DeCoInter – Decarbonisation of Maritime Sector and its Impact on Green Energy Transition

WP2 – Maritime ports and their regions as moderators of transition towards blue renewable energy

Development Status and Supply Potential of Blue Renewable Energy in the South Baltic Region: A Foundational Study for Port Energy Transition Strategies

Consolidated FINAL REPORT

Responsible Partner: PP9 – CPL Competence in Ports and Logistics GmbH

WP2.1 – Preparation of the state of play report on the capacity of blue renewable energy in the South Baltic Sea Region (supply)

“A report on the development status of the blue renewable energy potential in the South Baltic Region (Germany, Poland, Lithuania, Sweden, Denmark), where the key task will be to estimate its **supply potential and availability schedule**, will be the starting point for further activities aimed at creating port energy transition strategies.”

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1 Introduction

The maritime sector stands at a critical juncture in the global energy transition, facing mounting pressure to decarbonize operations and align with international climate commitments. Maritime ports, as key nodes in global trade networks and energy infrastructure, are uniquely positioned to serve as catalysts and moderators for the transition towards blue renewable energy systems. The Baltic Sea region, encompassing Germany, Poland, Lithuania, Sweden, and Denmark, presents a particularly compelling case study for this transformation due to its extensive maritime infrastructure, abundant marine renewable energy resources, and progressive policy frameworks supporting clean energy development.

Current developments across the region demonstrate varying degrees of maturity in blue renewable energy deployment, from Sweden's ambitious offshore wind expansion plans targeting 90 TWh of additional capacity, to Poland's offshore wind projects in the Ławica Odrzańska area consists of 19 wind farms with a total capacity of 17,5 GW, and Denmark's established position as a global leader in offshore wind technology. Major ports including Rostock, Świnoujście, Gdynia, Gdańsk, Klaipėda, Malmö, and Copenhagen are increasingly recognizing their potential to integrate marine renewable energy sources — including offshore wind, solar, tidal, wave, and marine biomass — into their operational frameworks while simultaneously supporting broader regional decarbonization goals.

However, significant challenges persist across technical, regulatory, financial, and collaborative dimensions. These include complex spatial planning requirements, marine biodiversity protection concerns, grid connectivity limitations, regulatory constraints, funding gaps, and coordination challenges among diverse stakeholders ranging from port authorities and energy utilities to private operators and municipal governments. The integration of emerging digital technologies and AI tools for energy forecasting and transition planning adds another layer of complexity while offering unprecedented opportunities for optimization.

Through this comprehensive analysis, the work package aims to provide actionable insights that support maritime ports in their role as key facilitators of the blue energy transition, contributing to regional decarbonization goals while enhancing energy security, economic competitiveness, and environmental sustainability across the Baltic Sea maritime corridor.

The study will focus on maritime territories and Exclusive Economic Zones (EEZs) of the following countries:

- Germany
- Poland
- Lithuania
- Sweden
- Denmark

It will include major ports (e.g. Rostock, Szczecin-Świnoujście, Gdańsk, Gdynia, Klaipėda, Malmö, and Copenhagen) and examine their proximity to blue energy sites.

Illustration: Map of involved project partners and regions, own illustration

2 Regional project landscape and strategic direction

Denmark's commercial ports are at the forefront of the green transition, dedicated to reducing environmental impacts by adopting advanced sustainable infrastructure. As part of national and EU climate goals, Danish ports are investing heavily in shore power systems, renewable energy production, and green partnerships. These initiatives aim to enable vessels to switch off their engines while docked, drastically cutting emissions, noise pollution, and greenhouse gases. This transition is transforming ports into clean energy hubs and innovative industrial clusters, positioning Denmark as a leader in sustainable maritime operations.

Copenhagen Malmö Port (CMP) marked a significant achievement in June 2025 by inaugurating the largest shore power facilities for cruise ships in Europe. The system, installed at the Langelinie and Ocean Quay terminals, initially provides 20 MVA capacity with plans to upgrade to 48 MVA by 2028. This shore power infrastructure allows cruise ships to connect to onshore electricity, significantly reducing emissions while docked. AIDAnova was the first cruise ship to utilize this facility, supporting CMP's ambition to reach net-zero emissions by the end of 2025.

Additionally, the port has maintained a shore power facility for the Copenhagen-Oslo ferry route since 2021. All cruise ships calling at CMP now contribute via mandatory fees, benefitting from incentives to use the shore power system designed to maximize emission reductions especially at Langelinie.

At Vordingborg Port, Arcadia eFuels received its environmental permit in May 2025 to build a large-scale sustainable aviation fuel (SAF) production plant, aiming to produce over 100 million liters annually to support Denmark's decarbonization goals. Green2X is also planning a biomethane plant at the port, though both projects face delays due to challenges in securing off-take agreements and adapting to market conditions.

In Fredericia, the ADP port expansion includes new container terminal infrastructure supported by approximately EUR 6.75 million in CEF funding, with shore power connections for container vessels planned as part of the phased upgrade expected to complete by summer 2025.

The Port of Aarhus completed shore power facilities for cruise ships in 2023 and plans to extend this to container vessels in 2025–2026 with similar CEF support.

Denmark's ports play a pivotal role in the country's offshore wind expansion, serving as key hubs for staging, assembly, and operations & maintenance (O&M) of Baltic Sea wind farms. Ports like Esbjerg, Aarhus, and those near Bornholm provide heavy-lift capabilities and logistics for turbine components, while the updated Danish Maritime Spatial Plan doubles sea areas for renewables to ~30%, enabling energy islands and cross-border hydrogen corridors that link offshore power directly to port electrification and PtX fuel production.

