offshore wind power plants is technically complex and requires two to three times higher construction costs than onshore wind turbines[53].

For the study conducted at the Port of Alexandria, the Darrieus turbine was chosen to meet the harbor's boundary conditions in terms of wind speed interaction[41].

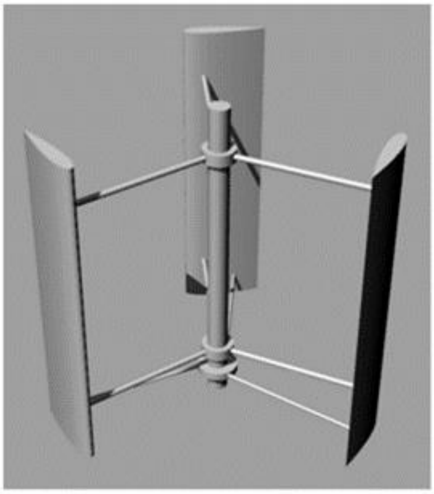

Fig. 6: Rotor H-Darrieus VAWT NACA0018[41].

Darrieus turbines, which are also known as lift-type Vertical Axis Wind Turbines (VAWT), have several advantages, such as receiving wind from all directions, operating at low wind speeds, and having relatively high efficiency. However, their weakness lies in their inability to self-start at low wind speeds[61]. Indonesia has established two wind power plants, one in the Sidarap region consisting of 30 wind turbines with a total capacity of 75 MW, and another one in the Tolo area of Turatea, South Sulawesi, with a capacity of 72 MW, comprising 20 wind turbines, each with a capacity of 3.6 MW[11].

Consider switching to biomass energy, which can be produced using gasification. This approach can capture 65-70% of the energy in solid fuel by converting it into combustible gas and generating energy. The underlying principle and integration of biomass generation are presented in Fig. 7[33]. A potential method for future biomass energy is co-firing waste and wood with coal in a steam power plant[11].

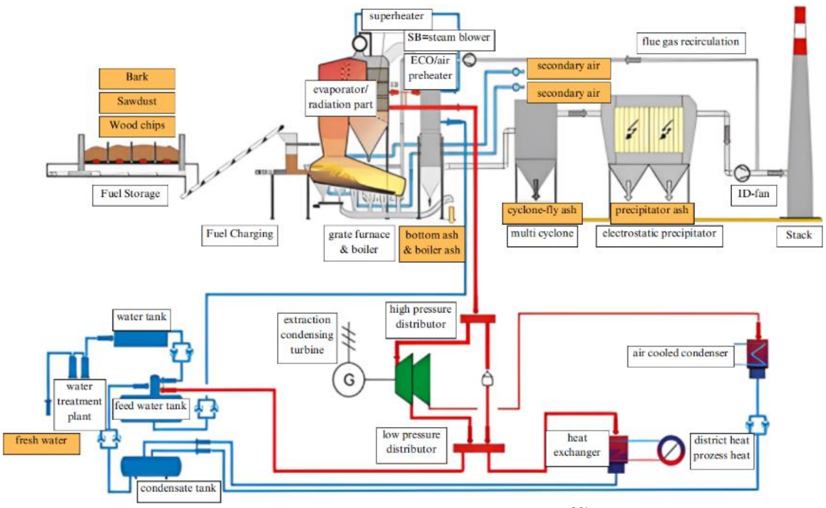

Fig. 7: Biomass plant integration[33].

In the Valencia Port case study, wave energy technology was found to be more effective when using the Overtopping Breakwater Converter (OBREC) type. This is because the overtopping device is more compatible with the wave-breaking infrastructure[57].

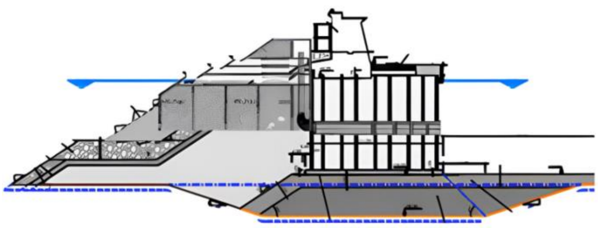

Fig. 8: OBREC integration[57].

