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Rethinking the Green Strategies and Environmental Performance of Ports for the Global Energy Transition

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Abstract: The relationship between ports and energy markets is undergoing a transition in their functions as suppliers, consumers, and energy processors. Environmental factors increasingly force the maritime sector to reduce its carbon footprint and improve energy efficiency. Governing the maritime sector's environmental performance requires leveling decarbonization through integration with energy supply chains and rethinking green strategies and environmental sustainability. This paper highlights that a port's energy management system can be an example of supply–demand equalizing sustainable alternative energy sources. Such systems engage more profoundly within the energy value chain by assessing green and environmental indicators in port operations, strategies, and investments. This manuscript investigates the challenges in ports' operations, strategies, and investments, considering their energy transition and decarbonization. Therefore, this research conducted a qualitative study on ports' energy efficiency and greening using an in-depth interview method in three seaports in the Adriatic, Baltic, and Black Sea basins. The paper proposes a framework for analyzing green variables in the ports' operations, strategies, and investments to improve their environmental performance. The framework examines a set of green variables, researching their cause-and-effect relationship, enabling testing and evaluation of the determined relationships, and identifying asynchrony in the balanced development of green investments and energy efficiency.

Keywords: seaports; energy efficiency; green strategy; environmental performance; green investments; energy consumption; renewable energy sources; CO_2 emissions; economic growth

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1. Introduction

The port and maritime transport sector is essential to the global economy, enabling most (80%) of the international trade in goods carried by sea [1–5]. The sector is also substantially energy dependent, with increasing consumption due to continuous growth in the global maritime trade. According to the United Nations Conference on Trade and Development (UNCTAD) [3], maritime trade is expected to grow by over 3% from 2024 to 2028. With the growth of global maritime trade and port infrastructure development, ports have become significant energy consumers [6], providers, and energy processors [7]. Many ports have developed into industry and energy hubs [8]. The urgency of the energy transition to reduce consumption and optimize energy efficiency is at the core of green strategies and the port sector's environmental performance, highlighting the issue's importance and immediacy.

Moreover, the port and maritime transport industry cause a considerable environmental footprint, adversely affecting natural resources, marine biodiversity, and the ecosystem. For instance, the sector generates notable and increasing greenhouse gas (GHG) emissions, with around a 3% share in the global emissions from human activities [1,2,7,9–11], thus contributing to climate change. There is an urgent need to address greenhouse gas emissions and energy efficiency, as these are critical considerations related to climate change [12]. Ports usually operate in climate change-sensitive areas [13]. A growing number of ports, e.g., the Port of Rotterdam and the Port of Antwerp-Bruges (Belgium), the Port of Barcelona (Spain), the Port of Gdansk (Poland), the Port of Gothenburg (Sweden), the Port of Raahe (Finland), etc. [4,14–19], strategically orient toward energy efficiency and zero GHG emissions and invest in greening their operations.

Ports are complex waterfront and land-related facilities that integrate diverse transport modes and industrial activities and, therefore, have a significant impact on the environment, particularly air quality, as an essential concern for European ports [4,5]. Moreover, as a critical priority in the sector, air quality focuses on emissions generated from port operations (i.e., port activities and infrastructure, ships' and vehicles' emissions, port hinterland transport system and logistics, industrial activities, and other related traffic) [4,5,20].

The complexity of port management and governance, considering the diverse port activities and stakeholders, makes greening a comprehensive and demanding task. There is a growing number of articles, studies, strategies, and reports on numerous areas of port greening and diverse environmental challenges (e.g., [4,5,8,9,11,14,17–50]. The literature classifies port greening into specific groups, each representing diverse aspects of the environmental footprint resulting from port operations (e.g., energy consumption, air quality, noise pollution, and biodiversity impacts). Greening has become one of the essential priorities in port management and governance. Moreover, green ports actively seek to engage users in responsible practices that promote the sustainable utilization of port space and the surrounding environment [51]. Developing a green port requires diverse actions (e.g., setting standards for emissions and waste and designing green zones in port areas) that make a port and its surroundings greener and more sustainable [52]. Furthermore, greening ports requires balancing economic and environmental concerns, minimizing the environmental footprint while fostering long-term economic growth [24]. Energy efficiency is crucial for economic viability and environmental conservation and, thus, a critical factor in greening ports [4,31]. Ports offer great potential for reducing energy consumption and transitioning to green energy [17].

The ESPO [4,5,8,31] has identified energy efficiency as one of the top ten priorities for European ports. These priorities reflect the varying levels of commitment that port authorities can undertake to enhance their energy efficiency [19]. Energy production is a significant source of CO_2 emissions. In response, ports invest in strategies to minimize energy consumption and enhance energy efficiency. Deloitte [30] emphasizes the pivotal role of energy in the European economy, with energy efficiency being a cornerstone of the EU's energy policy. The European Union (EU), the third-largest global energy consumer (11%) after China (23%) and the United States (17%), relies heavily on fossil fuels for 72% of its energy supply, posing challenges for achieving its climate targets. Recent advancements highlight the growing importance of integrating renewable energy sources (RES), such as wind and solar power, into port operations to reduce carbon footprints and enhance energy self-sufficiency [21,53]. For instance, the Port of Rotterdam's adoption of hydrogen systems and renewable energy hubs exemplifies the EU's shift toward decarbonized port infrastructure, leveraging its Renewable Energy Community framework [53,54]. Similarly, Italian ports like Anzio use digital twin technologies to optimize energy efficiency and achieve zero-energy operations [21]. It is important to note that green investments in energy efficiency technologies, such as cold ironing and LED systems, are playing a significant role in accelerating decarbonization, with promising GHG reductions reported at ports like Antwerp–Bruges and Hamburg [53,55]. These integrated approaches underscore the synergy between energy efficiency, renewable energy adoption, and targeted green financing in advancing sustainable port operations across Europe [53,54].

The essential idea of energy efficiency is using less energy to achieve the same or improved level of output or service [4,31,56]. Moreover, energy efficiency, i.e., reducing energy consumption, is directly related to minimizing emissions and green transitioning, which leads to mitigating climate change. Transportation, industrial processes, and power production generated about 37 billion tons of carbon dioxide emissions in 2022 [57]. Moreover, the level of carbon concentration in the atmosphere has almost doubled (from 280 to 420 ppm, molecules per million) since the Industrial Revolution [58].

The role of ports in mitigating climate change, primarily by reducing greenhouse gas (GHG) emissions in their operations, has gained increasing attention among scholars and practitioners. Recent studies [59,60] highlight innovative green strategies such as the adoption of renewable energy technologies (RETs), digitalization of port operations, and energy efficiency measures as pivotal for decarbonizing port activities, including onshore power supply, alternative fuel bunkering, and electrification of port equipment. Ports like Rotterdam and Antwerp–Bruges exemplify this shift by integrating renewable energy systems and investing in carbon capture and storage (CCS) technologies [60,61]. Strategies also include retrofitting yard trucks to electric or LNG systems [62], integrating wave energy converters in breakwaters [63], and implementing energy efficiency measures like smart grids and energy management systems [64]. Additionally, collaborative frameworks, such as emissions trading systems (ETSs) in the maritime sector, incentivize stakeholders to align their operations with stringent environmental regulations, further accelerating the reduction of carbon footprints [65,66]. This surge in interest underscores the pivotal role ports play in driving sustainability and combating climate change.

Deloitte [30] highlights that reducing GHG emissions indicates energy efficiency, renewable energy sources, and climate change mitigation and suggests that this indicator should be promoted for assessing the broader impacts of energy efficiency policies on overall energy and climate strategy and to prioritize energy efficiency measures based on their overall impacts. While climate change may not be directly monitored, tracking energy efficiency, air quality, and carbon footprint can provide valuable insights [12]. Pursuing net zero and sustainability, now firmly established as policies with clear objectives, targets, and timelines, is paramount in shaping political, economic, and social agendas [12].

There is a growing urge to stop the increase in GHG emissions to avoid and combat increasing and more frequent catastrophic droughts and other extreme weather events, such as hurricanes and heavy rainfall [67–69]. Also, ports worldwide have recognized their responsibility for GHG emissions and are increasingly investing in renewable energy sources (e.g., solar, wind, hydro, and nuclear). Bilgili et al. [67] point out that energy efficiency and renewable energy can significantly help mitigate CO_2 emissions. Conventional energy sources, i.e., fossil fuels, are responsible for around 40% of GHG emissions [70]. Burning fossil fuels for energy production increases CO_2 concentrations [70–72]. Therefore, as energy-intensive activities, port operations contribute to climate change [41,72] and impose adverse environmental and energy effects [36]. Carfora and Scandurra [73] note that shifting to renewable energies may contribute to a more resilient and stable energy landscape by protecting countries from the volatility of traditional energy markets and geopolitical conflicts. The authors highlight that green energy infrastructures are essential for addressing energy poverty's immediate and long-term challenges. Moreover, in their energy transitioning, ports tend to replace conventional fossil fuels (e.g., diesel) with types that generate less CO_2 (e.g., LNG) for onshore power supply (OPS) for ships. Recently, LNG-related projects have been growing, particularly in the shipping sector [74].