Together, these efforts illustrate Denmark's commitment to sustainable port infrastructure, significantly reducing maritime emissions while advancing innovative green technologies and supporting European climate objectives.

Denmark's long-term direction combines large-scale offshore renewable expansion, PtX/hydrogen scale-up, and cross-border energy infrastructure, with ports positioned as enabling hubs. A key framework condition is the updated Danish Maritime Spatial Plan, which reflects political intent to double the sea area designated for renewable energy and energy islands from ~15% to ~30% in order to enable a comprehensive offshore wind build-out (including areas in the Baltic Sea and around Bornholm). In parallel, Denmark is advancing the system-level "backbone" needed to move energy across borders: Energinet's feasibility work explicitly addresses a hydrogen transmission corridor in Jutland with a connection toward Germany, and recent public updates indicate timelines shifting into the early 2030s, underlining the scale and complexity of the build-out.

At port level, long-term plans are increasingly expressed through electrification, shore power (OPS), and port-as-energy-hub positioning. The Port of Aarhus frames its transition through operational decarbonisation and electrification, including the commissioning of Denmark's first cruise shore power facility (2023) and a corporate goal of being CO_2-neutral by 2030. Port Esbjerg's strategy emphasizes green transition as a strategic priority (infrastructure, partnerships, and innovation activities) — illustrating how ports are planning not only to reduce their own footprints, but also to enable renewable energy logistics and emerging fuel value chains over the coming decade.

Current and future blue renewable energy projects in Mecklenburg-Vorpommern's port regions are dominated by offshore wind and hydrogen initiatives, with ambitious targets, significant investments, and clearly identified challenges. The main projects span 2025-2027, featuring both ongoing installations and new large-scale developments that underpin Germany's decarbonization drive.

As of 2025, Mecklenburg-Vorpommern hosts multiple offshore wind farms, including Wikinger, Arkona, and the upcoming Baltic Eagle, positioned near the island of Rügen. The O-2.2 Offshore Wind Project (Baltic Sea) is a major development with 1,000 MW capacity, set to begin construction in 2026 and planned for commercial operation by 2030. Westmecklenburg's wind priority areas have been officially designated for development until 2027, covering 1.4% of the planning region, with expansion goals of 2.1% by 2032. The region will host Germany's first power-to-gas hydrogen plant connected to the natural gas grid (RH2-PTG) near Altentreptow, producing renewable hydrogen directly from wind power. Additionally, a 100 MW electrolyser is under construction in Rostock's port area, scheduled for completion by end of 2026, with possible scale-up to 1,000 MW and an annual output of up to 6,500 metric tons of green hydrogen.

Table 1. Overview of Offshore Projects in Mecklenburg-Pomerania

Project/Initiative	Region	Status (2025)	Capacity/Scale	Timeline/Notes
Baltic Eagle offshore wind	Rügen area	Planned/underway	>300 MW	Priority marine area, expansion ongoing
O-2.2 Offshore wind	Baltic Sea	Permitting	1,000 MW	Construction 2026; operation 2030
RH2-PTG hydrogen plant	Altentreptow	Operational/expanding	Pilot scale	Integration to grid, new tech
Rostock Mega Hydrogen Plant	Rostock port	Construction	100 MW (expandable)	Complete by end 2026; up to 1,000 MW
Onshore wind expansion	Westmecklenburg	Priority areas set	1.4% of region	Goal: 2.1% by 2032

Germany approved a record 7.8 GW of new wind power capacity (onshore/offshore) in the first half of 2025; Mecklenburg-Vorpommern is a key contributor due to large marine areas and port infrastructure. Offshore wind turbines commissioned in German waters (including MV) averaged 10.2 MW each in 2024, with total installed offshore wind capacity at 9.2 GW and annual additions expected to increase towards the end of the decade. Around 72% of electricity generated in MV already comes from renewable sources, emphasizing the pivotal role of blue energy in the regional mix.

