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The Role of Polish Local Ports on the Central Baltic Coast in the Development of Offshore Wind Farms

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Abstract: This paper examines the critical role of Polish local ports, particularly those on the Central Baltic coast, in the development of offshore wind farms. The study investigates how offshore wind energy development affects local port infrastructure, logistics, and the broader maritime economy while identifying opportunities and challenges arising from their integration into the offshore wind supply chain. To achieve this, a comprehensive methodological approach was employed, combining qualitive and quantitative analyses. The research utilized statistical data, policy documents, and spatial development plans to evaluate the current state of offshore wind energy projects in Poland. A specific focus was placed on assessing the infrastructure capabilities of local ports, including Kołobrzeg, Darłowo, Ustka, and Łeba, to serve as service hubs for offshore wind farm operations. Criteria such as waterway depth, quay length, storage facilities, and connectivity to transportation networks were analyzed in detail. Additionally, the study highlights the socio-economic benefits these ports can bring to the regions, such as job creation, economic revitalization, and enhanced regional competitiveness. The findings reveal that while these ports possess significant potential, strategic investments and modernization are essential to fully realize their role in supporting offshore wind energy. Recommendations are provided for policymakers, port authorities, and stakeholders to optimize the port's development as part of Poland's transition to renewable energy. This study contributes to broader discourse on renewable energy and maritime economic development, offering valuable insights into integrating small port infrastructure into large-scale energy projects.

Keywords: offshore wind farms; local ports; energy transformation; port infrastructure; development

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1. Introduction

Energy is one of the fundamental human needs, utilized in nearly every aspect of life. It encompasses everyday activities like cooking, heating, and powering electronic devices, as well as more complex processes such as transportation, industrial operations, and the functioning of critical infrastructure. Access to reliable energy sources is essential for improving living standards, fostering economic growth, and promoting social development. What is more, wind energy is one of the key driving forces behind energy transformation and decarbonization.

In recent years, there has been a significant shift toward renewable energy sources to meet the growing global demand for energy while addressing environmental concerns. Among these sources, offshore wind energy stands out as a rapidly growing sector in Europe and around the world.

As countries strive to meet their climate goals, offshore wind energy is poised to play a pivotal role in the transition to a cleaner, more sustainable energy future.

Poland, with its extensive Baltic Sea coastline, has significant potential for offshore wind energy development. The sector is expected to drive the country's energy transition

and contribute to the European Green Deal objectives. The added value of the study is the analysis of the potential of Polish local ports in terms of offshore wind energy. By examining the unique characteristics and capabilities of these ports, the study underscores their strategic importance in the expanding offshore wind sector. Additionally, it contributes to the broader discourse on renewable energy development and provides recommendations for enhancing the roles of these ports in this rapidly growing industry.

To guide the analysis, the following research questions were developed:

RQ1: What are the current capabilities of Polish local ports on the Central Baltic coast to support offshore wind energy development?

RQ2: What are the primary challenges and limitations faced by these ports in becoming operational hubs for offshore wind farms?

RQ3: How can investments in port infrastructure and logistics be optimized to align with the demands of the offshore wind energy sector?

RQ4: What socio-economic benefits can the development of offshore wind energy bring to the regions surrounding these local ports?

The paper's structure is designed to yield substantive insights aligned with the research objective. The layout of the study is organized as follows:

(a) Introduction;
(b) Background of analysis;
(c) Analysis of documents and strategies for the development of offshore wind farms;
(d) Analysis of the current state of offshore wind farm projects;
(e) Analysis of the potential of local ports in the development of the Polish offshore wind energy sector;
(f) Assessment of local ports' infrastructure for the development of offshore wind energy;
(g) Analysis of the economic and social benefits for local ports and regions from the establishment of offshore wind farm service ports;
(h) Discussion;
(i) Conclusions.

2. Background of Analysis

Wind energy is one of the oldest renewable energy sources exploited by humans. The earliest references to the use of wind power can be found in the Code of Hammurabi. Wind is the movement of air caused by differences in the density of heated air masses and their upward movement. Air moves due to the action of solar radiation, which heats it, causing pressure differences. The resulting low pressure creates a suction effect, drawing in colder air masses [1]. With the accelerating exploitation of fossil fuels, global climate change, rapid technological growth, and increasing world energy demand, there is a growing need to shift electricity production from conventional sources to renewable energy [2].

Over the past decade, wind power has experienced sustained and rapid growth worldwide. The Global Wind Energy Council (GWEC) has presented the latest data on wind energy. According to the GWEC report, 2023 was a record year for growth in installed wind energy capacity. A total of 116.6 GW of wind power was added globally, marking a 50% increase compared to the previous year. New wind power plants were established in 54 countries across all continents in 2023. The five largest markets in wind energy are China, the USA, Brazil, Germany, and India. Together, these countries installed 82% of new capacity in 2023 [3].

Wind energy is a popular source of green energy generation, and in this context, offshore wind power plays a significant role. The dynamic development of offshore wind energy makes it one of the fastest growing energy technologies in the world. The renewable energy sources found in the marine environment include the following: wind, waves, ocean currents, and tides [4]. The first offshore wind farm, Vindeby, was established in 1991 in Denmark (Kattegat Strait) and consisted of 11 turbines with a capacity of 0.45 MW [5]. It was dismantled in 2017. Subsequent development in Europe began after the year 2000, with

significant acceleration over the past decade, during which installed capacity increased by an average of 30% per year [6].

Offshore wind energy has been rapidly developing in various locations around the world that meet the necessary conditions for many years now. However, at the beginning of 2010, only 2000 wind megawatts had been installed offshore [7]. In the offshore wind market, 10.8 GW of new capacity was commissioned in 2023, bringing the total global offshore wind capacity to 75.2 GW. This represents a 24% increase in new offshore wind additions compared to 2022, making 2023 the second-highest year for new offshore wind capacity [3].

The development of offshore wind farm (OWF) technology is a strategic direction for implementing the European Green Deal of 2019. Additionally, in 2020 the European Commission published the EU strategy for offshore renewable energy, titled "EU Strategy on the Use of the Potential of Offshore Renewable Energy for a Climate-Neutral Future". The strategy aims to increase the production of electricity from offshore renewable energy sources (ORESs) in the EU from 12 GW in 2020 to over 60 GW by 2030 and 300 GW by 2050 [8].