In addition to other technologies, two types of wave energy converters (WEC) are worth mentioning. The first one takes into account the variability and extremely significant wave height conditions (SWH)[57] while the second one, known as Wave SAX technology, is applied to the Port of Civitavecchia due to its high accuracy[58].

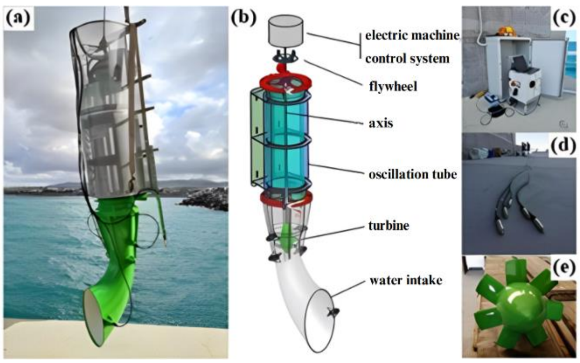

Fig. 9: Parts of the Wave SAX tool[59].

3.3 Potential ad Challenges of NRE

Utilizing renewable energy sources to produce electricity is crucial for transitioning toward a low-carbon energy system and promoting sustainable development[62]. It aids in cutting down greenhouse gas emissions, mitigating the effects of climate change, diversifying the energy mix, generating job prospects, boosting the economy, preserving the environment, and securing a prosperous and sustainable future for future generations[39].

3.3.1 Solar

Installing solar power plants can generate electricity for bulk cargo[38]. Solar panels installed on the building provide sufficient electrical power, thus supporting the port building's consumption[41]. Solar energy can provide up to 40% of the energy required by a ship[39]. Additionally, by installing floating solar PV, the need for extra land can be minimized[19]. Using solar energy in ports has numerous environmental advantages.

1. Reduction of Carbon Emissions: Ships can significantly reduce their ecological impact and greenhouse gas emissions by utilizing solar energy[63,64].
2. Improved Energy Security: Port facilities that utilize solar energy can improve their energy security by diversifying their energy sources and protecting against power supply disruptions[63].
3. Reducing Dependence on Conventional Fuel: The use of solar energy in ports can help reduce operational costs and contribute to environmental sustainability by reducing dependence on conventional electricity[64,65].
4. Improved Environmental Sustainability: The installation of solar panels at ports can help reduce the carbon footprint and environmental impact of maritime operations, leading to improved environmental sustainability[41,65].

The use of solar energy in ports can significantly reduce environmental impacts and enhance energy sustainability.

3.3.2 Wind

Renewable energy systems such as wind turbines can help ports save costs and reduce their Levelized Cost of Electricity (LCOE)[44]. Offshore wind turbines use high wind speeds at sea to produce high amounts of energy[19]. Economically, wind energy has been proven to be the best green energy option, with an electricity cost of \$0.101/kWh[54]. Wind energy also plays a role in sustainable development, stimulates research innovation, and enhances the design, materials, and efficiency of wind turbines, ultimately lowering costs and enhancing performance[38]. Radiation from the sun heats the earth at different speeds, causing changes in temperature, humidity balance, and air pressure, which in turn creates wind[47]. Compared to other conventional energy sources, wind energy has several environmental benefits, especially in ports.

1. Electric power does not produce carbon emissions, making it an effective means to reduce overall carbon emissions[66,67].
2. Electricity-based operations do not release air pollution or waste during their operation[66,67].
3. The use of electric power can provide a clean and renewable energy source[66].
4. Providing clean and renewable energy sources[67].
5. The adoption of electric power can also create profitable employment opportunities[68].

However, it should be noted that the development of offshore wind energy ports can also have significant environmental impacts, especially related to infrastructure development and operational activities, such as impacts on marine life and land use[69].