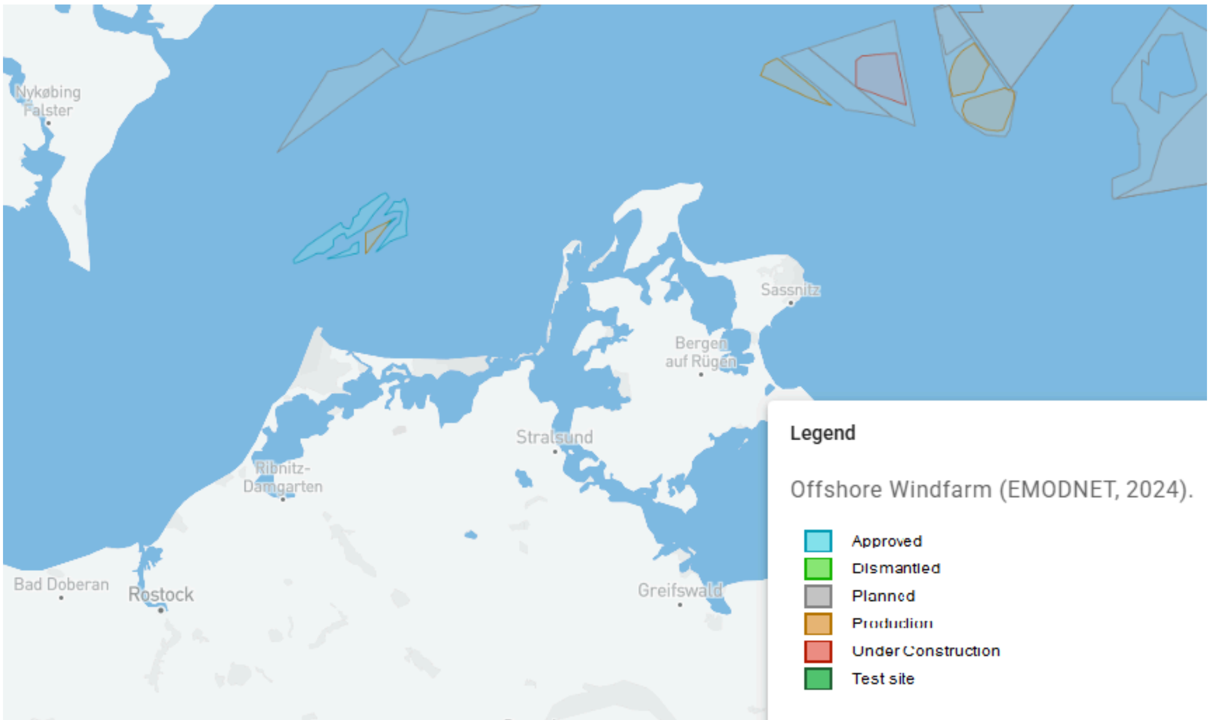

Figure 1. Map of German Baltic sea offshore wind parks;
Source: https://viewer.openearth.nl/compendium-greater-north-sea

Many blue energy projects in MV are either at the permitting stage or under construction for 2025–2027, with commercial operational dates targeted for 2027–2030. Scaling up to 1,000 MW hydrogen projects and expanded offshore wind zones position MV as Germany's leading "energy state" and Baltic gateway for marine renewables. Significantly higher rates of annual wind and hydrogen capacity additions are projected for late 2020s, with ongoing emphasis on digital solutions, public engagement, and regional export connectivity.

Mecklenburg-Vorpommern's ports anchor Germany's transition to blue renewable energy, with substantial new wind and hydrogen projects scheduled for 2025-2027, coupled with both technical and social innovation and growing infrastructure investment. Mecklenburg-Vorpommern has a nationally leading technical and theoretical potential for offshore wind, with important but much smaller prospects for marine solar, tidal, wave, and biomass energy in its Baltic port regions. Offshore wind is by far the largest contributor — both in existing port operations and future planning — with renewables overall making up more than 70% of regional electricity generation.

- **Offshore Wind:** Technical potential exceeds 2,500 MW in designated Baltic Sea zones, with up to 1,500 MW additional capacity planned — offshore wind can theoretically cover over 180% of the region's electricity needs, and the foreshore port terminals are central to installation and maintenance. Wind energy is available 24h a day but seasonal limited (high availability in autumn-spring, moderate-high in summer seasons)

- **Solar (coastal/on marine infrastructure):** Theoretical offshore solar (floating/facade systems) potential is much lower — typically single-digit MW per site. ; current port solar installations account for less than 3% of local generation, but scalable demonstration projects are ongoing.
- **Tidal, Wave, Marine Biomass:** The potential for these in the southern Baltic is technically low because of limited tidal range, moderate wave action, and constrained biomass yields. Tidal and wave projects may reach a few MW capacity in demo settings by 2030 but are not central to energy strategies; marine biomass (e.g., algae) research remains at pilot stage.
- **Port Power Mix (2025):** Wind (onshore/offshore): 48%, Biomass: 16%, Solar: 8% of MV's electricity generation — ports and terminals are major hubs for wind and hydrogen, but alternative marine renewables remain at experimental scales.

Table 2. Overview of Used vs. Planned Energy Capacity in Mecklenburg-Pomerania

Energy Source	Percentage Used in Ports 2025	Planned 2030 Target
Offshore Wind	>50%	Up to 70%
Onshore Wind	>30%	Stable/declining
Solar (PV)	<3%	Up to 7%
Biomass/Biogas	<5%	5-8%
Tidal/Wave/Marine	<1% (demo only)	Up to 2% (possible)

Most port electrification and hydrogen electrolysis rely on wind and solar, with other sources contributing marginally or not at all. Offshore wind and hydrogen are prioritized in most port-terminal investments.

Acceptance and Incentives

- **Most Accepted:** Offshore wind and hydrogen projects are favoured by policymakers, service operators, and terminal managers because of mature technology, grid integration, and export capacity.
- **Solar and Biomass:** Accepted as supplementary but not primary sources; more focus on pilot and demonstration projects, especially floating PV as tech matures.

- **Tidal/Wave/Marine:** Low acceptance for large-scale deployment — mainly scientific curiosity or future diversification.
- **Incentives:** The state provides up to 45% investment grants for establishment of renewables installations (especially wind and hydrogen), R&D funding for innovative solar and marine projects, and prioritized grid access for renewables. EU ERDF funding mechanisms, local technology networks, and workforce development all actively support wind, hydrogen, and sector-coupling projects, but specific support for wave/tidal/marine biomass is limited to early-stage or academic research.

Challenges in Adapting/Using Alternatives:

- **Wind:** Grid bottlenecks, planning conflicts, and local opposition remain challenges for additional expansion.
- **Solar:** Limited space on terminals for PV, coastal exposure to salt/marine weathering affects systems, high costs for offshore floating solar.
- **Tidal/Wave:** Physical constraints in the southern Baltic Sea (low tidal range, moderate wave heights), high costs, unproven reliability.
- **Marine Biomass:** Technological and scaling barriers, uncertain yields, and few economic incentives for marine biomass energy.