In 2023, Europe commissioned 3.8 GW of new offshore wind capacity across six markets. This brought Europe's total offshore wind capacity to 34 GW by the end of 2023, 43% of which was in the UK and 24% in Germany. Currently, most offshore wind farms are located in the North Sea, as are the majority of planned farms that have already been approved for construction or are awaiting approval. The Baltic Sea is another favorable location for the development of offshore wind energy, where Germany and Denmark already have farms, and Sweden is currently expanding its offshore wind capacity [9].

Offshore wind farms are particularly promising because they offer more consistent and reliable wind resources at sea compared to on land [10]. The conditions for electricity production at sea are definitely more favorable. Wind strength at sea is greater and more stable—wind blows at sea for about 90% of the year. The density of wind energy, or the average wind power that can be obtained per square kilometer of installation area, is highest in the North Sea, followed by the Baltic Sea.

3. Materials and Methods

This study employed a multifaceted methodological approach to evaluate the role of Polish local ports on the Central Baltic coast in the development of offshore wind farms, utilizing a combination of data sources and analytical methods to ensure a comprehensive evaluation. The research methods included the analysis of source data, an examination of documents and statistical data, and the application of cause-and-effect analysis to understand the relationships between the identified challenges and the potential of local ports to support offshore wind energy development.

To achieve this, a variety of data sources were utilized, including statistical data such as infrastructure parameters and economic performance indicators gathered from government agencies, maritime authorities, and port authorities. Furthermore, key policy and strategic documents were analyzed, including Poland's Energy Policy until 2040, the Maritime Spatial Plan, and the Act on Promoting Electricity Generation in Offshore Wind Farms, which provided valuable insights into the regulatory framework, strategic priorities, and planned investments in the offshore wind energy sector. The academic literature comprising peer-reviewed articles, technical reports, and case studies on offshore wind energy and port infrastructure, was reviewed to identify best practices and situate the findings within the broader European and global context.

The analysis focused on key infrastructure parameters to assess the readiness of the selected ports, including physical infrastructure such as quay length, depth at quays, turning basins, storage capacity, and waterway characteristics. What is more, connectivity was scrutinized, with an emphasis on the accessibility of road and rail transport networks to evaluate the logistical suitability of each port. Moreover, port facilities were examined for the availability of specialized equipment, waste management systems, and facilities

for crew transfer vessels to determine the ports' capacity to support offshore wind operations. Finally, investment needs were identified by analyzing deficiencies in the current infrastructure and prioritizing areas for future development.

Additionally, a cause-and-effect analysis was employed to identify and understand the relationships between challenges such as infrastructure limitations, connectivity issues, policy gaps, and financial constraints, as well as their direct and indirect impacts on the readiness of the ports to support offshore wind energy projects.

The research focused on four local ports located along Poland's Central Baltic coast—Kołobrzeg, Darłowo, Ustka, and Łeba—situated within the Słupsk subregion of the Pomeranian Voivodeship, the Lębork subregion of the Pomeranian Voivodeship, and the Koszalin subregion of the West Pomeranian Voivodeship. These ports were selected based on their strategic geographic location, proximity to the designated offshore wind farm areas, and potential to function as operational hubs for the offshore wind energy sector, with a detailed assessment conducted for each port to evaluate its infrastructure, connectivity, and logistical capabilities.

4. Results

4.1. Offshore Wind Farms in Poland

4.1.1. Documents and Strategies for the Development of Offshore Wind Farms

The development of offshore wind energy is a key priority in Poland's energy policy, essential for meeting European climate goals [11,12]. The "Energy Policy of Poland until 2040" is a strategic document developed by the Ministry of Climate and Environment, which has been adopted by the government of the Republic of Poland as binding in the context of the development and transformation of the Polish electricity system. According to its assumptions, by 2040, more than half of the installed capacity in the country is expected to come from zero-emission sources. One of the priority directions outlined in the "Energy Policy of Poland until 2040" is an investment program worth approximately PLN 130 billion, covering the construction of offshore wind farms. As a result, by 2040, up to 11 GW of installed capacity is expected to be developed in Poland's exclusive economic zone in the Baltic Sea [13].

At the national level, the legal foundations for the functioning of offshore wind energy are defined by the Act of 10 April 1997, Energy Law, which establishes the principles of shaping the energy policy of the state [14]. Important changes enabling the development of wind energy were introduced by the law promoting the generation of electricity in offshore wind farms, adopted by the Polish Parliament on 17 December 2020. The investment process for offshore wind energy began to take shape only after the enactment of the Act of 17 December 2020, on Promoting Electricity Generation in Offshore Wind Farms [15]. The law includes key regulations concerning the development of offshore wind farms, such as the support system, local supply chain, and grid connection. It also introduces a number of procedural improvements regarding construction, operation, and administrative proceedings aimed at accelerating the implementation of investments.

Additionally, creating conditions for the use of energy from renewable sources at sea, including wind energy, is one of the goals of Poland's maritime policy. The law regulating the construction of all structures at sea and defining the legal status of Polish maritime areas is established by the Act of 21 March 1991, on the Maritime Areas of the Republic of Poland and Maritime Administration [16]. According to the Act on Maritime Areas of the Republic of Poland and Maritime Administration, the construction and operation of offshore wind farms is permitted only within Poland's exclusive economic zone in the Baltic Sea.

The National Energy and Climate Plan for 2021–2030 is a government document developed by the Minister of State Assets [17]. The NECP outlines the assumptions and objectives, as well as the policies and actions aimed at achieving the five dimensions of the energy union: energy security, internal energy market, energy efficiency, a reduction of emissions, and research, innovation, and competitiveness [18].

4.1.2. Current State of Offshore Wind Farm Development

The National Power System in Poland, with a total installed capacity exceeding 41 GW, is over 70% based on coal-fired power plants. In the coming years, the oldest power generation units will be phased out. By 2035, it will be necessary to shut down more than 20 GW of generating capacity. This is due, among other factors, to their age and level of depletion [19].