3.3.3 Bioenergy/Biomass

Integrating renewable energy sources like wind, solar, biomass, and hydro into the current energy system can fulfill up to 40% of the annual electricity needs and substantially cut down greenhouse gas emissions. This is in contrast to systems that solely rely on fossil fuels[38]. Biomass power plants can operate as base loads since they are not intermittent and use mostly agricultural and plantation solid waste as fuel sources[41]. Developed energy (bioenergy/biomass energy) has various environmental benefits that are better than conventional energy in different aspects. Here are some of the environmental benefits of growing energy:

1. Clean and renewable energy: Biomass energy is obtained from renewable sources and can be used to produce fuels such as ethanol and biodiesel[70]. These sources can be divided into two categories: coarse biomass (containing only carbon and water) and shiny biomass (containing carbon, water, and minerals).
2. Reduction of carbon emissions: Biomass energy can help reduce carbon emissions in the atmosphere. Some prominent entrepreneurs, such as Biomass Ventures, have developed systems in which carbon emissions from whiskey distillation plants are transferred to algae, which then thrives on additional carbon dioxide. When the algae die, they are collected and subjected to the process of making biodiesel or fish food[70].
3. Encouraging resource use: Biomass energy can be used in a variety of applications, such as fuels, renewable chemical products, bioplastics, polymers, and heat and electricity heating[71].
4. Resilience and economics: Developing biomass energy can contribute to a safer, more sustainable, and economic future by reducing dependence on oil and gas and importing more renewable resources[72].
5. Waste reduction: Biomass energy can help reduce waste in various ports by replacing unsustainable fossil resources.

However, it should be remembered that the use of biomass as a source of energy for development also has several negative impacts, such as the impact on the ecosystem and unsustainable land use[73]. Therefore, it is important to ensure sustainable management of biomass resources and maintain a balance between the use of biomass and the use of other fossil resources.

3.3.4 Geothermal

Geothermal power plants are a commercially viable source of energy that can reduce emissions by 27.4%. These power plants have a capacity of 7.4 GW[42]. Geothermal energy is presently accessible solely in Indonesia and the Philippines among ASEAN countries[44]. Geothermal energy has been around for over a century, with the first geothermal well located in Kamojang, Netherlands, in 1926[11]. Compared to conventional energy sources, geothermal energy offers many environmental benefits in ports. According to[73], geothermal power plants have low emission levels and can even renew geothermal resources by injecting used geothermal steam and water back into the earth, thus reducing emissions. Direct application and geothermal heat pumps have minimal negative effects on the environment and can even have a positive impact by reducing the use of energy sources that can have negative effects. Furthermore, geothermal energy can help reduce greenhouse gas and sulfur dioxide emissions[74]. Several European ports, including the ports of Marseille and Rotterdam, have explored geothermal and biomass energy. The Port of Rotterdam is even planning to become a major center for biomass by implementing plans for co-firing biomass in power plants. Therefore, geothermal energy can play a vital role in achieving energy efficiency and improved environmental objectives in ports.

3.3.5 Wave

Wave energy offers a reliable, sustainable, and environmentally friendly alternative to traditional energy sources, with potential economic and energy security benefits[58]. The use of wave energy can bring about significant environmental benefits. Wave energy converters utilize the natural motion of waves to generate electricity, thus reducing the dependence on fossil energy sources[74]. This technology has enormous potential, especially along the U.S. West Coast, and could account for more than 64 percent of all utility-scale electricity generated in the country by 2021, according to the U.S. Energy Information Agency[75]. By generating electricity from a clean and renewable source, wave energy as the potential to decrease greenhouse gas emissions, enhance air quality, and alleviate the effects of climate change. Wave energy is an abundant, clean, and predictable resource with great electricity potential. The impact of wave energy generation on the world's coasts is estimated at around 2.1 TW or the equivalent of 18,500 TWh available annually and three-quarters of global electricity consumption in 2021[36].

Wave energy is s an eco-friendly energy source in ports when compared to conventional energy sources. Here are some of the environmental benefits of wave energy:

1. Reduce carbon emissions: Wave energy generation can help reduce carbon emissions in ports by producing energy that is more environmentally friendly than fossil energy sources[76].
2. Generation of renewable energy sources: Wave energy converters can produce energy from sources that have never been obtained before, such as electrical energy and natural gas[74].
3. Reduce dependence on fossil energy sources: By using wave energy, ports can reduce their dependence on fossil energy sources, thereby helping to reduce negative impacts on the environment[74].
4. Port infrastructure training: Wave energy converters can be integrated into existing port infrastructure, such as in midship and deep sea[76]. This simplifies the development process and makes management easier.
5. Environmentally friendly energy transportation: Wave energy can help provide environmentally friendly energy for devices and equipment in ports, such as electric transportation for vehicles and other equipment[76].
6. Monitor climate adaptation: Well-designed wave energy converters can avoid the negative impacts of

climate change, such as increased flooding and marine erosion[74].