Energy transition is changing the port landscape, bringing numerous opportunities to many ports, e.g., green energies, and requiring substantial investments to turn them into energy hubs [16]. Moreover, Rodrigue et al. [7] highlighted that the energy transition presents a unique opportunity for ports to evolve into energy platforms with diverse and interconnected roles. They can serve as energy transport platforms (gateways for the exports or imports of energy products, including their temporary storage), energy transformation platforms (sites for the energy industry to perform their activities), and energy generation platforms (provide conventional and alternative energy sources to their users) [7]. Therefore, ports are beginning to play a crucial role in the global energy transition. The EU strategically aims for a net-zero GHG emissions economy, striving to achieve climate neutrality by 2050 and positioning Europe as the world's first major economy to do so [75,76]. Also, the European Commission's (EC) green initiatives strive to accelerate the transition from predominantly fossil-based energy to renewable sources, aiming to reduce GHG emissions by 55% by 2030 [75]. Concerning the clean energy transition, the EU's new renewables target is a share of 32% of total sources by 2030 [76]. Moreover, in 2021, global investments in energy transition technologies (e.g., renewable energy, energy efficiency and storage, hydrogen, electrified transport and heat, and carbon capture and storage) surged to USD 1.3 trillion [77].

Numerous initiatives in ports are aimed at greening transport, entering and transporting renewable energy, and greening (port) industry [17]. For instance, Guo et al. [39] proposed a hybrid power system (i.e., a set of multiple generators), suggesting an approach that enables ports to achieve low fuel consumption, emissions, and noise and simultaneously high efficiency, environmental protection, flexibility, and safety. Hybrid power systems improve energy savings and lower emissions [39,59]. Electrification of port equipment reduces noise and air pollution, benefiting local communities [7,41,78]. By investigating port competitiveness and minimizing adverse environmental impacts, Aksoy and Durmusoglu [32] proposed using renewable and environmentally friendly energy generated using the Organic Rankine Cycle (ORC) method as an Onshore Power Supply System (OPS) to reduce ship emissions. Renewable energy installations, such as wave energy converters in Spanish ports, demonstrate significant potential for emissions reduction [42]. Bekun et al. [79] proved that renewable energy reduces carbon emissions while transitioning to renewable energy generates innovation and economic growth. Lu and Huang [47] found that government policies are crucial in promoting green investments, underlining that regulations and incentives encourage green practices (e.g., SPS for ships and emission-based port fees). Iris and Lam [41] note that research on energy efficiency and greening ports has increased, underscoring the valuable contributions of scholars in this field.

Furthermore, Acciaro [80] highlighted diverse examples of green initiatives (including energy efficiency solutions) by analyzing numerous ports worldwide, e.g., the Port of Hamburg (Germany), the Port of Los Angeles (Long Beach, CA, USA), the Port of Zeebrugge (Belgium), the Port of Rijeka (Croatia), the Port of Singapore (Republic of Korea), the Port of Antwerp (Belgium), and the Port of Genoa (Italy). The author [80] identified various green innovations and solutions in the observed ports, for instance, environmental energy-related plans, quay electrification of ship-repair docks, cold ironing, switching to renewables (e.g., windmills), different investment programs (e.g., vessel speed reduction programs, green solutions for vehicles, i.e., clean trucks, electrification/greening of autonomous vehicles, etc.). Case studies such as the Port of Dongjiakou (China) demonstrate the importance of predictive modeling for sustainable port planning and operational improvements, highlighting pathways for balanced economic and environmental outcomes [81]. Satta et al. [66] emphasize that the effective implementation of port' green strategies is contingent on the active involvement of stakeholders and the enhancement of employee engagement in sustainability initiatives. This underscores the integral role of the stakeholders in the process and the collaborative nature of implementing green strategies.

The green transition toward port decarbonization through zero CO_2 emissions and by improving energy efficiency, switching to renewable energies, and using low-emission energy sources is a long-term process [82]. Thus, one of the critical problems in the port greening process is the asynchrony in the balanced development of green investments and energy efficiency. Therefore, this paper investigates the relationship between green variables in port operations and analyzes the asynchrony between energy efficiency and green investments.

Despite the solid and growing body of literature, it is essential to highlight that investigating energy-related and greening challenges in port management and governance requires further research using a scientific approach and methods. Thus, this manuscript firstly sets up an energy efficiency and greening ports triangle (EEGP triangle) presented in Figure 1 to investigate energy transition and green performance management in the port sector.

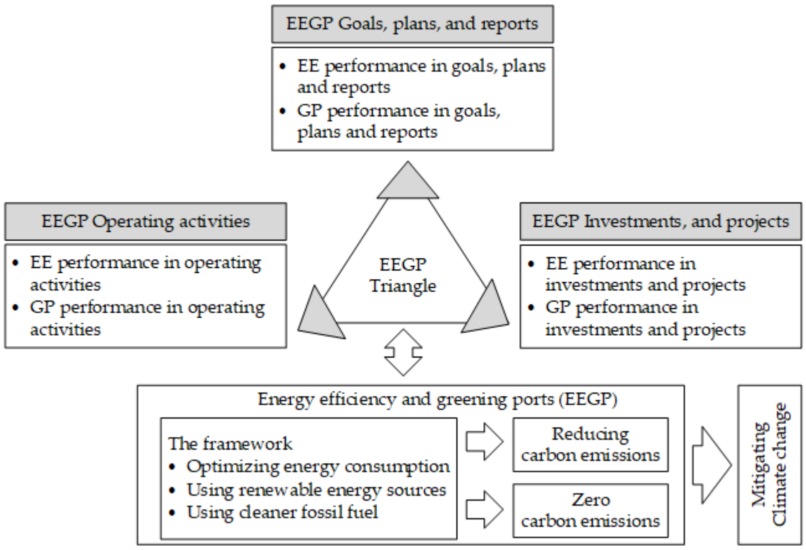


Figure 1. The energy efficiency and greening ports triangle (EEGP triangle) (source: developed by the authors).

As presented in Figure 1, the EEGP triangle addresses the energy transitioning and greening issues in the three vital aspects of the ports' management as follows: (i) in ports' goals, plans, and reporting, (ii) in ports' operational activities, and (iii) in ports' investments and projects. Also, Figure 1 shows the EEGP framework that focuses on optimizing energy consumption and using renewables in ports, which leads to reducing or zero carbon emissions. The outcome of ports' energy transitioning and greening leads to mitigating climate change. This manuscript uses the EEGP triangle to identify indicators (performance) across port operations and management related to energy transition and environmental factors.

2. Materials and Methods

This paper analyzes the cause-and-effect relationship between diverse green variables in port operations to analyze the asynchrony between energy efficiency and the progress of green investment implementation. To conduct the research, the paper created the research model, as presented in Figure 2.

The research model (Figure 2) consists of the following steps: (i) literature background; (ii) identification of the energy efficiency and the greening ports indicators (EEGP indicators) in the business triangle; (iii) selecting a set of variables (measures) to analyze the research problem; (iv) setting research hypotheses (H1 and H2); (v) testing the hypotheses (H1 and H2) by using descriptive statistics and convergence analysis to perform cause-and-effect investigation and estimation of EEGP variables (v1, v2, v3, and v4) and asynchrony between energy consumption and green investments in the example of three European seaports located in three different countries and sea basins (Port of Split, Croatia, Adriatic Sea; Port of Gdansk, Poland, Baltic Sea; Port of Pivdennyi, Ukraine, Black Sea); (vi) proposing an energy efficiency and greening ports framework (EEGP Framework); and (vii) providing conclusions.

The activities of the three investigated ports (Port of Split, Port of Gdansk, and Port of Pivdennyi) to complete the research goals (test the hypothesis, perform cause-and-effect investigations and estimation of EEGP variables, and asynchrony between energy consumption and green investments) are vital at the local and regional levels regarding transport, economy, community, and geopolitical situation.