The offshore wind energy potential in the Baltic Sea is estimated at 83 GW, of which 28 GW is attributed to Polish maritime areas. At the same time, according to the Polish Power Grid (PSE), the maximum average annual and daily electricity demand in Poland between 1980 and 2020 did not exceed 28 GW [20].

The Spatial Development Plan for Polish Maritime Areas, adopted in April 2021, designates 2.34 thousand km^2 of area for the construction of offshore wind farms, which represents 10% of Poland's exclusive economic zone [21]. Offshore wind farm projects will be developed in Poland's exclusive economic zone in the Baltic Sea within the areas designated in the maritime spatial planning for the Słupsk Bank, Central Bank, and Odra Bank regions (Figure 1).

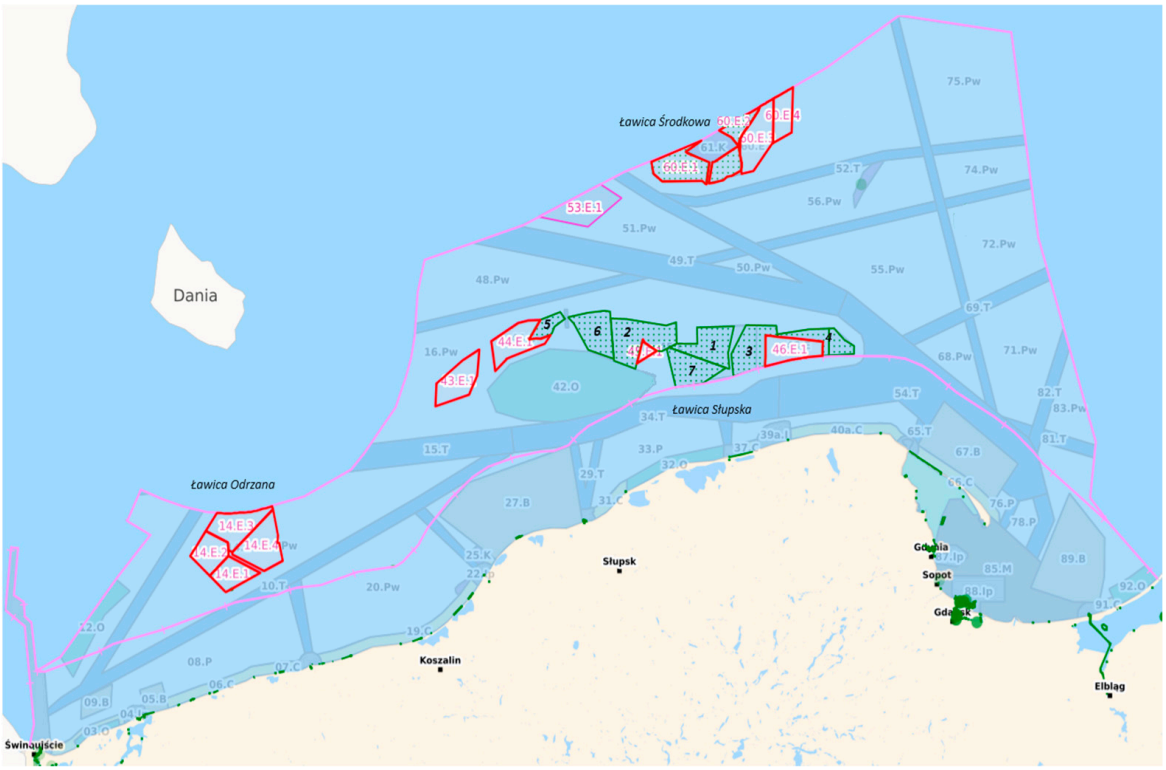

Figure 1. Location of offshore wind farms in the Polish Exclusive Economic Zone. Source: https://www.gov.pl/web/morska-energetyka-wiatrowa (accessed on 25 October 2024).

Offshore wind farms are of interest to both leading state-owned companies, such as PGE and Orlen, as well as domestic private investors, like Polenergia, and global giants, such as Equinor and Ørsted. As of the second quarter of 2024, nine offshore wind farm projects have received location permits and are currently under development, including seven projects in the first phase of the support system (Table 1). The first offshore wind farms are expected to start producing energy in 2026, with an estimated investment value of approximately 130–150 billion PLN.

The most advanced offshore wind energy projects are MFW Bałtyk II and MFW Bałtyk III, developed by the energy groups Polenergia and Equinor. Offshore wind farms are planned in relatively shallow areas (20–50 m) at a safe distance from shipping routes (minimum 2 nautical miles), avoiding conflicts with the most valuable natural areas and

those designated for purposes such as defense or the extraction of aggregates and hydrocarbons [22].

Table 1. Currently implemented offshore wind farm projects under the first phase of the offshore wind energy support system in Poland.

Project Name	Developer	Max. Power (MW)	Depth of the Area (m)	Environmental Decision	Planned First Energy Export
Baltica 3	PGE Baltica/Orsted	1050	30–50	+	2026
Baltica 2	PGE Baltica/Orsted	1500	20–50	+	2027
Baltic Power	Orlen/Northland	1200	30–50	+	2026
BC-Wind	Ocean Winds	500 (2 × 250)	30–50	+	2027
FEW Baltic II	RWE Renewables	440	40	+	2030
MFW Bałtyk II	Polenergia/Equinor	720–1200	23–41	+	2027
MFW Bałtyk III	Polenergia/Equinor	720–1200	25–39	+	2027

Source: own study based on https://www.gov.pl/web/morska-energetyka-wiatrowa/program-rozwoju-morskich-farm-wiatrowych (accessed on 20 October 2024).

According to PEP2040, Poland commits to installing 5.9 GW by 2030 and up to 11 GW by 2040, with analyses indicating a potential of up to 28 GW in Polish waters by 2050. On 29 March 2022, the Council of Ministers adopted the framework for updating Poland's Energy Policy 2040 (PEP2040), aimed at strengthening the country's energy security and independence [23]. The framework includes plans to increase technological diversification and expand capacity based on domestic sources, including the further development of renewable energy sources (Figure 2).