State actors and port authorities prioritize wind/hydrogen in all strategic investments and grid planning, while most service providers focus on proven technologies and reliability. Local terminal operators cautiously support solar and biomass pilots but remain reserved about tidal/wave due to risks and costs, and report little market pull for these alternatives at present. Policy incentives and public funding reflect clear favouring of offshore wind, followed by port-sector hydrogen, with alternatives rarely prioritized except in niche or demonstration contexts. Mecklenburg-Vorpommern's port regions will remain highly wind- and hydrogen-centric, with solar scaling slowly and other alternatives limited by technical and economic challenges.

Table 3. Overview of Existing and Planned Renewable Energy Capacity in Mecklenburg-Pomerania

Energy source	**Technical Potential (MW)**	**Seasonal variabilility**	**Diurnal (24h) Variability**	**Planned availability timeline**
Offshore wind	2,500 MW technical potential; about 50% of the current mix (target 70% by 2030)	High (autumn–spring), moderate–high (summer)	24h	Ongoing – O-2.2 (1,000 MW by 2030), Baltic Eagle (300 MW under development)
Onshore wind	About 30% of regional power generation (2025), planned to decrease share	Moderate–high (autumn–spring)	24h	Expansion of designated areas until 2027–2032 (from 1.4% to 2.1% of the region)
Solar PV	About 3% in 2025, target up to 7% by 2030	High (late spring–summer), low (winter)	Day time, peak at midday	Ongoing pilot and demonstration projects
Green hydrogen	100 MW electrolyser (completion end of 2026), expandable up to 1,000 MW	Depends on wind/solar, storable year-round	24h	RH2-PTG in operation, large-scale plant in Rostock planned until end of 2026
Marine biomass	About 16% of generation in 2025, target 5–8%	Stable year-round	24h	Ongoing use with limited expansion plans

Tidal/wave energy	Up to about 2% potential (demo scale only)	Tidal predictable, wave weather-dependent	Tidal predictable, wave weather-dependent	Research and pilot phase towards 2030

Mecklenburg-Vorpommern's maritime strategy sets clear goals: climate neutrality in energy by 2045, ports as hydrogen hubs, acceleration of solar and offshore wind expansion. Plans include expanding sector coupling (energy, industry, shipping), integrating digital infrastructure, and reinforcing external economic relations via Baltic Sea partnerships. National initiatives align with regional plans, targeting full renewable supply for electricity, heat, and mobility, and supporting CO2-free port operations and smart city connections. Port authorities and industry groups commit to continuous infrastructure upgrades, research investment, and development of export-oriented green maritime economies.

Concrete recommendations include expediting planning/approval, facilitating technology transfer, co-financing large-scale energy projects, and building out digital and hydrogen capacities — anchoring Mecklenburg-Vorpommern as a gateway of Germany's Baltic energy transition.

Over the past decade, the Port of Klaipėda has embarked on a progressive energy transition journey, with several pioneering projects laying the groundwork for its current green infrastructure initiatives.

One of the earliest major steps was the commissioning of an LNG (liquefied natural gas) bunker vessel in 2017, marking Klaipėda as a regional forerunner in adopting cleaner marine fuel alternatives. The LNG bunker ship has provided more environmentally friendly fuel options for vessels, significantly reducing sulfur and particulate emissions, and preparing the port for upcoming stricter emission regulations. This project positioned Klaipėda as a key LNG hub in the Baltic Sea region.

During much of this period, Klaipėda's electricity supply was partly dependent on a grid interconnection with Russia. This connection, however, presented notable geopolitical and energy security risks. Over recent years, Lithuania has decisively reduced reliance on Russian energy networks, diversifying and reinforcing national grid connections with neighboring countries and expanding domestic renewable energy generation capabilities. This energy independence drive has been critical to enabling Klaipėda's transition to greener energy sources.

Grid Decoupling and Strengthening: The disconnection from the Russian grid was completed by 2023, which enhanced Klaipėda's energy security and enabled full integration into the Baltic and European electricity markets. Concurrent investments in grid infrastructure, substations, and interconnectors laid the foundation for renewable energy integration.

Energy Efficiency and Port Electrification Efforts: Early voltage conversion and port electrification investments facilitated the initial deployment of shore power for smaller vessel classes prior to the large-scale OPS projects currently underway.

Sustainability and Environmental Certifications: Over the decade, Klaipėda port progressively adopted environmental management standards and climate action plans, increasingly incorporating renewable energy and emission reduction targets, aligned with EU directives.

Today's ambitious rollout of advanced OPS infrastructure for Ro-Ro, Ro-Pax, and cruise vessels, along with the landmark green hydrogen production facility, build directly upon this decade of energy innovation. The transition from LNG bunkering to hydrogen and electrification represents a clear evolution towards zero-emission port operations.

The decoupling from Russian grid influence has not only reduced geopolitical risk but also enabled Klaipėda port to coordinate more effectively with national and EU renewable energy policies, receive international funding, and participate in coordinated maritime energy transition strategies.

The cumulative impact of projects from LNG bunkering through grid independence to the latest green hydrogen and shore power initiatives underscores Klaipėda's transformation into a climate-resilient, sustainable port. It exemplifies the strategic layering of innovations over time to advance energy transitions systematically, balancing immediate emission reductions with long-term clean energy adoption.

This comprehensive history enhances Klaipėda's position as a model green port in the Baltic region, supported by a matured infrastructure network, diverse clean fuel options, and a clear pathway to net-zero operations by 2030 and beyond.