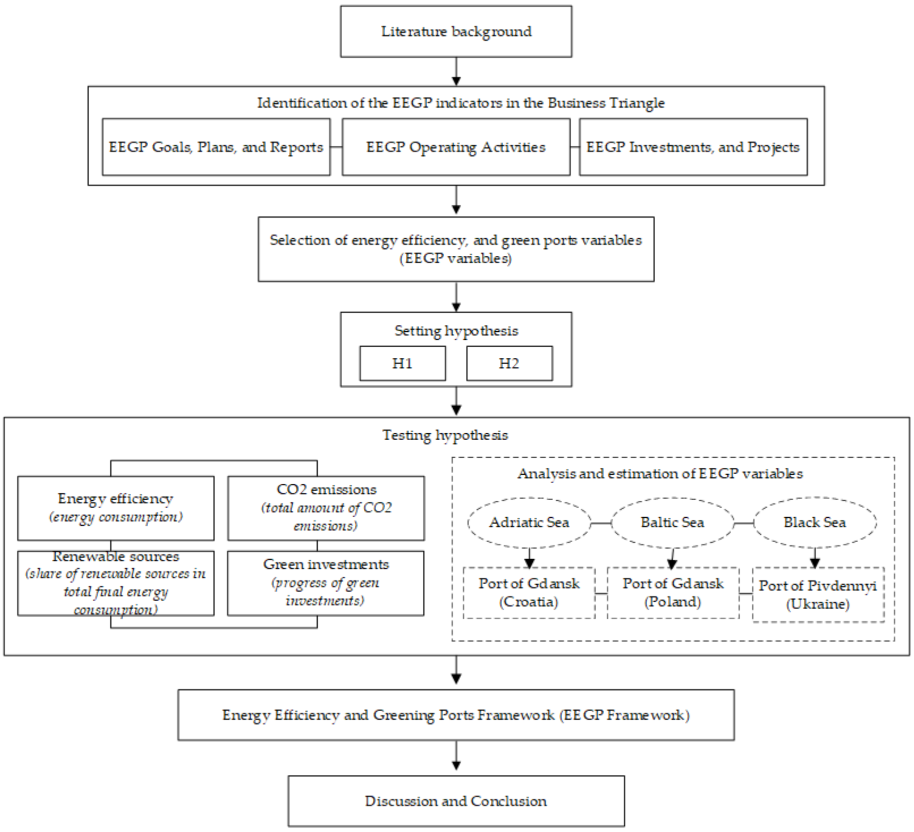
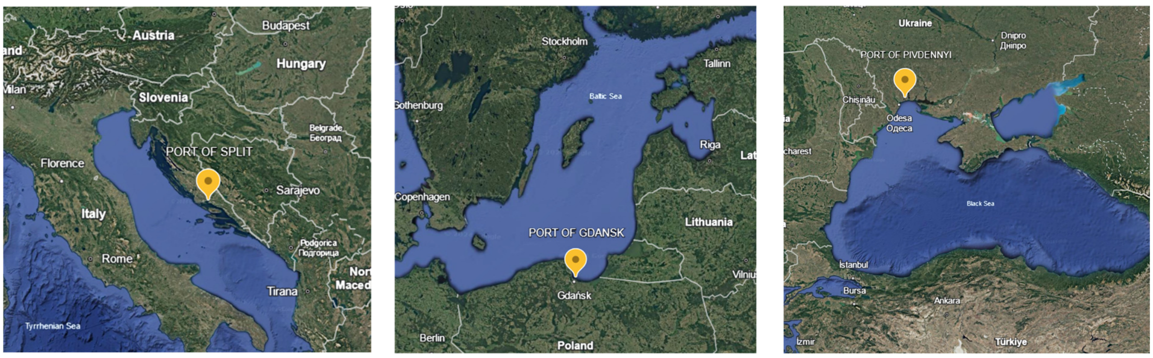


Figure 2. The research model (source: developed by the authors).

2.1. Description of Investigated Ports

Figure 3 shows the geostrategic locations of the three investigated ports, the Port of Split (Croatia, Adriatic Sea), the Port of Gdansk (Poland, Baltic Sea), and the Port of Pivdennyi (Ukraine, Black Sea).



(**a**) Port of Split (**b**) Port of Gdansk (**c**) Port of Pivdennyi

Figure 3. The geostrategic location of the three investigated ports: (**a**) the Port of Split (Croatia, the Adriatic Sea) [83], (**b**) the Port of Gdansk (Poland, the Baltic Sea) [84], and (**c**) the Port of Pivdennyi (Ukraine, the Black Sea) [85].

External factors influence port operations and management regarding their energy transition and greening, e.g., technological, economic, eco-environmental, and political. For instance, Ukraine's geo-political situation impacts the ports' operations in the Black Sea and the Baltic Sea basins. Consequently, the Port of Pivdennyi (Port Pivdennyi—research was conducted in two parts (periods) within the framework of the Ukrainian Black Sea Corridor of the Grain Initiative: from 2017 to 2021 (pre-war period) and from 2022 to 2023) is facing diverse risks of strategic importance. The disruptions from the war in Ukraine are considerably changing shipping and trading patterns, causing an increase in cargo distances and ton-miles, particularly for strategic commodities (e.g., oil and grain) [3]. Ukraine's geopolitical situation has reshaped the European maritime trade, notably influencing green policies, strategies, and investments at the EU and member-state levels.

2.1.1. Port of Split

The Port of Split, strategically located as the largest passenger port in Croatia, the second largest in the Adriatic Sea, and the fifth largest in the Mediterranean, is a crucial driver of the region's development. It primarily serves passenger-cargo vessels and cruise ships, attracting over 5 million visitors annually [86]. In 2022, traffic peaked at over 5.3 million passengers and 278,103 cruise passengers. Regarding cargo traffic, the Port of Split ranks third in Croatia, handling 3,365,698 tons of load in 2022 [87], following the Port of Rijeka and the Port of Ploče. Moreover, the Port of Split is on a significant growth trajectory with six functionally different harbor basins in four cities. It is one of the twenty largest passenger ports in the EU, with increasing importance and influence.

Over the last two decades, the number of passengers and vehicles in the City Port, the central passenger port basin, has doubled to almost six million passengers and a million vehicles a year. In 30 years, traffic projections of the Port's authority indicate that traffic will double. The main challenge is to avoid significant congestion-caused environmental damage and shift as much traffic as possible from the road to the sea. The port aims to relocate more than 200,000 trucks from the City Port basin in the city center and move as much passenger traffic as possible from the Split Airport to the port from the road to the sea. The port aims to revitalize the geostrategic position of cargo transport [14].

Complementing its infrastructural works, the Port of Split is unwavering in its commitment to sustainable development. This commitment is not just about becoming a smart port to adapt to the rapidly changing global environment characterized by climate change and conflicts. The Port of Split is strategically oriented toward greening by introducing new digital technologies and implementing sustainable development policies. This commitment is crucial, given the City Port's integral role in Split's city center, next to the ancient city center. The port's dedication to sustainability ensures that its operations are efficient and environmentally responsible, providing a model for other ports to follow.

2.1.2. Port of Gdansk

The Port of Gdansk is the largest in Poland, the sixth-largest economy in the EU, and the 20th-largest in the World [88]. The port is ranked 9th among the most significant European ports and 2nd among the largest ports on the Baltic Sea. The port is also ranked first in the Baltic Sea in terms of the number of containers handled, and it is said to be the fastest-growing port of the last decade [89]. Since 2020, the Port of Gdansk has recorded an annual increase in the tonnage of cargo handled. In 2023, the Port of Gdansk handled as many as 81 million tons of cargo, ranking it as the ninth cargo port in Europe [89]. The increase is due to the war in Ukraine and the raw material crisis, resulting in increased handling of grain and energy raw materials. According to the latest data (2023), the annual number of commercial ship' calls at the Port of Gdansk was 362,615 regular connections. An estimated 2532 trucks and 1440 wagons daily are handled at the Port of Gdansk [88].

The port has extensive investment areas, is free of tides and icing, and is called a deepwater port (17 m deep) with the capacity to receive the largest vessels with a draft of up to 15 m in the Outer Port [88]. The Port of Gdansk, situated in the central part of the southern coast of the Baltic Sea in one of the fastest-growing regions in Europe, is an important international transport hub. In line with EU strategy, the Port of Gdansk is a significant link in the Trans-European Transport Corridor VI, connecting Scandinavian countries with South-Eastern Europe.

The Port of Gdansk has two areas with naturally varying exploitation parameters: The Inner Port, situated along the Dead Vistula and the Port Channel, and the Northern Port, with direct access to the Gdansk Bay. The Inner Port comprises a container terminal, a base and terminal for passenger ferries and ro-ro ships, a base for the transshipment of passenger cars and citrus fruit, a base for the handling of sulfur and other bulk cargoes, and a base for the transshipment of phosphate. Due to the installed equipment and infrastructure, the remaining quays have a universal character and enable the transshipment of conventional general cargo and bulk cargo such as metallurgical products, heavy and oversized pieces, cereals, fertilizers, ore, and coal.