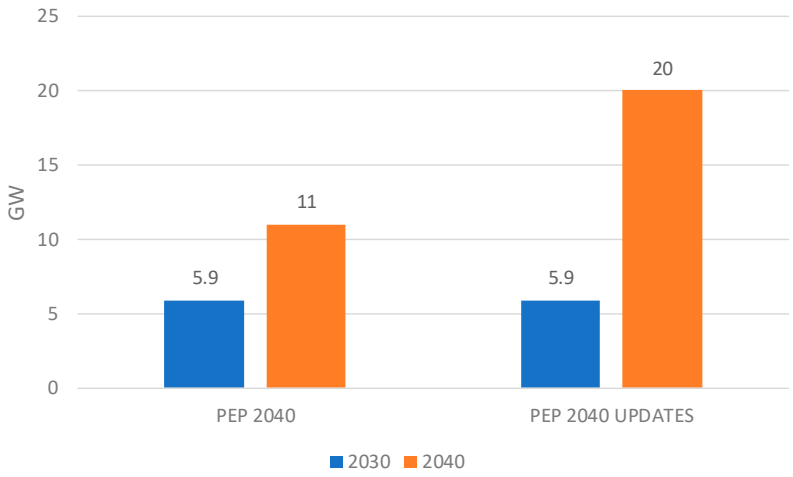

Figure 2. Poland's offshore wind energy forecasts. Source: own study.

Currently, offshore wind farm projects in Poland have a total capacity of approximately 8.4 GW. Whereas 5.9 GW of projects are in the so-called Phase I, having already received support through decisions from the President of the Energy Regulatory Office. The remaining 2.5 GW of capacity consists of projects in Phase II, which will seek support under rules similar to those of the existing renewable energy auctions.

4.2. Potential of Local Ports in the Development of the Polish Offshore Wind Energy Sector

According to the Act of 20 December 1996, on Seaports and Harbors, there are four ports of primary importance to the national economy in Poland, located in Gdańsk, Gdynia, Szczecin, and Świnoujście [24]. Additionally, the Polish coastline features 29 local ports and 46 marinas [25]. Small and medium-sized ports serve as regional centers of entrepreneur-

ship (Figure 3), providing a variety of economic functions, making them significant for the country, the region, and local governments.

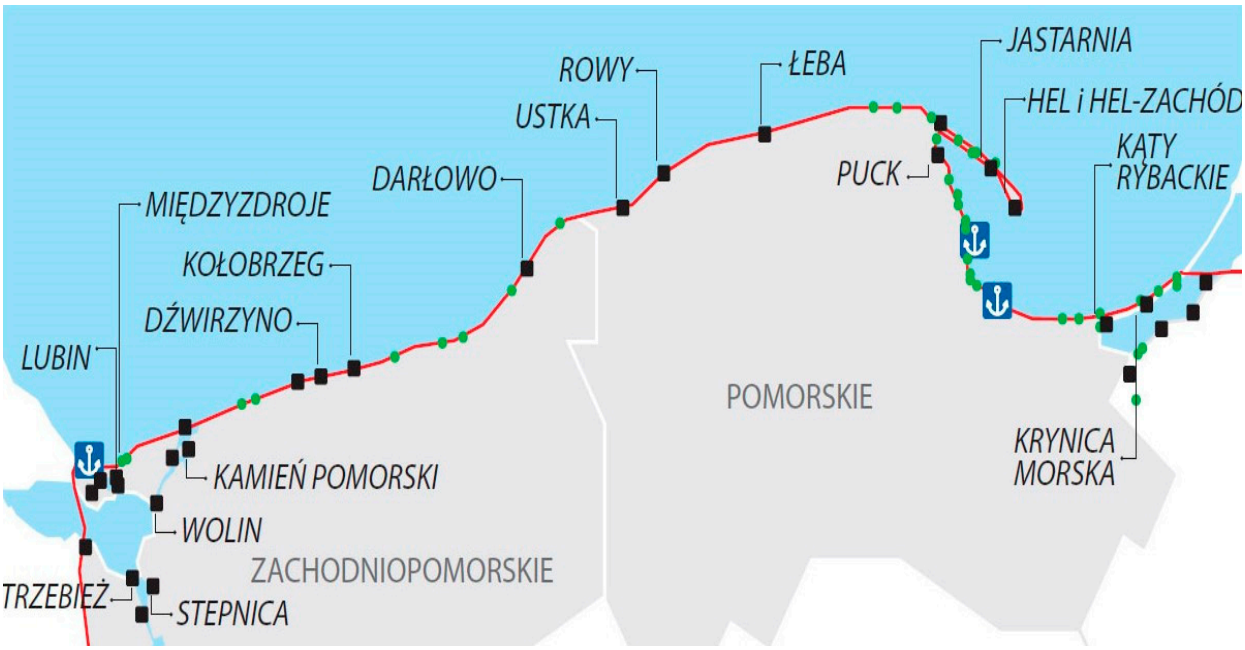

Figure 3. Ports and marinas in Poland. Source: www.nik.gov.pl (accessed on 25 October 2024).

The "Program for the Development of Polish Seaports until 2020 (with a perspective until 2030)" characterizes small seaports as highly diverse, particularly in terms of port infrastructure, area, functions performed, and management forms (Figure 3). Polish small seaports are multifunctional economic structures that have both direct and indirect local significance, with only the largest among them having regional importance [26]. To clarify the distinctions between ports that are not of fundamental importance to the national economy, it is advisable to differentiate between regional and local ports. The first group includes ports such as Darłowo, Elbląg, Hel, Kołobrzeg, Łeba, Police, Ustka, and Władysławowo. The remaining ports are classified as local. Ports are service providers who are in competition with each other [27]. Additionally, ports have a positive relationship with regional economic development [28].

The Polish coastline of the Baltic Sea, along with the Vistula and Szczecin Lagoons, stretches for 775 km, of which the section delineating the territorial sea from the border with Germany to the border with Russia is 440 km long. The area of influence of small seaports, depending on their size and economic functions, primarily includes the marine waters of the Republic of Poland and the Southern Baltic. According to the law, these areas encompass internal marine waters (2005 km^2), territorial sea (8682 km^2), and the exclusive economic zone (22,634 km^2). The marine areas of the Republic of Poland constitute the main operational territory for users of small ports. On land, the primary area of influence of these ports includes the towns and municipalities where they operate.