Although wave energy offers many benefits to the environment, it is important to consider the sustainability, resilience, and availability of clean energy sources such as surplus energy sources[76]. In addition, the development of wave energy projects in ports must consider the impact of the loss of existing fossil energy sources and optimize the use of existing land and infrastructure[77].

3.3.6 Hydro

The Jelok Hydroelectric Power Plant, established during the Dutch era in 1938, is a dependable and trustworthy source of hydro energy[11]. The potential for renewable energy, such as waves, sea heat, and sea tides, is relatively large[37]. Hydro energy has a 25.61% share of the energy produced in total energy consumption[39]. This energy source is still in development and has yet to operate commercially[42]. Based on the latest data report in the fourth quarter of 2021, the newly utilized hydro energy potential is estimated to be 6,601.80 MW. This includes a hydropower plant of 5,638.7 MW, a micro-hydro of 126.4 MW, and a mini hydro of 375.5 MW. The mini-hydro segment accounts for approximately 6.5% of the total hydro energy potential[78]. The goal for building a hydroelectric power plant is to reach 21.9 GW by 2030[79]. It's great to see that the national energy strategy has a roadmap for renewable energy plants with a target to build 7.7 GW by 2030. This shows a strong commitment towards sustainable development and reducing the carbon footprint. With the aid of renewable energy, it is possible to achieve a cleaner and more efficient energy supply that benefits both the environment and the economy. It will be interesting to see how this target is achieved and the impact it has on the overall energy mix in the coming years.

3.4 Indonesian NRE Opportunities

Electrifying ports is a crucial aspect of promoting sustainability in the transportation industry and mitigating its environmental impact. In Indonesia, opportunities for NRE involve harnessing renewable energy to power port activities[80]. Such opportunities require exploring potential port demand, identifying potential resources, and addressing challenges related to utilizing NRE.

3.4.1 Port Demand Potential

Indonesia needs to focus on developing a sustainable maritime sector that supports the energy transition by exploring green fuels and related technologies[78]. The country has enormous potential for utilizing NRE in its port sector. As the largest archipelagic nation in the world [79], Indonesia has a significant demand for NRE in its port sector [80]. Currently, there are 1,241 ports in Indonesia, including 39 main ports, 241 collecting ports, 235 regional feeder ports, and 726 local feeder ports, as stated in the Decree of the Minister of Transportation of the Republic of Indonesia Number KM 217 of 2022 concerning the Third Amendment to the Decree of the Minister of Transportation Number KP 432 of 2017 concerning the National Port Master Plan[81].

3.4.2 Policy

The rising concentration of greenhouse gases in the atmosphere is leading to global warming and climate change, which can affect environmental conditions[81]. Greenhouse gas inventories are conducted to collect, measure, and record data on greenhouse gas emissions and absorption. The main goal of these inventories is to understand and monitor the amount of greenhouse gases released or absorbed by an area or country[82].

To provide environmentally friendly port operations, the use of renewable energy as a source should be replaced with electrification and renewable energy. In line with Indonesia's national energy policy, a Presidential Regulation (Number 112 of 2022) was created to accelerate investment in renewable energy development, reduce greenhouse gas emissions, and meet new energy targets[83]. It is necessary to reorganize the mechanism for utilizing renewable energy to accelerate its development[84].

Port electrification is an effort to control pollutant gas emissions through the use of clean energy, low-emission machines, onshore power supply for docked ships, electrification of port equipment, control of dust, handling of waste, and compliance with pollution prevention provisions in the port area[85]. The Port Authority is responsible for regulating, controlling, and supervising port activities and ensuring environmental sustainability[86-88]. Port managers must monitor and assess environmental impacts arising from port activities to maintain environmental sustainability[89]. Control of pollutants in the port environment must be carried out precisely and quickly to minimize damage and pollution[90].