The Port of Klaipėda is advancing a comprehensive green hydrogen production and Onshore Power Supply (OPS) strategy as key pillars of its energy transition. The green hydrogen project centers on a polymer electrolyte membrane (PEM) electrolyser with an installed capacity of approximately 2.25 MW — capable of producing up to 127 tons of green hydrogen annually once fully operational. This state-of-the-art facility, scheduled to commence operations in early 2026, is the first of its kind in Lithuania and the broader Baltic region. It supports decarbonizing port logistics, powering port vessels, heavy-duty vehicles, and public transportation, marking a milestone in regional green fuel deployment. The project, valued at around €12 million, has secured approximately half its funding from EU sources such as NextGenerationEU.

Complementing hydrogen production, the Port Authority is building OPS infrastructure designed to deliver clean electricity to Ro-Ro, Ro-Pax, and cruise vessels directly at berth. Initial OPS stations with a combined 6 MW capacity for Ro-Ro and Ro-Pax vessels will be operational from April 2026, with further expansions planned to accommodate cruise and container vessels, pushing total capacity beyond 30 MW in the coming years. This setup directly reduces emissions from berthed ships, significantly improving local air quality and port sustainability.

Looking to the future, the Port is developing a new approximately 100-hectare area where electricity demand could reach up to 200 MW. This new zone aims to be fully powered by green energy, further integrating offshore wind energy and participation in renewable energy clusters under evaluation. The port works closely with ESO (the distribution system operator) and LITGRID (the transmission system operator) to reinforce grid infrastructure and ensure reliable supply for expanding renewable energy and storage solutions, including batteries and hydrogen storage.

Klaipėda's approach represents a forward-looking, integrated strategy to transform the port into a green energy hub within the Baltic region, supporting Lithuania's national targets for renewable energy expansion, decarbonization, and energy independence by 2030 and beyond.

Table 4. Overview of Existing and Planned Renewable Energy Capacity in Klaipėda Region

Energy source	Technical Potential (MW)	Seasonal variabilility	Diurnal (24h) Variability	Planned availability timeline
Offshore wind	About 1,400 MW (two farms combined), around 6 TWh annual output expected	High year-round (expected)	24h	Expected to be operational by around 2035
Onshore power supply (OPS)	Multiple 110/10 kV substations; about 43.66% of supply already from renewables	Year-round, when vessels are at berth	24h	Full OPS rollout for RoRo, cruise and container vessels by 2028

Green hydrogen	About 1.27–2.25 MW electrolyser capacity, around 127 tons annual output	Flexible production, storable year-round	24h	Installation from 2025 onwards, operation expected by 2026
Solar PV	Rooftop PV at Port of Klaipėda (small-scale)	High (summer peak), low (winter)	Day time, peak at midday	Ongoing, mainly via supply from the external grid
Tidal/wave/marine biomass	No commercial capacity	Research only	24h	Early-stage research

Poland's offshore wind energy sector is experiencing rapid development, with major projects underway and significant future investment planned for 2025–2027 and beyond. ORLEN Neptun has secured five sites in the Baltic Sea for offshore wind farms totaling approximately 5.2 GW: four on the Oder Bank and one on the Słupsk Bank, adjacent to the Baltic Power project (1.14 GW capacity).Baltic Power, a joint venture between ORLEN and Northland Power, is Poland's first major offshore wind farm, currently installing turbines with a total capacity of 1.1–1.2 GW (76 turbines at 15 MW each), set to be fully operational in 2026, ultimately covering up to 3% of Poland's electricity needs. Additional major projects are Bałtyk 2 and 3 (Equinor/Polenergia, 1.44 GW) which are scheduled for completion in 2028, Baltica 2 (PGE/Ørsted, 1.5 GW), starting construction in 2025, with power delivery set for 2027 and BC-Wind (Ocean Winds, 500 MW): contract phase, with first power expected in 2028.

Table 5. Overview of Existing and Planned Renewable Energy Capacity in Voivodeships Pomerania and West Pomerania

Name	**MW (planned)**	**Commissioning**	**Partners**	**Status (2025)**
Baltic Power	1,140–1,200	2026	ORLEN/Northland Power	Turbine installation
Bałtyk 2+3	1,440	2028	Equinor/Polenergia	FID reached
Baltica 2	1,500	2027	PGE/Ørsted	Construction begins
BC-Wind	500	2028	Ocean Winds	Supplier agreement

The target is to reach 5.9 GW installed offshore wind capacity by 2030, with up to 18 GW planned by 2040.