4.2.1. Requirements of Local Ports to Serve as Support Facilities for Offshore Wind Farms

The service port plays a crucial role in its maintenance of an offshore wind farm. Its responsibilities include the delivery and collection of equipment and components essential for the functioning of the installation, such as spare parts, oils, and waste. The port also stores structural elements of the turbines, including those designated for replacement or repair, and facilitates the rotation of personnel living on the platforms for wind turbine construction.

There are several key criteria for determining a preferred service port. The most important of these are technical criteria, which include the length of the docks, the depth of

the waterways, and the availability of storage space. Geographical criteria regarding the distance of the port from the wind farm are also significant. Another set of criteria involves accessibility, which includes local road and rail infrastructure, as well as proximity to an airport. Factors such as the availability of skilled workers and the financial capabilities of local authorities are also often considered.

Polish ports that could serve as a support base for production and service work related to offshore wind energy should be characterized by the following [29]:

- Technical depth of the waterway and port—no less than 3.5 m for CTVs (Crew Transfer Vessels);
- Turning basin for vessels up to 75 m in length,
- Berth length for docking—minimum 80 m or a quay accommodating three CTVs;
- Allowable load on the berth adapted for cargo handling—5–20 kN/m^2;
- Loading equipment suitable for the function of the service port (including adaptations for maneuvering self-propelled cranes, loaders, forklifts);
- Equipped with modern water and electrical installations;
- Infrastructure for receiving waste, oily water, and garbage;
- Protection of the port/terminal against waves and rising sea levels;
- Total area of the service terminal—minimum 1500 m^2 (including storage area; space for securing office and social facilities for at least 40 people—minimum 500 m^2);
- Location with direct access to the quay;
- Good connectivity with the road network.

The technical requirements of ports to support offshore wind projects vary significantly depending on the phase of the project. The installation/construction phase demands more extensive infrastructure and logistical capacity due to the scale and complexity of activities. In contrast, the operation and maintenance (O&M) phase requires ports to maintain specialized facilities for ongoing servicing and support. This section presents a detailed analysis of the distinct requirements for each phase.

Key requirements identified in the installation/construction phase include factors such as extended quay lengths and deeper water depth, which are crucial to accommodate large installation vessels. Another key element is heavy-load bearing capacity, essential to support the heavy components and cranes used during loading and unloading operations. Additionally, ports require expansive storage areas for pre-assembled components, such as turbine blades and tower segments. Investments in heavy-duty quay infrastructure and advanced cargo handling systems are, therefore, prioritized for installation ports.

In the operation and maintenance phase, the focus shifts to ongoing support for the operational efficiency and longevity of offshore wind farms. Key requirements for this phase include crew transfer facilities, which are used for transporting personnel to offshore sites. Furthermore, waste and resource management are essential because of handling waste, recycling, and resource provisioning, such as fuel and water supplies. Additionally, ports must offer workshop spaces for minor repairs and offices for operational planning and coordination. Finally, good road and rail connectivity are vital to ensure the timely delivery of replacement components and maintenance supplies [30].

4.2.2. Assessment of Local Ports' Infrastructure for the Development of Offshore Wind Energy

The offshore wind energy sector represents an opportunity for Poland's economic development, including the creation and growth of so-called local content, with a key element being the construction of port infrastructure to support the building and subsequent operation of offshore wind farms [31].

Small seaports are not considered essential to the national economy. However, they play a crucial role in the development of individual regions by driving the economic growth of port municipalities. They are also an area of intensive economic activity, which favors attracting capital from outside and locating investments there [32]. The primary elements determining the current capabilities of small seaports as service ports for offshore wind

energy and their development potential are port infrastructure, port access infrastructure, and port real estate [33]. Ports like Kołobrzeg, Darłowo, Ustka, and Łeba can become service ports for all types of services related to the construction and operation of offshore wind farms [34]. Small ports of the South Baltic Sea have a range of close connections with production and service companies involved in the broadly understood maritime economy. Table 2 presents key parameters of infrastructure in small ports on the Polish coast.

Table 2. Infrastructure of seaports on the Polish coast.

Port	Total Area (ha)	Length of Quays	Length of Cargo Quays	Depth at the Quays	Waterway in the Port	Parameters of Ships Entering Ports (Length, Width, Height)
Kołobrzeg	63 ha	4.91 km	786 m	5.5 m	1.25 km × 26 m × 6.3 m	100 m × 15 m × 5 m
Darłowo	117.16 ha	5.3 km	2 km	4–5 m	2.36 km × 23 m × 5.5 m	75 m × 13 m × 4 m
Ustka	29.2934 ha	3.417 km	160 m	4.5–5.5 m	1175 km × 24 m × 5.5 m	60 m × 12 m × 4 m
Łeba	23.74 ha	2117.3 km	-	3.5–4 m	1 km × 20 m × 3.5 m	50 m × 15 m × 3 m

Source: own study based on Maritime Port Development Strategy for Ustka until 2030, Actia Forum, 2019; spatial development plan for the maritime Port of Ustka environmental impact assessment, Gdańsk, January 2022; draft spatial development plan for internal marine waters—maritime Port in Darłowo environmental impact assessment.

Port of Kołobrzeg

The significance of the Port of Kołobrzeg has remained substantial, both within the region and across Poland. Port Kołobrzeg is located at the mouth of the Parsęta River, providing direct access to the sea [35]. It falls administratively under the city and county of Kołobrzeg. The port serves various functions, including fishing, trade, yachting, and passenger services. In terms of cargo volume, the Port of Kołobrzeg ranks sixth among commercial seaports in Poland.

The administrative boundaries of the Port of Kołobrzeg encompass an area of 63 hectares, integrating with both urban and spa zones. The port in Kołobrzeg has five basins and quays with a total length of 4.91 km, of which the cargo quays measure 786 m. The maximum size of vessels entering the port cannot exceed 100 m in length, 15 m in width, and 5 m in draft. The parameters of the waterway in the Port of Kołobrzeg are as follows: it has a length of 1.25 km, a width of 26 m, and a depth of 6.3 m. These dimensions enable the port to accommodate various types of vessels and facilitate efficient maritime operations. The port has a turning basin with a diameter of 94 m and a depth of 6.3 m and a turning basin with a diameter of 140 m and a depth of 6.3 m.