3.4.3 Resource Potential

Solar. Indonesia, being a tropical country, has a huge potential for utilizing solar energy sources as it receives sunlight throughout the year with an average of 4.80 kWh/m2/day. The solar energy resources available in Indonesia are much greater than all other energy resources combined with an income of more than 200,000 TWh per year. The use of photovoltaic cells in Indonesia is very promising, particularly in coastal areas[40].

Wind. In Indonesia, there are several wind power plants located in different regions, which have a combined installed capacity of more than 4.4 GW. Each unit of these wind power plants is capable of generating electricity equivalent to hundreds of MW produced by fossil fuel power plants, provided that there are enough potential resources available[42]. Indonesia is abundant in renewable resources, including hydroenergy. As per the International Renewable Energy Agency (IREA), Indonesia has the capacity to generate more than 3,500 gigawatts of solar, wind, and geothermal energy. However, more than 99 percent of this potential remains untapped[80]. The potential for wind energy in Indonesia is estimated at around 9,500 MW with average wind speeds ranging from 1.3 to 6.3 m/s[82,83]. However, the current installed capacity is only around 1.2 MW, far below the existing potential[82]. According to the latest report from the Indonesian government, the potential for wind energy in Indonesia reaches 154 GW, consisting of 60.6 GW onshore and 94 GW offshore[84,85]. Nonetheless, the potential for wind energy in Indonesia remains relatively low due to the country's average wind speeds ranging only from 3 to 6 m/s, which is lower than the minimum wind speed required to rotate a windmill of 5 m/s[86]. However, Indonesia has started developing wind energy since 2010 and currently, there are 8 wind power generation projects planned with a total capacity of 597 MW[85]. The Indonesian government has also issued a policy to encourage the development of renewable energy, including wind energy[82].

Bioenergy/Biomass. A variety of raw materials, including livestock manure, agricultural residues, plantation byproducts, and waste, are readily available in different regions of Indonesia[11]. Solid waste from the palm oil, rice and sugar cane industries has great potential including palm shells and fruit bunches, old palm trunks, rice straw, rice husks, bagasse, as well as plant shoots and leaves[87]. Indonesia is rich in bioenergy resources through biomass pellets produced from the remains of palm oil, rice, sugar cane, and rubber wood to be used for electricity generation[44]. The potential for biomass energy in Indonesia is quite large, estimated to generate approximately 146.7 million tons of biomass annually, which is equivalent to roughly 470 GJ/year. While biomass energy sources are distributed across the country, the greatest potential for concentrated biomass energy can be found on the islands of Sumatra, Papua, and Sulawesi[88,89]. Indonesia has extensive forest resources, which allows various options to optimize biomass production capacity[88]. Apart from that, Indonesia also has great potential to use forest energy and wood waste as a source of biomass[90]. However, the development and utilization of biomass as an energy source is still relatively small compared to its potential[90]. Indonesia has pledged to boost the utilization of new and renewable energy (EBT) with a target of EBT contributing 23% of the national energy mix by 2025. Bioenergy is highlighted as one of the strategic measures to achieve this goal[91,92].

Geothermal. Indonesia is situated on the Ring of Fire, which provides the country with geothermal energy sources[43]. The potential of geothermal energy in Indonesia is around 23.7 GW, and new utilization is expected to be around 2,185.7 MW[11]. According to reports, Indonesia has the largest potential for geothermal energy resources in the world, estimated at 29,000 MW[101]. However, the utilization rate is still less than 8% of Indonesia's installed geothermal power capacity of about 2.28 GW[102,103]. Nevertheless, the Indonesian government is planning to develop geothermal energy to reach the target of 9,000 MW by 2025[104].