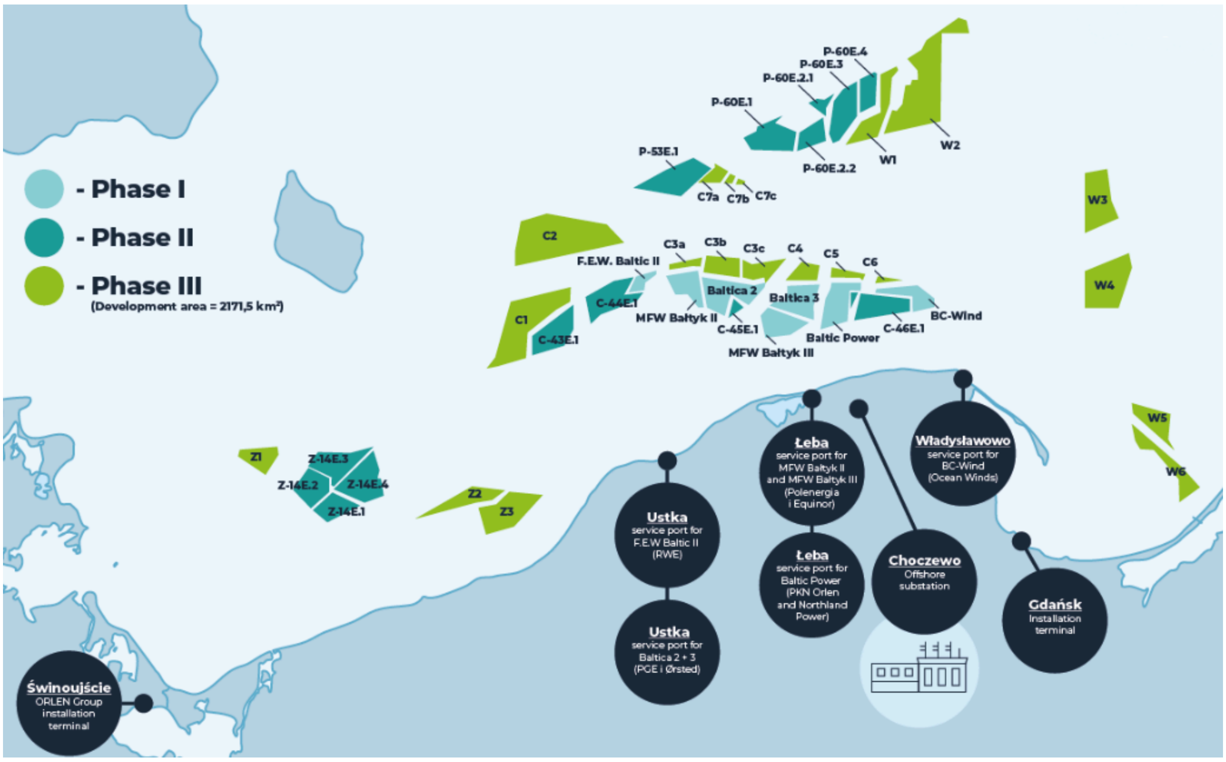

Figure 2: Map of offshore wind parks in voivodeships Pomerania and West Pomerania
Source:https://balticwind.eu/szesc-kolejnych-lokalizacji-ii-fazy-polskiego-offshore-przyznane/

Key Challenges

- The integration of Polish companies into the supply chain is still limited (currently 12–15%, with a target of 20–38% for future projects).
- High investment and financial barriers, especially for local SMEs; international partners are crucial for expertise and capital.
- Infrastructure expansion: major ports in Gdańsk, Gdynia, and Szczecin/Świnoujście are being modernized as assembly and transport hubs, with new service bases already launched.
- Regulatory and political reliability is essential for international investment and supply chain security.

ORLEN Neptun opened the first modern offshore installation port in Świnoujście in mid-2025.Global consortia are leading technical delivery (e.g., turbine manufacturing, cables, towers) and logistics, ensuring advanced technology and local job creation. Local manufacturing plants such as Baltic Towers in Gdańsknow produce towers for 15 MW+ turbines with an annual capacity of over 150 units.

The offshore wind sector in Poland will trigger annual investment of between €5–6 billion for 2024–2027. Up to 77,000 new jobs could be created by 2030, especially in coastal areas. Offshore wind development is expected to generate approximately 3.7 billion EUR in tax revenue by 2030. Offshore wind is the backbone of Poland's energy transformation, aiming for 5.9 GW installed by 2030 and 18 GW by 2040, with phased auction rounds and price caps for further capacity allocation. Poland's offshore sector will see further rounds for up to 12 GW additional capacity, with innovative solutions like hydrogen integration and floating wind considered for future phases, but current focus is on fixed offshore wind projects.

Sweden is actively advancing its blue renewable energy sector, with offshore wind playing a central role in delivering an additional estimated 90 TWh of annual electricity generation in the coming decades. This expansion is particularly significant for the Blekinge region, which is expected to become a key node in the offshore grid through the development of planned connection points (offshore hubs). These hubs will facilitate the integration of large-scale offshore wind capacity from the Baltic Sea into the national grid while strengthening regional energy infrastructure.

Despite having only around 190 MW of offshore wind capacity installed across four wind farms by the end of 2023, Sweden has a substantial project pipeline. Several major offshore wind developments are planned between 2025 and 2027 and beyond. For example, the Nordlicht 1 and 2 projects are expected to be operational by 2026, adding approximately 1.6 GW of capacity. Statkraft is also advancing multiple large-scale projects, including the 2.5 GW Beta project—targeted for completion by 2030—and Delta North (2.1 GW) in Sweden's Baltic Sea exclusive economic zone. Together, these initiatives contribute to a projected pipeline of nearly 98 GW, with parts of this capacity expected to connect via offshore hubs serving regions such as Blekinge.

Swedish ports and their governing organizations have articulated ambitious long-term plans to actively support and realize the energy transition in maritime operations, aligning with national and EU climate goals. At the organizational level, ports aim to significantly reduce fossil fuel dependency by expanding renewable energy integration, particularly offshore wind power and solar photovoltaic systems, to supply shore power and terminal operations efficiently.

Concrete plans include the development of infrastructure to enable widespread use of green hydrogen as an alternative fuel for heavy-duty equipment and vessels, supported by investments in hydrogen production, storage, and refuelling facilities within port areas. Pilot projects and feasibility studies focus on validating hydrogen's operational viability and safety, paving the way for scaled deployment.

3 Resource potential and technology portfolio

Danish ports and terminals are increasingly adopting digital and AI tools to forecast energy demand and design energy transition strategies. A key technology gaining prominence is the use of digital twins — virtual replicas of port infrastructure and operations. These digital twins enable real-time simulation and analysis, helping port operators optimize energy consumption, plan renewable energy integration, and assess the impact of new energy systems such as shore power or local generation facilities.