The port of Kołobrzeg has full infrastructure, the most important elements of which are hydrotechnical structures, such as port basins, port quays with accompanying roads, railway lines, and energy networks. What is more, the port has water and sewage systems. The superstructure, in turn, includes primarily warehouses, devices, and reloading equipment.

The total area of the storage facilities at the Port of Kołobrzeg is approximately 50,000 m^2, with office space covering around 2000 m^2 [36]. Additionally, the commercial port is equipped with two grain elevators, each with a capacity of approximately 6000 tons. This infrastructure supports the port's operations and contributes to its efficiency in handling various types of cargo. It has a railway siding measuring 621 m in length.

Access to the Port of Kołobrzeg from the land side is facilitated by the S6 road, which connects Szczecin and the Tri-City area. Additionally, national road number 11 and railway lines number 402 and 404 provide further connectivity to the port.

The port of Kołobrzeg boasts an extensive reserve of quays and ample investment areas. The facility specifically has parking spaces for vessels engaged in wind farm servicing and meets the general criteria for access infrastructure to the offshore wind energy sector. According to these criteria, the quay length should be 300 m, with a load capacity of 10–20 tons per square meter, and a depth of at least 6.5 m. The port infrastructure also enables efficient use of storage and office spaces, which contributes to further development

and an expansion of service offerings. However, there is a need to enhance the technical parameters of the port entrance, the fairway, and the turning basin.

Port of Darłowo

The Port of Darłowo is included in the group of small seaports—structures of fundamental importance for the local economy. The port serves as a multifunctional economic structure where fishing, recreational, sports, and cargo handling activities take place. The Port of Darłowo is situated at the mouth of the Wieprza River, approximately 25 nautical miles west of the Port of Ustka and 33 nautical miles east of the Port of Kołobrzeg [37].

The port consists of two sections connected by a 2.5 km port channel. The first section is located in close proximity to the sea and includes breakwaters, an entrance to the port, an outer harbor, a fishing basin, and a bridge. The second section is located approximately 2.3 km from the port entrance, in direct proximity to the town of Darłowo. This section includes a turning basin, an industrial basin, and the channel of the Wieprza River—Darłowo [38].

The total area of the port is 117.16 hectares, which comprises 88.76 hectares of land and 28.40 hectares of the port basin. The port in Darłowo has quays with a total length of 5.3 km, of which the cargo quays measure 2 km. The maximum size of vessels entering the port cannot exceed 75 m in length, 13 m in width, and 4 m in draft. The parameters of the waterway in the Port of Darłowo are as follows: a length of 2.36 km, a width of 23 m, and a depth of 5.5 m. The port has a turning basin with a diameter of 110 m and a depth of 5.5 m.

In July 2022, an update to the Development Plan for the Port of Darłowo for the years 2020–2025 was adopted, focusing on five key areas: service for commercial vessels, maritime tourism, fishing, environmental protection, and offshore wind energy market [39]. This plan aims to transform the port into a logistics hub for servicing offshore farms in the Baltic Sea. For the years 2020–2025, investments have been planned, funded by the budget of the Darłowo municipality, EU funds, and private capital. The investments include the renovation of the Słupsk Quay I and II, construction of new storage areas and offices, as well as new port infrastructure for marine turbines. There are also plans to increase the diameter of the ship turning basin [11].

It is worth noting that the port hosts a transshipment terminal operated by the Gdynia Maritime Agency, which provides services for the offshore wind energy market (OWE) in the ports of Gdynia and Świnoujście. Additionally, in Sińczyca near Darłowo, there is a local service center for wind turbines operated by Wind Service. These infrastructures support the development of the renewable energy sector in the region by offering specialized services related to the maintenance of wind farms.

Port of Ustka

The Port of Ustka is one of the largest small ports on the Polish coast, located at the mouth of the Słupia River. It is administratively part of Słupsk County. Since 2013, the Ustka Sea Port Authority, appointed by the Mayor of Ustka, has been responsible for managing the port of Ustka [40]. The port of Ustka serves both industrial–commercial and fishing functions. However, in recent years, its significance as a commercial–industrial port has declined, which is attributed to the closure of the Ustka Shipyard and a notable reduction in cargo handling and visits by commercial vessels [26]. Currently, the Port of Ustka fulfills mainly a fishing function.

The total area of the port is 29.2934 ha. The port's size and its infrastructure allow vessels with a draft of up to 4.0 m (at average water level) to dock, with a maximum overall length of 60 m and a width of 12 m. In the port of Ustka, the quays and port basins are located along the eastern and western banks of the river. The port of Ustka has quays with a total length of 3.417 km, of which the cargo quays measure 160 m. The parameters of the waterway in the Port of Ustka are as follows: a length of 1 km, a width of 24 m, and a depth of 5.5 m. The port has a turning basin with a diameter of 67 m and a depth of 5.5 m.

The port of Ustka is strategically located near wind farms, providing significant economic opportunities. It is strategically located for projects on the northwestern and northeastern slopes of the Słupsk Bank, such as FEW Baltic II, Bałtyk II, and Baltica 2. Additionally, the nearby shipyards and repair facilities in Słupsk, just 20 km away, enhance the project's appeal. This close proximity would allow for the comprehensive servicing of wind farms, including crew changes and supply provisioning [41]. According to information obtained from the Maritime Office in Gdynia and the Port Authority in Ustka, a new concept is being developed for the expansion of the Port of Ustka to include an Outer Port, which will cover an area of approximately 14 hectares.

Port of Łeba

The port of Łeba is a fishing port on the Baltic Sea, located in the northern part of the Pomeranian Voivodeship, on the Słowiński Coast, in Lębork County, within the city of Łeba. It is situated at the mouth of the Łeba River and its tributary, the Chełst River [42]. The port is managed by the Łeba Port Captain's Office, a local unit of the Maritime Office in Gdynia, which, in accordance with the Act on Seaports and Harbors, serves as the administrative entity for the port. The maritime port in Łeba is a regional fishing and tourist port located approximately 29 nautical miles east of the port in Ustka, 20 nautical miles east of the port in Rowy, and 32 nautical miles west of the port in Władysławowo.