2.1.3. Port of Pivdennyi/Odesa (Ukraine)

The Port of Pivdennyi belongs to the Black Sea basin region and is located on the northwestern coast in the water area of the non-freezing Maly Ajalytsky estuary of the Odesa region (Ukraine) [90]. Its geographical location is the space of NATO's geopolitical interests, the EU's good neighborhood policy, and the strategic imperatives of the Silk Road from Asia to Europe. During Russia's military aggression against Ukraine, the Port of Pivdenny demonstrated high competitiveness compared to other ports of Ukraine (Odesa and Chornomorsk) due to its geographical location, a year-round guarantee of safe shipping, and uninterrupted cargo operations.

The Port of Pivdennyi is the deepest and most profitable port in Ukraine. The port is strategically important for ensuring the operation of the Danube cluster of ports from the transition of river logistics to the sea. The depth of the approach channel and berths allows for the reception of a large fleet with a total carrying capacity of up to 200,000 tons. The port is traditionally the leader among the ports of Ukraine in cargo turnover (30% of the cargo turnover in the country). The Port of Pivdennyi has a developed infrastructure and energy supply system. Thus, it can receive vessels with a draft of up to 18.5 m and a carrying capacity of up to 175 thousand tons. There are 30 moorings with a total length of 5.9 km in the port water area. The Port of Pivdenny is a universal port specializing in the transshipment of chemicals and fertilizers, bulk, and general cargo [91]. The port participated in the Grain Initiative but, like other Ukrainian Black Sea ports, was blocked by the Russian fleet in 2023 and resumed operations in May 2024 [92].

2.2. Research Variables and Hypothesis

As previously described (in the Introduction), this research paper investigates the relationship between green port performance or variables (v1–v4) related to carbon emissions (v1), energy efficiency (v2), renewable energy sources (v3), and green investments (v4). The paper further analyzes energy efficiency and green investments to prove the existence of asynchrony in the progress of implementing green investments (v4) and the balanced development of energy efficiency (v2).

To investigate the relationships, as mentioned earlier, between the variables (v1–v4) and further analyze selected variables (v2, v4), this research sets the following two hypotheses:

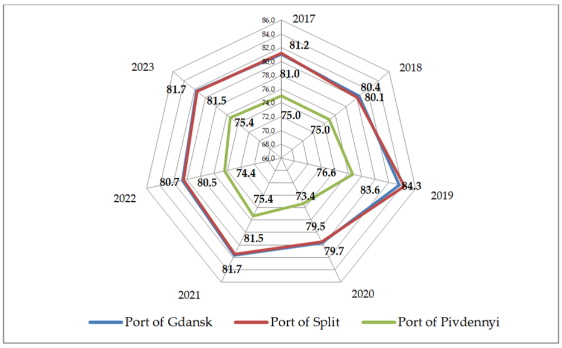
H1: *There is a relationship between the amount of CO_2 emissions and the level of energy efficiency, the specific weight of renewable sources in the total final energy consumption, the volume of green investments, and CO_2 emissions in ports.*

H2: *There is asynchrony in the progress of implementing green investments and the balanced development of energy efficiency.*

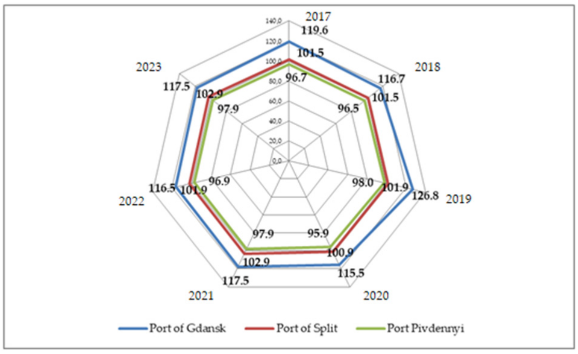
The institutional determinants of port-centric energy production, ship energy supply systems, and renewable energy production determined the existence of asynchrony in the progress of implementing green investments and the balanced development of energy efficiency (H2). The integration of port energy systems elicits gaps in energy efficiency between the ports of the Adriatic Sea (Port of Split), the Baltic Sea (Port of Gdansk), and the Black Sea (Port of Pivdennyi).

The data were collected via in-depth interviews with port managers and administrative staff. A semi-structured questionnaire was developed based on the literature (presented in the Introduction). The empirical research was conducted from 2017 to 2023 by interviewing three respondents per investigated port in each observed year, for a total of twenty-one interviews.

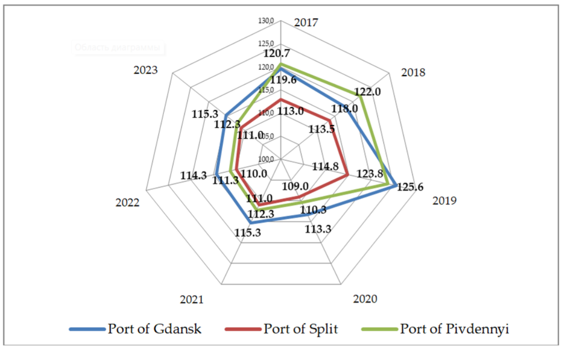
The estimated determinants of green and environmental indicators in port operations were established. Figure 4 presents the results of green performance analysis (variables v1–v4) in three ports: the Port of Split (Adriatic Sea), the Port of Gdansk (Baltic Sea), and the Port of Pivdennyi (Black Sea).



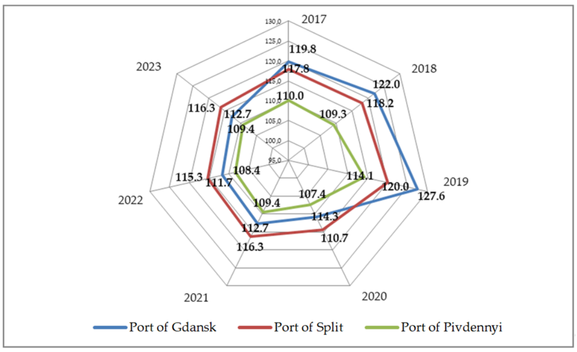
(**a**) Carbon emissions



(**b**) Energy efficiency



(**c**) Renewable energy sources



(**d**) Green investments

Figure 4. The green port performance (variables) of the three investigated ports: (**a**) carbon emissions (v1), (**b**) energy efficiency (v2), (**c**) renewable energy sources (v3), and (**d**) green investments (v4) (source: developed by the authors).

Figure 4 shows the dynamics of the four variables (v1–v4) on the seven spider graph axes (a–d), representing changes in each variable in the percentage rate (growth rate) over seven observed years (2017–2023) in the studied ports. Regarding the changes in the first variable (v1), Figure 4 (graph a) shows the reduction in carbon emissions at all three ports over the seven years, with the Port of Gdansk reaching the highest reduction (maximum 84.3% in 2019) on average, followed by the Port of Split with a slight difference in this performance (maximum 83.6% in 2019), while the Port of Pivdennyi had a 10% lower CO_2 emissions reduction (maximum 76.6% in 2019) on average compared to the first two ports. Regarding the changes in the second variable (v2), Figure 4 (graph b) shows that all three ports reached the targeted level of energy efficiency considering their green strategies and energy efficiency goals. Like in the first variable, the Port of Gdansk had the best performance in energy efficiency compared to the other two ports, reaching a higher level of performance than planned (maximum 126.8% in 2019) in terms of reducing energy consumption. The Port of Split also reached a higher level of performance than planned in energy efficiency (maximum 102.9% in 2021 and 2023), while the Port of Pivdennyi almost reached the planned goal in energy efficiency (maximum 98% in

2019). Regarding the changes in the third variable (v3), Figure 4 (graph c) shows that the investigated ports reached the planned goals (over 100%) regarding using renewable energy sources in total energy consumption. Like with the first two variables (v1 and v2), the Port of Gdansk had the highest performance (maximum 125.6% in 2019) in using renewable energy sources in total energy consumption, followed by the Port of Pivdennyi (maximum 123.8% in 2019), and the Port of Split (maximum 114.8% in 2019). Regarding the changes in the fourth variable (v4), Figure 4 (graph d) shows that all three ports achieved progress in implementing green investments (over 100%). The best-performing port in green investments over the seven observed years is the Port of Gdansk (127.6% in 2019), followed by the Port of Split (120.0% in 2019) and the Port of Pivdennyi (114.1% in 2019). The determinants presented in Figure 4 have significant practical implications, guiding management decisions regarding rethinking green strategies and parameters of environmental sustainability in ports, namely the volume of green investments, CO_2 emissions, and the share of renewable sources in final total energy consumption. Measuring environmental performance is one of the most complex tasks in managing and governing ports, and this research sheds light on this intricate process [52].