The Danish state has designated significant areas in the Baltic Sea for offshore wind development, with the Energy Island Bornholm project as a central element. The island is expected to generate between 3 and 3.8 GW of offshore wind power, with the potential to expand by an additional 1.5 GW. While current regional electricity demand is far below this projected capacity, this surplus creates a strategic opportunity rather than a limitation. In particular, it positions Bornholm and its associated infrastructure as a key hub for future energy distribution and conversion.

In this context, the Port of Rønne is expected to play a pivotal role as a distribution and logistics center for offshore wind energy. Beyond serving installation and maintenance activities, the port has strong potential to facilitate the handling, processing, and onward distribution of excess electricity. This surplus energy can be utilized for the production of green fuels such as hydrogen, e-methanol, or ammonia, enabling storage, export, and sector coupling. By linking offshore generation with fuel production and maritime logistics, the Port of Rønne could evolve into a critical node in the Baltic Sea's emerging green energy value chain.

Denmark's broader offshore wind developments reinforce this trajectory. The Kriegers Flak 1 offshore wind farm currently operates at 600 MW, while Kriegers Flak 2 is planned to reach up to 3.5 GW. Together with Energy Island Bornholm, these projects underline Denmark's ambition not only to expand renewable capacity but also to leverage surplus generation through integrated infrastructure and green fuel production pathways.

Figure3: Map of Danish offshore wind parks; Source:https://ens.dk/en/press/danish-energy-agency-presents-new-draft-tender-materials-6-gw-offshore-wind-and-invites

Onshore, the Danish government aims to increase solar energy capacity to four times the current levels. However, the solar build-out has largely stalled due to unfavorable business conditions linked to low electricity prices, making new investments less attractive at this time. There are currently no concrete plans for wave energy development in Denmark, though activities related to wave energy generation are permitted and could be pursued by ports seeking to expand their renewable energy portfolios.

Regarding tidal energy, marine biomass, and other emerging marine energy sources, these are not yet significant contributors in Denmark's energy mix, with more focus placed so far on offshore wind and solar power.

Challenges for adopting these alternative energy sources generally include regulatory uncertainties, grid integration issues, economic viability, and the evolving market conditions for renewable energy investments. The state largely supports offshore wind with clear strategic targets and designated development areas, while solar energy faces market-related hurdles.

Terminal operators, service providers, and policymakers tend to favour offshore wind as the primary renewable energy source due to its scale, maturity, and alignment with national climate goals. Solar energy is also recognized but currently lags in development pace. Wave, tidal, and marine biomass energies are less established and thus receive comparatively less focus.

Incentives by the Danish government and the European Union strongly favour offshore wind projects, including subsidies, state-backed loan guarantees, and co-funding frameworks like the Connecting Europe Facility. These measures aim to accelerate the deployment of large-scale offshore wind farms and support related infrastructure developments such as energy islands and port shore power facilities.

Overall, while offshore wind leads in technical potential and political support, other renewable marine energy forms remain in earlier stages of exploration and demonstration. This reflects a phased approach to transitioning maritime energy systems with proven technologies prioritized, and emerging options monitored for future integration.

Offshore wind is a key component of Germany's energy supply, with targets to expand capacity from the current 8 GW to 30 GW by 2030, 40 GW by 2035, and 70 GW by 2045, requiring not only more turbines but also more powerful ones. Research on wave and tidal energy is supported by advanced facilities such as the GWK+ flume in Hannover, which can simulate tidal currents up to 20,000 L/s and waves up to 3 m, while a smaller 40 m flume in Braunschweig allows for cost-effective testing of turbine designs. These research and development infrastructures enable the creation of optimized and reliable offshore turbines, helping to accelerate expansion and reduce deployment costs.

Germany's energy transition faces high costs, grid expansion needs, reliance on imported fossil fuels, and technical challenges integrating renewables and green hydrogen. Phasing out coal and nuclear creates regional economic impacts and energy gaps. Solutions include green hydrogen development, renewable energy expansion, and improved energy efficiency and demand management. Geopolitical shifts, especially the Ukraine war, have heightened energy security concerns and accelerated diversification efforts.

In Mecklenburg-Vorpommern, offshore wind is prioritized as the main renewable energy source, taking advantage of coastal locations and port infrastructure in Rostock, Sassnitz-Mukran, Wismar, Stralsund, Lubmin/Greifswald, Barth, Wolgast, and Ueckermünde. Projects such as Wikinger, Baltic Eagle, and Windanker support regional development and align with Germany's national climate goals. While solar energy is acknowledged, its growth is slower due to market-related challenges, and emerging marine energy sources such as wave, tidal, and marine biomass, remain largely experimental. Germany has long been a global leader in renewable energy, with early policies like the Renewable Energy Act and feed-in tariffs boosting solar and wind adoption. Wind energy faces land, environmental, and wildlife constraints. Overall, Mecklenburg-Vorpommern and Germany continue advancing renewables despite economic, environmental, and geopolitical challenges.

Generally, while offshore wind holds a leading position in Germany's renewable energy strategy and enjoys strong political and financial support, other forms of marine renewable energy such as wave, tidal, and ocean thermal remain at early research and pilot stages. This reflects Germany's pragmatic, phased approach to maritime energy transition, prioritizing mature offshore wind technologies while continuing to monitor and assess emerging marine energy concepts for future integration.

Germany's ports benefit from strong policy and funding support for renewable energy, while adopting digital twins and AI tools to optimize energy use and integrate green technologies.

Ports and terminals in Mecklenburg-Vorpommern are advancing in the use of digital and AI tools to forecast and design energy transition demand, especially as they expand renewable energy integration and electrification efforts.