The total area of the port is 23.74 ha including 16.63 hectares of land plots and 7.11 hectares of water surface. The size of vessels entering the port must not exceed 50 m in length (65 m with the Port Captain's approval), 15 m in width, and a draft of 3.0 m. The Port of Łeba has three port basins. The parameters of the waterway in the Port of Łeba are as follows: a length of 1.175 km, a width of 20 m, and a depth of 3.5 m. The port has a turning basin with a diameter of 50 m and a depth of 3.5 m.

The port of Łeba is directly accessible via the partially modernized provincial road number 214, which intersects with provincial road number 213 and, further along, with the S6 expressway.

The location of the port in Łeba makes it an attractive site for the establishment of a service port at this time. Additionally, among the factors that support the port's transformation into a service port for offshore wind farms, the following should be mentioned: the shortest distance from the port to all areas designated for wind energy development in the Spatial Development Plan for Polish Marine Areas, convenient transport connections to the highway and express road network, and the large available and undeveloped land in the western part of the port, allows for the relatively low-cost establishment of a service facility to support the planned wind farms [43]. The implementation of operational and service functions for offshore wind farms from the port in Łeba involves the necessity of incurring costs to adapt and maintain the port's parameters in accordance with the requirements of offshore wind energy.

The analysis conducted in this study provided critical insights into the readiness of Polish local ports on the Central Baltic coast to support offshore wind energy development. The cause-and-effect analysis revealed that infrastructure limitations, such as inadequate quay lengths, shallow waterway depths, and insufficient storage capacity, directly impede the ability of these ports to handle large offshore wind components and vessels. These deficiencies result in logistical inefficiencies and increased operational costs, ultimately diminishing the ports' attractiveness to offshore wind energy operators. Furthermore, the findings underscore that targeted infrastructure upgrades, including the enhancement of quay designs and the expansion of storage facilities, could effectively address these challenges, significantly improving port functionality and operational capacity.

The analysis also identified poor road and rail connectivity as a significant constraint on the efficient movement of materials and personnel to and from the ports. These logistical bottlenecks lead to delays and higher transportation costs, further complicating operations. The indirect effects of these connectivity issues extend to reduced competitiveness, as offshore wind operators may prefer alternative ports with superior transport links. Ad-

dressing these challenges through strategic infrastructure and connectivity investments is essential to enhancing the ports' ability to serve as efficient hubs for offshore wind energy operations.

4.3. Economic and Social Benefits for Local Ports and Region from the Establishment of Offshore Wind Farm Service Ports

The potential benefits of developing offshore wind energy can be assessed based on the experiences of countries that have already implemented such projects. Examples from Denmark, Germany, and the United Kingdom demonstrate that the development of offshore wind energy contributes to increasing renewable energy production, creating new jobs, fostering economic growth, and improving energy security.

The development of the offshore wind energy sector in Poland is crucial for the country's energy transition and sustainable economic growth. The scale of benefits is dependent on the level of development in this sector. Various analyses suggest that by 2030, the sector could contribute as much as 60 billion PLN to Poland's GDP and create approximately 70,000 new jobs [44,45]. This growth will significantly benefit local economies, particularly in coastal regions engaged in the wind energy supply chain.

The establishment of offshore wind farm service ports can deliver a range of economic benefits to local regions and ports, primarily through job creation, increased investment, and local spending. The development of offshore wind energy also creates opportunities for the Polish industry [46], which accounts for 17% of GDP and 19% of employment [46].

As ports develop to support offshore wind operations, they transform into employment hubs for various sectors, including construction, maintenance, logistics [47,48], and sea transport [49,50]. The growth of this sector also necessitates the modernization of several branches of the economy not directly linked to energy production [51]. Key areas of focus include expanding shipbuilding capabilities to construct specialized vessels for transporting and installing turbines and their components. Equally important is enhancing port infrastructure to provide logistical support for these investments [52,53], along with developing storage facilities for components and equipment. Additionally, supporting sectors involved in cable production, storage, transportation [54], intermodal transport [55], intermodal terminal [56,57], and installation, as well as technical services for offshore wind farms, is vital for the overall success of the industry [58].

Examples of investments that, by supporting offshore energy, will invigorate local markets include the Vestas factory in Szczecin, which is set to produce turbines starting in 2026, creating 1000 jobs [59]. Another example of investments supporting the development of the offshore market is the construction of a production hall for offshore towers, intended for the largest planned wind turbines with a capacity of over 15 MW. This facility will have a production capacity of more than 150 towers annually, and approximately 400 people will be employed there [60,61].

5. Discussion

Wind energy, as a key element of the global energy transition, is gaining a significant share in the energy mix, enhancing energy security while promoting social and economic development at both local and national levels. Offshore wind energy, in particular, offers unique opportunities for coastal regions, including those along Poland's Central Baltic coast. The ports located on the Central Pomerania coast are not fundamental to the maritime economy; however, they are strategically positioned to become critical support hubs for offshore wind farms operations. Their geographic proximity to designated wind farms areas, coupled with Poland's ambitions to transition toward renewable energy, presents a unique opportunity for these ports to integrate into the rapidly expanding offshore wind energy sector.

Despite their potential, the findings reveal that these ports face several challenges that must be addressed to enable their active participation in offshore wind farm development. Key barriers include insufficient quay lengths, inadequate waterway depths, and

limited storage and cargo handling capabilities. Additionally, the lack of robust transport connectivity—particularly road and rail networks—hampers the logistical efficiency of these ports, reducing their competitiveness in attracting offshore wind energy operators.

The research also highlights the importance of coordinated investments in port infrastructure and superstructure. Expanding and modernizing these facilities is critical not only for accommodating larger vessels but also for enhancing the overall logistical capabilities required for supporting offshore wind energy projects. Improvements in quay design, turning basins, and specialized facilities for crew transfer vessels are essential for meeting the operational demands of this sector. Additionally, investments in waste management systems and the development of dedicated storage areas for wind turbine components will be necessary to ensure the ports can handle the specific requirements of offshore wind operations [62].