Based on the bibliometric analysis (e.g., [20,26,93–98]), it was established that scientists also investigate these determinants when evaluating the port's energy efficiency.

Figure 5 shows how using renewable sources in port operations and green investments in ports' energy transition decrease carbon emissions, i.e., leading to energy efficiency with zero CO_2 emissions.

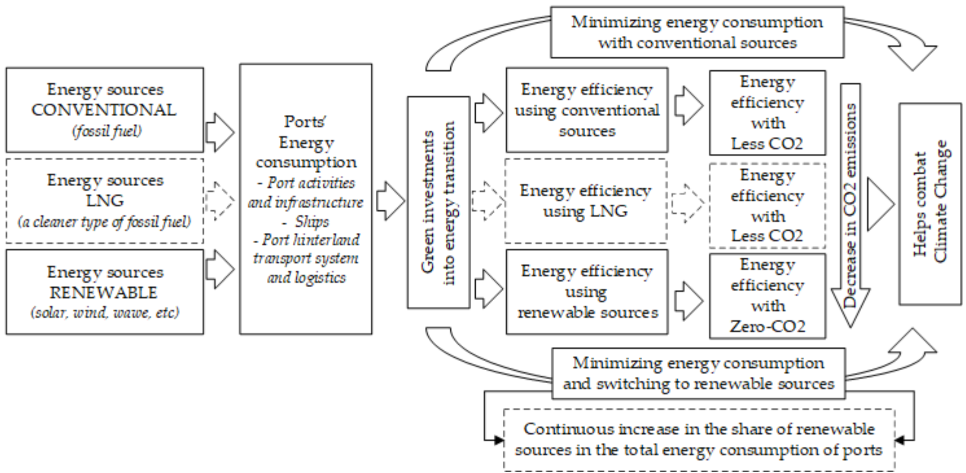


Figure 5. Energy efficiency and greening ports: the effects of using renewable sources (source: developed by the authors based on [4–6,8,17,20,26,30,31,41,52,93–100].

As shown in Figure 5, ports use conventional and renewable energy sources for operations (port activities and infrastructure, ship onshore power supply, and port hinterland transport system and logistics). Given the diversity of port operations and services, the port's energy consumption can be considered 'wasteful' [13]. Energy consumption and port greening are central to any port's energy transition plan [100]. Ports generate environmental impacts through cargo handling, maritime and land transport networks, energy production, distribution, and industrial, logistics, and distribution activities [52]. Furthermore, ports and terminals have a pervasive transportation network, and their heavy machinery consumes vast amounts of energy and emits considerable amounts of carbon dioxide. Thus, ports invest in the energy transition to minimize energy consumption and decrease their CO_2 emissions. Researchers have studied how ports can reduce energy consumption and improve energy efficiency. For instance, Wilmsmeier and Spengler [6] explored ways to increase energy efficiency by using more modern cargo handling equipment, diversifying port and terminal fees, and implementing energy management systems.

Port energy consumption is also highly related to the onshore power supply (OPS) for ships. Therefore, switching to renewable sources or using cleaner fossil fuels like LNG as part of an energy transition reduces CO_2 emissions, as presented in Figure 5. Ports can also use green practices for vessels regarding their energy efficiency and CO_2 emissions via penalties or incentives for using cleaner power or LNG. Similar to using LNG on the open sea, LNG on vessels approaching the port and within the port area is an attractive option for reducing emissions [101]. Therefore, to make ports greener, reducing fossil fuel consumption and shifting the focus to renewable energy is vital [31]. Whereas high-volume fossil fuel cargo is traditionally the primary source of income for some ports (throughput dues and rental and leasehold income), there is now a tendency to move away from fossil fuels due to the need for a transition to a carbon-neutral economy and a decarbonized shipping sector (with a critical role for alternative fuels) [17]. Energy consumption is essential in port operations and port-related economic activities; with energy costs increasing for land-based industries, port authorities also strive to reduce fuel consumption [6], which leads to decreasing carbon emissions.

As vital nodes in maritime transport, ports are crucial in the sector's decarbonization and fossil-free transition [4,5,12,14,15,18,99,100]. Shifting from fossil fuels to electricity and alternative fuels in port operations and vessels is not just a trend but a necessary and urgent step that enables ports to become energy hubs, providing power to their internal operations, port tenants, and external users (surrounding energy systems) [4,5,100]. Rodrigue et al. [7] underline that the share of energy consumption from renewable sources in all new power generation is expected to be around 60% by 2040. More importantly, energy efficiency and renewable energy have the potential to provide over 90% of the required energy-related CO_2 emission reductions, making them essential for the energy transition [102].

Energy efficiency aims to optimize energy consumption, reduce waste, and mitigate the environmental impacts of energy production and consumption [4]. Many ports and terminals actively strive to improve energy efficiency due to the urgent need for climate change mitigation, exacerbated by the current energy crisis. The port industry has prioritized sustainability, making energy efficiency essential for reducing energy consumption, lowering emissions, and transitioning toward greener operations [4].

3. Results

As previously pointed out, this manuscript aims to research greening ports in terms of the relationship between diverse green port performance, i.e., variables (presented in Figure 4) that relate to decarbonization by decreasing CO_2 emissions, energy efficiency, renewable energies, and green investments. The results of testing hypotheses (H1 and H2) are presented below, underscoring the importance of these findings in understanding and improving the sustainability of port operations.

3.1. The Relationship Between the Green Variables

This research paper assumes a relationship between the amount of CO_2 emissions and the level of energy efficiency, the specific weight of renewable sources in the total final energy consumption, the volume of green investments, and CO_2 emissions in ports (H1). The estimated determinants of green and environmental indicators in port operations were established, which are important when making management decisions regarding the rethinking of green strategies and parameters of environmental sustainability in ports, namely the volume of green investments, CO_2 emissions, and the specific weight of renewable sources in final energy consumption. Based on the bibliometric analysis [20,26,93–99], it was established that scientists also investigate these determinants when evaluating the port's energy efficiency. Therefore, this paper has chosen the following indicators to assess cause-and-effect relationships: the volume of green investments, CO_2 emissions, and the share of renewable sources in total final energy consumption.

The formed hypothesis is based on the functional relationship and linear dependence of one indicator on another or several others [103]. Such an assumption (H1) is described by a static approach based on regression analysis of data, which is the mathematical basis for building hypothetical models. Thus, to test the hypothesis, a regression linear model (1) was formed:

$$lnLEP_{it} = \alpha lnGI_{it} + \beta lnEC_{it} + \gamma lnSRS_{it} + \varepsilon_{it} \quad (1)$$

where α, β, and γ are the regression parameters that were estimated and explain the elasticity of output, referring to the level of energy efficiency of the ports (*LEP*) depending on the level of green investments (*GI*), CO_2 emissions (*EC*), and the share of renewable sources in the final total energy consumption (*SRS*); ε is the error term; $i = 1,\ldots, n$; $t = 1,\ldots, T$. Testing the presence of unit roots proved that the formed data sample is stationary.

In the next stage, the long-term relationship between the studied variables was assessed (Table 1).

Table 1. Results of assessing the long-term relationship between the studied variables.

Variables		FMOLS		DOLS	
Dependent	**Independent**	**Coefficient**	**Probability**	**Coefficient**	**Probability**
LEP	*EC*	−0.16	0.05 **	−0.28	0.00 *
	SRS	0.46	0.00	0.32	0.00 *
	GI	0.71	0.00	0.72	0.00 *
EC	*LEP*	−0.24	0.02 **	−0.35	0.00 *
	SRS	−0.41	0.00 *	−0.28	0.00 *
	GI	−0.53	0.00 *	−0.64	0.00 *
SRS	*LEP*	0.35	0.00 *	0.38	0.00 *
	EC	−0.3	0.00 *	−0.26	0.00 *
	GI	0.34	0.00 *	0.37	0.00 *
GI	*LEP*	1.01	0.00 *	0.98	0.00 *
	EC	0.57	0.33	0.68	0.56
	SRS	0.53	0.00 *	0.42	0.00 *

Note: * and ** statistical significance at the 1% and 5% levels. Legends: *LEP*—port energy efficiency level; *EC*—CO_2 emissions; *SRS*—share of renewable sources in the total energy consumption; *GI*—green investments (source: developed by the authors).

The Granger Causality test was performed in the next step to evaluate the cause-and-effect relationships between the identified determinants. The results of the causality assessment are presented in Table 2.

Table 2. Results of the assessment of causal relationships between the studied variables.