Waves. Wave energy in the Indonesian sea and surrounding waters has been studied using the WAVEWATCH III simulation, comparing the results with buoys and satellite observations to test the reliability of the model, it was found that ocean wave energy has prospective potential for use as renewable energy in Indonesia, in addition to Indonesia's configuration as an archipelagic country. This is unique because most of its territory is a wetland area represented by the ocean, thus supporting this energy exploration[58]. The potential for ocean wave energy in Indonesia is quite large. Research findings indicated that Cilacap, Yogyakarta, Jember, and Bali possess wave energy potential exceeding 40 kW/m, whereas areas like Cianjur, Trenggalek, Lombok, and Sumba exhibit a moderate potential ranging from 20 to 30 kW/m. Overall, Indonesia's ocean wave energy potential could reach 1.49 TW, based on a threshold of 10 kW/m[93,94]. In addition, a review of wave energy in Indonesia shows that Indonesian waters, especially in the western part, have significant wave energy potential[95]. Several studies also show that several areas along the southern coast of Java have great potential for generating wave energy[93,96]. Indonesia's ocean wave energy potential presents a promising renewable energy source that merits further exploration.

Hydro. In the Sumatera region, hydro energy has a potential of 8,300 MW, but hydropower plants are still in development and have yet to operate commercially in Indonesia[42]. Hydropower generation is a renewable technology with great potential, but installed capacity still needs to be improved due to relatively low capacity compared to other ASEAN countries[44]. A hydropower plant with an intermediate pond would store river water during the day to reduce electricity production and would increase production at night when demand peaks[97]. Furthermore, for downstream reservoir type and cascade type power plants, seasonal adjustments will be considered by storing river water during the rainy season in reservoirs[97].

3.4.4 Challenges

The port sector in Indonesia faces several challenges in transitioning to NRE, including limited infrastructure, harmonized access to electricity, and the need to depend on renewable resources.

Indonesia faces several challenges in providing equal access to electricity due to its diverse geography and population[98]. One of the significant obstacles is the lack of infrastructure such as roads and bridges, which makes it difficult to reach remote and inland areas. While there has been notable progress in the energy sector in recent years, there remains a necessity to expand the national electricity grid to encompass these regions[98]. Another challenge is the country's dependence on renewable energy sources, which poses a threat to regional development. Indonesia possesses plentiful renewable energy resources like solar, hydro, bioenergy, wind, and geothermal sources, but effectively harnessing them remains a challenge[98]. Moreover, Indonesia aims to become a developed country and overcome the middle-income trap while meeting its electricity demands, which poses a significant challenge to regional development across all its islands. Renewable energy projects often require large areas of land[99]. Apart from that, there are other challenges from the social side, namely lack of awareness, education, and technological developments that need to be developed[99].

To tackle this challenge, the Indonesian government has established several regulations to implement environmentally friendly technologies by 2036. This includes the deployment of Green Ships, as well as the adoption of e-ammonia, hydrogen, and biofuels[100]. Achieving electrification in Indonesia requires collaborative efforts between the government, society, BUMN, and experts to ensure equitable distribution of renewable energy[98].

4. Conclusion

According to the results, NRE usage at ports was mainly dominated by solar energy which accounted for 29.11% of the total energy consumed. Wind energy came second with a percentage gain of 27.85%, followed by bioenergy and wave energy which accounted for 10.13% of the energy consumption. Geothermal energy, hydropower, and other sources accounted for a percentage of 7.59%. Solar energy was found to be the most dominant energy source due to its significant sustainability advantages and zero greenhouse gas emissions during production. However, despite its benefits, some challenges still need to be addressed such as unequal availability of resources, infrastructure still in the development stage, and significant investment costs.

Indonesia has vast potential for implementing renewable energy in the port sector. However, several challenges need to be addressed, such as limited infrastructure, access to harmonized electricity, and dependence on renewable resources. To achieve equitable national electrification as per the national energy policy, collaboration between the government, society, BUMN, and experts is required. With technological innovation and supportive policies, renewable energy applications will continue to grow and significantly contribute to meeting global energy needs. Several existing technologies are applied to solar energy, such as solar PV, onshore and offshore, and on-grid and off-grid. For wind energy, onshore and offshore technologies are used, employing turbines. Co-firing technology is used for biomass energy, while wave energy is harnessed using an Overtopping breakwater converter and Wave Energy Converters (WEC).

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