From an economic perspective, the development of offshore wind energy offers substantial socio-economic benefits for the regions surrounding these ports. The establishment of small service ports can facilitate the creation of a local supply chain, fostering economic revitalization across the coastal areas. Local industries such as tourism and fishing, while not directly related to wind energy, stand to benefit from opportunities to retrain and engage in new sectors. Moreover, these investments are expected to generate long-term economic benefits by creating jobs, attracting external capital, and enhancing regional competitiveness.

The discussion also underscores the importance of strategic planning and collaborating among stakeholders, including policymakers, port authorities, and private investors. Developing coherent strategies to address the identified challenges, particularly in the areas of policy support, funding, and infrastructure modernization, will be pivotal in realizing the full potential of these ports. International case studies from countries such as Denmark and Germany demonstrate that targeted investments in port infrastructure and supportive policy frameworks can significantly enhance the integration of small and medium-sized ports into the offshore wind energy value chain.

6. Conclusions

This study has demonstrated that the local ports along Poland's central coast—Kołobrzeg, Darłowo, Ustka, and Łeba—are well-positioned to play a significant role in the development of offshore wind farms. The findings of this study suggest that the transformation of these local ports into efficient offshore wind service hubs could serve as a catalyst for regional development and help Poland achieve its renewable energy goals. By leveraging their strategic location and addressing identified gaps, these ports can contribute not only to national energy security but also to the global fight against climate change.

The cause–effect chart (Figure 4), presented below, summarizes the key components of the analysis, which include causes, effects, and solutions. Causes highlight the limitations in infrastructure, connectivity, policy and finances. Effects demonstrate their impact on port readiness, logistical efficiency, costs, and competitiveness. Solutions propose targeted upgrades, improved connectivity, policies, and strategic investments. Moreover, the chart integrates challenges and recommendations of the study.

The study identifies key cause–effect relationships that shape the readiness of Polish local ports for offshore wind energy development, closely aligning with the critical challenges and opportunities revealed in the research. Infrastructure limitations, such as inadequate quay lengths, hinder the ability of ports to accommodate large vessels, resulting in logistical inefficiencies. Similarly, connectivity issues, such as the ports' access to provincial roads, delay material transport, increasing operational costs. The study also highlights regulatory deficiencies, which discourage private investment and result in limited investor confidence. Moreover, financial limitations impede critical infrastructure upgrades, leaving these ports underdeveloped and unable to meet the demands of offshore wind energy operations.

However, the study emphasizes that targeted solutions can effectively address these challenges. Infrastructure upgrades, including expanded quay lengths and enhanced stor-

age capacities, can transform these ports into efficient operational hubs for offshore projects. Improved transport connections and infrastructure would facilitate faster movement of materials and personnel, reducing both costs and delays. Introducing supportive policies can attract private investment, ensuring a steady influx of capital for modernization. Finally, strategic investments would position these ports as competitive logistics hubs, driving regional socio-economic growth and enabling them to capitalize on their proximity to designated wind farm areas.

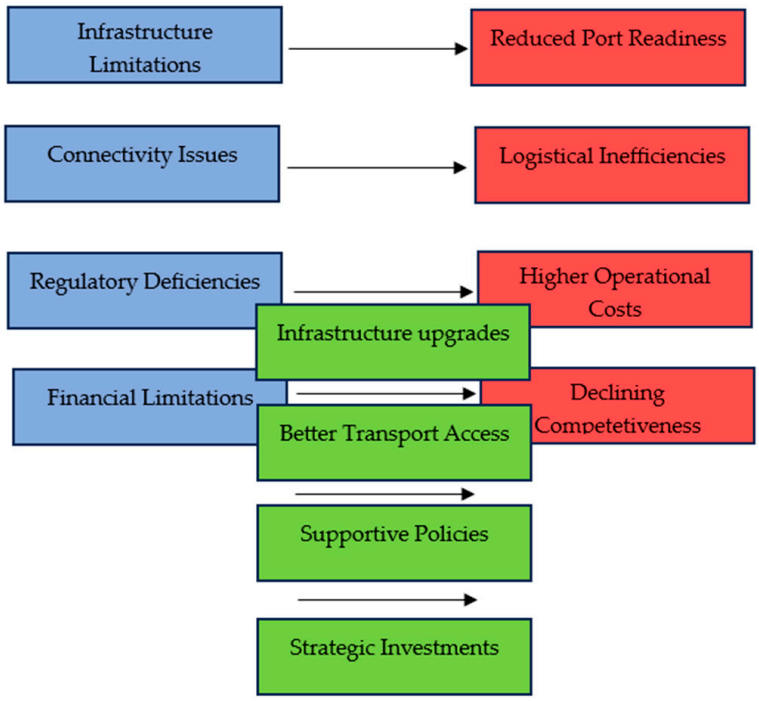

Figure 4. Cause–effect analysis of Polish ports and offshore wind energy. Source: own study.

To apply these findings to emerging markets, it is important to prioritize infrastructure upgrades, focusing on quay expansion, waterway deepening, and increased storage capacity to meet the operational demands of offshore wind energy. Improving transport connectivity through enhanced road and rail links is vital to establishing efficient logistical systems. Supportive policy frameworks are also essential. Governments in emerging markets must provide consistent regulations, streamlined administrative processes, and incentives to attract private investment in offshore wind infrastructure.

Encouraging the development of local supply chains is another key recommendation. Workforce training programs and partnerships between local suppliers and global developers can strengthen the integration of regional economies into the offshore wind sector. Public–private partnerships can also play a vital role in mobilizing resources and sharing risks, fostering sustainable development. Emerging markets should draw lessons from successful European leaders in offshore wind development and adapt them to their specific contexts, ensuring that investments are aligned with long-term national energy strategies.

In conclusion, the role of Polish local ports on the Central Baltic coast provides valuable insights for regions aiming to establish or expand offshore wind infrastructure. Targeted efforts and collaborative planning can transform these ports into vital components of Poland's renewable energy strategy, driving economic growth and sustainability. By applying these recommendations, emerging markets can address challenges, seize opportunities, and contribute meaningfully to the global energy transition. Future research should explore how these findings can be tailored to diverse regional contexts, ensuring their applicability at various stages of offshore wind development.

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