Hypothesis	Zbar-Statistic	W-Statistic	Probability	Connection Type
LEP→*EC*	2.72	2.03	0.04 **	Unidirectional relationship
EC→*LEP*	2.43	1.55	0.12	
GI→*EC*	2.61	1.85	0.06 ***	Bidirectional relationship
EC→*GI*	1.8	0.5	0.02 **	
SRS→*EC*	4.89	5.63	0.002 *	Bidirectional relationship
EC→*SRS*	1.67	0.29	0.04 **	
GI→*LEP*	2.60	1.83	0.04 **	Bidirectional relationship
LEP→*GI*	1.17	0.55	0.06 ***	
SRS→*LEP*	3.68	3.62	0.0003 *	Unidirectional relationship
LEP→*SRS*	1.67	0.28	0.78	
SRS→*GI*	2.57	1.78	0.03 **	Unidirectional relationship
GI→*SRS*	1.55	0.08	0.93	

Note: *, **, and ***—statistical significance at the 1%, 5%, and 10% levels (source: developed by the authors).

The results of this study confirm the existence of a unidirectional relationship between the following variables: (i) the volume of CO_2 emissions and the level of energy efficiency and (ii) the specific weight of renewable sources in final energy consumption, volumes of green investments, and CO_2 emissions. A bidirectional relationship was found between the following variables: (i) the level of energy efficiency of the port and the specific weight of renewable sources in the final energy consumption; (ii) the level of energy efficiency of the port and the amount of green investment and volumes of CO_2 emissions and green investments.

3.2. The Asynchrony in the Progress of Implementing Green Investments and the Balanced Development of Energy Efficiency

This research paper assumes that there is asynchrony in the progress of implementing green investments and the balanced development of energy efficiency (H2). The methodological basis for the assessment was the concept of σ- and β-convergence. The related research papers results [97,98] indicate that scientists use integrated energy efficiency indicators (energy use/intensity of energy consumption, energy productivity, energy intensity, etc.) to assess σ- and β-convergence. At the same time, the rapid growth of negative consequences caused by environmental contradictions and an increase in the volume of energy consumption and CO_2 emissions requires the development of effective mechanisms for solving and eliminating the abovementioned problems. In turn, this will enable an increase in ports' energy efficiency and the implementation of green strategy parameters for environmental sustainability.

This manuscript aims to assess the level of asynchrony of the energy strategy of the investigated ports—Gdansk (Poland), Split (Croatia), and Pivdennyi (Ukraine)—based on the concept of σ-convergence and to determine the sensitivity of ports to changes in national politics (GDP and globalization) using the concept of β-convergence. Therefore, the methodological basis for the analysis is the concept of σ-convergence and β-convergence.

To estimate the σ-convergence, the standard deviation between ports i in the corresponding time period t was used (2):

$$\sigma_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(lnSSE_{jit} - \overline{lnSSE_{jit}}\right)^2} \quad (2)$$

where *SEE*—the energy efficiency sub-indices; *j*—energy efficiency, distribution of energy resources, and green investments; *N*—the number of ports; *i*—port; *t*—time.

Thus, according to the concept, σ-convergence between ports is observed when the *rms* deviation decreases, while divergence occurs otherwise. The regression equation was used to estimate β-convergence as part of the study (3):

$$ln\left(\frac{SSE_{jit}}{SSE_{jit-1}}\right) = \alpha + \theta ln\left(SSE_{jit-1}\right) + \varphi X_{it} + \varepsilon \quad (3)$$

where X is the matrix of additional endogenous variables that indicate the port's features and allow one to maintain the stationarity of the variables at the same level; α, θ, and ϕ are the calculated variables; and ε are the remainder.

If θ is less than zero, then convergence exists for the selected parameters. The absolute value of the parameters characterizes the relationship between the initial level of energy efficiency and the rate of its growth. The β value indicates the convergence rate, the percentage of long-term energy-efficient equilibrium distance the port achieves simultaneously. The exogenous variables are the globalization index [104] and the GDP indicator [105].

The objects of the study are the three previously described ports, i.e., one Ukrainian port (the Port of Pivdennyi) and two European Union (EU) ports (the Port of Gdansk, Poland, and the Port of Split, Croatia). The leading indicators for ports (and countries) selected for analysis include the following: energy efficiency (*EP*), distribution of energy resources (*DE*), green investments (*GI*), globalization index (*IG*), and gross domestic product (*GDP*).

Table 3 shows the descriptive statistics of the selected variables. The standard deviation of the variables for all ports was less than 10%, which indicates low variability in the features of the investigated ports.

Table 3. Descriptive statistics of the *EP*, *DE*, *GI*, *IG*, and *GDP* variables for the three ports (2017–2023).

Indicators	Port	AVG	Med	Max	Min	STD	As	Ex
EP	Port of Gdansk	119.64	116.7	126.8	115.5	4.61	0.54	1.63
	Port of Split	101.49	101.5	101.9	100.9	0.33	−0.59	2.54
	Port Pivdennyi	96.7	96.5	98	95.9	0.69	0.96	2.91
DE	Port of Gdansk	119.59	118	125.6	113.3	4,61	0.16	1.72
	Port of Split	112.99	113.5	114.8	109	1,97	−1.26	3.48
	Port Pivdennyi	120.67	122	123.8	110,3	4.63	−1.93	4.93
GI	Port of Gdansk	119.79	122	127.6	110.7	6.55	−0.29	1.67
	Port of Split	117.83	118.2	120	114.3	2.05	−0.59	2.19
	Port Pivdennyi	109.99	109.3	114.1	107.4	2.63	0.41	1.67
IG	Port of Gdansk	81.00	80.40	83.57	79.67	1.57	0.87	2
	Port of Split	81.18	80.08	84.32	79.52	1.96	0.78	1.89
	Port Pivdennyi	74.99	74.95	76.62	73.38	1.13	0.06	1.98
GDP	Port of Gdansk	101.86	101.5	101.9	100.9	0.33	−0.59	2.54
	Port of Split	93.79	96.5	98	95.9	0.69	0.96	2.91
	Port Pivdennyi	100.34	116.7	126.8	115.5	4.61	0.54	1.63

(Source: developed by the authors).

According to the abovementioned methodology, the σ-convergence was estimated at the first stage of the research. Table 4 shows the results of the σ-convergence estimation.

Table 4. Empirical substantiation of σ-convergence between variables for the studied ports.

σ-Convergence	2017	2018	2019	2020	2021	2022	2023
Energy efficiency (*EP*)							
EU ports *	0.21	0.02	0.04	0.05	0.05	0.05	0.04
Port of Ukraine	0.22	0.03	0.05	0.07	0.07	0.02	0.03
Distribution of energy resources (*DE*)							
EU ports *	0.01	0.01	0.02	0.02	0.02	0.05	0.04
Port of Ukraine	0.01	0.01	0.01	0.03	0.02	0.03	0.02
Green investments (*GI*)							
EU ports *	0.03	0.01	0.04	0.01	0.01	0.03	0.04
Port of Ukraine	0.06	0.04	0.03	0.01	0.02	0.05	0.01

Note: * data are taken for the Port of Gdansk and the Port of Split (source: developed by the authors).

The decrease in the standard deviation of the natural logarithms of the energy security and environmental sustainability sub-indices confirmed that the strategic imperatives of managers' approaches are focused on achieving the convergence of energy efficiency and environmental sustainability processes. At the same time, there was an increase in the standard deviation of the natural logarithms of the sub-index of the distribution of energy resources for selected countries from 2017 to 2023. Thus, this indicates the spread of introducing energy efficiency and environmental sustainability parameters into the strategic imperatives of port development.

Confirmation of σ-convergence made it possible to test the hypothesis of β-convergence between processes for the countries under study.

In the next stage of the study, the stationarity of the selected variables was determined for the assessment of β-convergence. The results of the panel data unit root test are shown in Table 5.

Table 5. Results of stationarity analysis using the panel data unit root test.

Statistical Data (p-Value)		c	Hadri	ADF-Fisher Chi-Square	PP-Fisher Chi-Square
$ln(EP_{t-1})$	in level in 1st differences	−56.37 (0.00) −23.61 (0.00)	3.14 (0.00) 1.69 (0.04)	6.58 (0.76) 31.86 (0.00)	9.22 (0.51) 23.45 (0.01)
$ln\left(\frac{EP_t}{EPt-t}\right)$	in level in 1st differences	−23.98 (0.00) −21.78 (0.00)	1.69 (0.04) 4.37 (0.00)	31.94 (0.00) 35.79 (0.00)	23.36 (0.01) 39.68 (0.00)
$ln(DE_{t-1})$	in level in 1st differences	−4.11 (0.00) −10.09 (0.00)	2.89 (0.00) 3.77 (0.00)	14.52 (0.15) 47.49 (0.00)	1.67 (0.99) 65.98 (0.00)
$ln\left(\frac{DE_t}{DEt-1}\right)$	in level in 1st differences	−10.13 (0.00) −8.36 (0.00)	3.76 (0.00) 2.61 (0.00)	47.50 (0.00) 49.65 (0.00)	66.02 (0.00) 68.34 (0.00)
$ln(GI_{t-1})$	in level in 1st differences	0.01 (0.51) −4.00 (0.00)	3.46 (0.00) 3.03 (0.00)	14.04 (0.17) 26.13 (0.00)	6.71 (0.75) 31.38 (0.00)
$ln\left(\frac{GI_t}{GIt-1}\right)$	in level in 1st differences	−4.00 (0.00) −2.14 (0.00)	3.03 (0.00) 4.84 (0.00)	26.14 (0.00) 28.76 (0.00)	31.42 (0.00) 38.20 (0.00)
$lnIG$	in level in 1st differences	4.68 (1.00) −1.52 (0.06)	4.00 (0.00) 4.04 (0.00)	3.21 (0.97) 17.06 (0.07)	0.09 (1.00) 17.02 (0.06)
$lnGDP$	in level in 1st differences	0.20 (0.58) −2.85 (0.00)	2.98 (0.00) 2.03 (0.02)	7.87 (0.64) 16.35 (0.03)	2.65 (0.98) 27.09 (0.00)

(Source: developed by the authors).

Checking the stationarity of time series in the level confirmed that for $ln(EP_{t-1})$ (PP-Fisher Chi-square and ADF-Fisher Chi-square tests), $ln(DE_{t-1})$ (PP-Fisher Chi-square and AD-Fisher Chi-square), $ln(GI_{t-1})$ (tests ADF-Fisher Chi-square, Levin–Lin–Chu, and PP-Fisher Chi-square), $lnIG$ (tests ADF-Fis-Chi-square, Levin–Lin–Chu, and PP-Fisher Chi-square), and $lnGDP$ (tests PP-Fisher Chi-square, Levin–Lin–Chu, and ADF-Fisher Chi-square). The absolute values of the τ-statistics are smaller than the absolute values of the minimum value at 1%, 5%, and 10%. The minimum probability that the time series was non-stationary is 49% (p-value > 10%). Furthermore, the results of ADF-Fisher Chi-square, Hadri, Levin–Lin–Chu, and PP-Fisher Chi-square tests confirmed the stationarity of the modified variables for all variables in the first differences. Thus, the time series in the first differences are stationary. The results of the β-convergence estimation are shown in Table 6.

Table 6. Results of β-convergence analysis.

	$ln\left(\frac{EP_t}{EPt-t}\right)$	$ln\left(\frac{DE_t}{DEt-1}\right)$	$ln\left(\frac{GI_t}{GIt-1}\right)$
$ln(EP_{t-1})$	−0.093 (0.068)	–	–
$ln(DE_{t-1})$	–	−0.007 (0.033)	–
$ln(GI_{t-1})$	–	–	−0.147 (0.02)
$lnIG$	0.031 (0.08)	−0.04 (0.709)	−0.209 (0.02)
$lnGDP$	0.029 (0.067)	0.049 (0.234)	0.048 (0.13)

(Source: developed by the authors).

According to Table 6, the absolute values of β-convergence vary, ranging from 0.093 (energy efficiency) to 0.147 (green investments), which confirms the high degree of convergence between ports in terms of these parameters. The positive statistically significant influence of the index of globalization and trade openness confirmed the possible acceleration of β-convergence for energy efficiency. This indicates that at the first stage, the rate of growth of energy efficiency was high and then slowed down as the values increased, approaching stability. At the same time, the influence of *IG* and *GDP* variables on energy efficiency was not statistically significant. The variables *IG* and *GDP* did not affect the convergence of ports in the distribution of energy resources.

Thus, the port's energy sector transformation should be carried out by implementing effective mechanisms of strategy convergence related to energy efficiency and greening. At the same time, introducing innovative energy technologies can become a vital tool for overcoming the negative consequences of various types of pollution. In addition, this will contribute to creating new scenarios for the port's sustainable energy development based on the green strategy and environmental sustainability parameters.

The assessment results of σ- and β-convergence confirmed the convergence of the two investigated EU ports. At the same time, it was established that the increase in the level of energy efficiency in the Port of Pivdennyi was limited by a significant share of fuel imports (including natural gas and oil) and high intensity of CO_2 emissions. In turn, the significant deterioration of the energy infrastructure has become a barrier to increasing energy efficiency. It requires additional investments for modernization from a post-war perspective for the Port of Pivdennyi (Ukraine).

4. Discussion

This manuscript aims to show that a port's energy management system can be an example of supply–demand equalizing sustainable alternative energy sources. Such systems engage more profoundly within the energy value chain by assessing green and environmental indicators in port operations, strategies, and investments. This is illustrated in the created EEGP triangle (Figure 1), which provides a framework for understanding and implementing energy-efficient practices in ports. Energy-efficient ports expand the scope of activities in transforming port-centric energy production systems, ship energy supply systems, renewable source energy production systems, and the integration of entire port energy systems. Also, energy-efficient ports integrate the green strategy and environmental sustainability parameters of energy value chains into their business portfolio.

This research proves that port energy efficiency can be improved through decarbonization strategies (reducing carbon emissions or zero carbon emissions). Decarbonization is achieved through more profound engagement with the energy generation and consumption chain based on assessing green and environmental performance in port operations and strategies. These strategies, often called green strategies, involve using environmentally friendly technologies and practices to reduce port operations' carbon emissions and environmental footprint.

The framework (EEGP) proposed in this manuscript facilitates optimizing the energy value chain of ports' stakeholders and enables further networking into the vaster energy-efficiency systems. This manuscript reveals new perspectives on energy efficiency management and decision-making on green solutions that reduce environmental footprint and promote sustainable economic growth of the maritime industry, providing practical insights for industry professionals and academics alike.

Following the research model (Figure 2), the manuscript identifies the performance of energy efficiency and greening ports (the EEGP framework), as presented in Figure 6.

The energy efficiency and greening ports framework presented in Figure 6 suggests the interconnections between the applications of green strategies in port operations, adopted from Du et al. [20], energy efficiency in greening ports as the central concept in this research, and the diverse aspects of environmental performance in greening ports and energy consumption. Following the idea of Du et al. [20], this paper identifies the three vital aspects of the green strategies' implementation: (1) port activities and infrastructure, (2) ship emissions and ship energy consumption, and (3) the port hinterland transport system and logistics. Furthermore, the paper suggests four phases in integrating energy efficiency into greening ports, each addressing diverse energy-related issues. The first phase relates to developing and implementing energy efficiency strategies in operating activities and monitoring, measuring, and assessing energy consumption and efficiency in port operations.

The second phase addresses green investments and reporting. It develops strategies for attracting green investments, investments in renewables, increasing the share of renewable sources in total energy consumption, and usage of cleaner types of fossil fuel. Also, it relates to reporting practices on energy consumption, energy efficiency management, and climate change action. The third phase considers developing and digitalizing the energy management system (EMS) and renewable energy sources (RES) management system, investments in green certifications, and creating a digital-based energy network to connect with stakeholders. Digitalization is particularly relevant in the context of energy efficiency in port operations and greening. It refers to using digital technologies to streamline and optimize energy management processes, thus reducing energy consumption and improving overall efficiency. Phase four relates to developing analytical frameworks for deciding on energy efficiency strategies related to port greening and environmental performance. Also, it considers connecting the energy management system (EMS) to diverse greening and environmental performance by developing a digital-based energy network to connect with stakeholders. This phase involves creating a green business portfolio based on energy efficiency and environmental performance. Figure 6 also shows the interconnectedness between energy efficiency in greening ports and diverse environmental performance in greening ports (air quality, water usage and quality, light control, noise control, waste and garbage control, and biodiversity conservation).

This study confirms the unidirectional relationship between the volume of CO_2 emissions and the level of energy efficiency, the specific weight of renewable sources in final energy consumption, volumes of green investments, and CO_2 emissions. A bidirectional relationship was found between the level of ports' energy efficiency and the specific weight of renewable sources in the final total energy consumption; the level of energy efficiency of the port and the amount/the value of green investments; volumes of CO_2 emissions and green investments. The results of this manuscript confirm similar research on the relationship between green variables focusing on decarbonization and energy efficiency (e.g., [93–96]) and even upgrade the previous findings. Furthermore, this manuscript's results confirm similar research on asynchrony based on convergence analysis of balanced green investments and energy efficiency (e.g., [97,98]). Previous research [88,89] that used convergence principles to investigate synchrony in the progress of green investments relative to energy efficiency in the port sector revealed asynchrony or imbalance.

The results of the assessment of σ- and β-convergence in this manuscript confirmed the convergence of the observed ports, the Port of Pivdennyi (Ukraine), and the two EU ports, the Port of Split (Croatia), and the Port of Gdansk (Poland). At the same time, it was established that increasing energy efficiency in the investigated ports depends on the intensity of their CO_2 emissions. It was established that increasing energy efficiency requires additional investments to modernize the port and implement the green strategy. Therefore, the findings correlate with previous research (e.g., [93–98]), as previously noted. The novelty of this research lies in the methodological development of the Energy Efficiency and Greening Ports Framework (EEGP Framework). Based on schematic models presented in Figures 1, 2 and 5 and confirmed hypotheses (H1 and H2), this manuscript proves that implementing green strategies related to the set of studied variables enables effective energy efficiency management in seaports when considering them together. Furthermore, compared to existing empirical findings, this comprehensive approach not only reveals the problem of green investments' effectiveness in decarbonization but also provides a comprehensive understanding of the issue. Based on regression analysis and convergence, calculations of the synchronicity between changes in the energy efficiency parameters for the three investigated ports determined the feasibility of implementing the existing efficiency not in progressive but in cumulative form. This research indicates that the observed variables should be analyzed together to comprehensively understand their relationships and dynamics. Furthermore, this research proposes the concept of an energy business portfolio as a novel approach to green and sustainable strategies using developed analytical roadmaps, as presented in Figures 1 and 4–6. These roadmaps provide conceptual and practical guidance for implementing green strategies in port operations, informing researchers, industry professionals, and policymakers about the broader impact of these strategies.

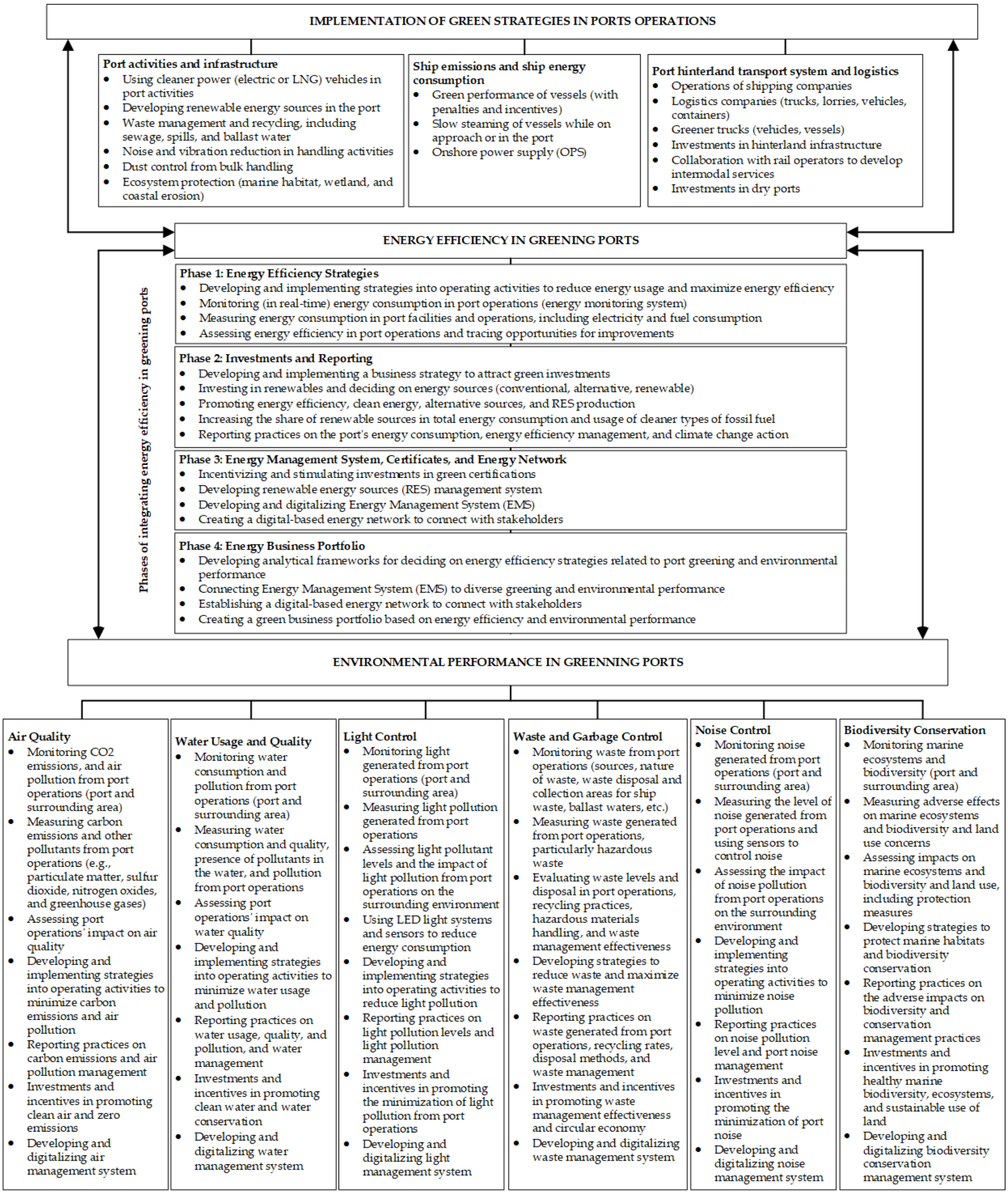


Figure 6. The energy efficiency and greening ports framework (source: developed by the authors based on [2,4–6,8,14–17,19–27,30,31,41,87,88,91–100].

The ports investigated in this manuscript are located near cities (Split, Croatia; Gdansk, Poland, and Odesa, Ukraine), as is the case for most European ports, and may act as an energy generator and engine for their city [17]. ESPO [5,8] highlights that 95% of Europe's ports are near urban areas, performing essential urban functions, supporting the local economy, and creating solutions to urban challenges. Due to the nature of the activity of ports, there are ample opportunities to promote green solutions for the city, circular economies, "green" city heating, green urban mobility services, etc. [17]. Creating a good shared port–city relationship is vital for the sustainability of seaports and their surroundings [5].

Finally, this manuscript aims to show that a port's energy management system can be an example of supply–demand equalizing sustainable alternative energy sources. Such systems engage more profoundly within the energy value chain by assessing green and environmental indicators in port operations, strategies, and investments (the triangle). Energy-efficient ports expand the scope of activities in transforming port-centric energy production systems, ship energy supply systems, renewable source energy production systems, and the integration of entire port energy systems. Also, energy-efficient ports integrate the green strategy and environmental sustainability parameters of energy value chains into their business portfolio.

5. Conclusions

Aside from the theoretical contribution discussed in the previous section (Discussion), this manuscript introduces the energy efficiency and greening ports framework (EEGP) and proposes an energy business portfolio as a significant advancement in port management. The EEGP framework optimizes the energy value chain of port stakeholders and facilitates their integration into larger energy efficiency systems. This research paper provides fresh insights into energy efficiency management and decision-making on green solutions, which are crucial for reducing environmental impact and fostering sustainable economic growth in the maritime industry.

The grounding idea of this study focuses on rethinking green strategies and environmental performance in ports, focusing on energy efficiency. Ports are vital hubs and networking points that connect numerous stakeholders in the maritime industry and energy markets. There is a growing urge for cooperation and sharing practices inside their clusters and communities to promote sustainable economic growth. The increasing number of collaborative initiatives and knowledge-sharing platforms within the port industry evidences this. Thus, ports must diversify activities related to energy consumption and monitor green strategy parameters and environmental sustainability in their business portfolio.

The framework (EEGP) proposed in this manuscript is a powerful tool to optimize the energy value chain of ports' stakeholders and enable further networking into the vaster energy efficiency systems. This manuscript provides new perspectives on energy efficiency management and decision-making on green solutions that can significantly reduce the environmental footprint and promote the sustainable economic growth of the maritime industry. The potential impact of the EEGP framework is immense, offering a promising path toward a more sustainable future for the maritime industry.

The main limitation of this research relates to a narrow range of variables and their measures to investigate the relationships among diverse green and environmental aspects (i.e., air quality, energy efficiency, water quality, light pollution, waste/garbage pollution, noise pollution, and biodiversity conservation). In other words, the limitations refer to:

- Analyzing only four variables in greening ports (carbon emissions, energy efficiency, renewable energy sources, and green investments)
- Using one measure for each analyzed variable only (the amount of CO_2 emissions, the level of energy efficiency, the specific weight of renewable sources in the total final energy consumption, and the volume of green investments).

Thus, more extended and comprehensive research should investigate a broader range of indicators to develop and test the proposed framework. Further research should integrate additional analytical methods to investigate and model the greening variables.

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