- **Energy Forecasting Platforms:** Advanced AI-driven models are used to forecast shore power demand, optimize energy purchasing, and balance renewable energy flows (wind, solar) with port and vessel needs. These forecasting tools analyze real-time weather, berth occupancy, ship schedules, and historical load to produce short- and medium-range energy demand forecasts.
- **Smart Grid and Battery Optimization:** AI platforms help manage the port energy microgrid, including battery energy storage and local renewable generation, by predicting supply/demand mismatches and proposing optimal storage or load shifting strategies.
- **Predictive Maintenance:** Machine learning tools process sensor data from wind turbines, solar panels, and port infrastructure, predicting maintenance needs and preventing downtime for both energy-producing and heavy operational equipment.
- **Scenario Planning and Maritime Routing:** Some ports deploy AI-supported decision tools to model complex decarbonization scenarios — modelling changes in vessel routing, port traffic, fuel switching, and evaluating renewable alternatives according to policy or market shifts.
- **Port Community Solutions:** As part of EU projects (e.g., REDII Ports), digital twins and online hubs create a virtual representation of the port energy ecosystem, supporting long-term investment, resource-sharing, and stakeholder decision-making.

These tools are applied in operational planning (site-level grid management, vessel charging), port expansion or new renewable integration projects, asset management (equipment upkeep, efficiency monitoring), and strategic energy transition planning. Pilot projects focus on optimizing shore power for vessels, reducing diesel reliance, and maximizing use of local wind power in real-time (especially in ports like Rostock and Sassnitz-Mukran). Port authorities and terminal operators work with tech providers, universities, and European partners to develop and adapt these AI systems to northern German port conditions.

The deployment of digital/AI tools in MV ports is heavily subsidized through EU programs, such as Interreg (REDII Ports), Horizon Europe, and the European Green Deal transition funds. These grants cover initial investments, pilot deployments, and technology transfer actions for smart port projects. Mecklenburg-Vorpommern's state government provides direct support for "digitalization of port infrastructure" and subsidizes the implementation of AI-driven energy solutions as part of broader harbour modernization and decarbonization plans.

At present, the Port of Klaipėda does not use dedicated digital or artificial intelligence (AI) tools for energy demand forecasting or transition planning. Energy needs and forecasts are handled by port energy specialists using traditional analytical methods, with more complex modelling developed within ongoing electrification and infrastructure studies (such as the 2025–2026 Electrification Study).

Conventional methods, not AI, are currently the norm for forecasting and scenario modelling for energy transition projects at the Port of Klaipėda. More advanced digital platforms and AI-based solutions — including forecasting energy demand, smart charging simulations, and optimizing logistics — are explored within collaborative innovation initiatives, such as hackathons and cluster projects in the Free Economic Zone, but are not yet systematically deployed for official port energy planning. Experimental AI models, including Large Language Models (LLMs) fine-tuned on historical maritime data, are being prototyped for tasks such as forecasting vessel arrivals, estimating CO_2 emissions, and optimizing electricity use, but remain in the trial or academic stages rather than in regular use at Klaipėda Port. Broader European maritime logistics and energy projects do employ digital forecasting and AI tools, but in Klaipėda, these are so far limited to research, pilot efforts, or are in the planning phase for future integration.

Digitalisation and AI-based forecasting remain emerging tools in Klaipėda Port's energy transition planning. While their adoption is being explored, current forecasting practices are traditional, and subsidies for AI are integrated within larger infrastructure or innovation budgets, not directed at energy transition-specific AI tools.

Here is a comprehensive summary of the technical and theoretical potential, current use, challenges, acceptance, and incentives for offshore wind, solar, tidal, wave, and marine biomass energy sources in Lithuania (Klaipėda region), particularly focusing on ports and terminals:

Offshore Wind: Lithuania has major plans for offshore wind farms in the Baltic Sea near Palanga, with a current capacity of around 700 MW with plans to expand to 1,4 GW. It is expected to generate up to 6 TWh per year, meeting about half of the country's current electricity demand by 2035. These farms will cover around 120-136 km² each and represent a key project for national energy independence with significant investments and job creation. However, no offshore wind turbines are installed inside ports due to space and operational constraints.

Solar Energy: Large-scale solar farms are not feasible inside port territories in Lithuania because all available land is leased. Nevertheless, rooftop solar PV installations are present on warehouses and offices within ports. Solar energy is also being planned or installed remotely and connected to the grid. Port Klaipėda tenants and other operators increasingly adopt solar PV on available rooftop spaces.

Tidal and Wave Energy: There is notable academic and prototype development activity in wave energy involving linear generators with high efficiency, suitable for small to larger scale deployments. However, large-scale tidal or wave energy deployment in Lithuanian territorial waters and ports remains unimplemented and in early research phases. Ice formation in the Baltic Sea limits wave energy in winter.

Marine Biomass: Lithuania has active research into marine biomass, particularly seaweed from the Baltic Sea, for use in energy generation through methods like slow-pyrolysis and anaerobic digestion.

In Lithuanian ports, especially Klaipėda, around 44% of total electricity consumption by port companies is obtained from renewable energy sources, mainly from rooftop solar and green electricity purchased through the grid. Offshore wind electricity supply to ports is expected in the future through national grid connections once wind farms become operational (~2035). Klaipėda Port is pioneering green hydrogen initiatives powered by renewable electricity, aiming to produce green hydrogen for vessels and port equipment, reflecting emerging renewable use beyond electricity. Other renewable sources like wave, tidal, and marine biomass are not yet deployed or planned in ports.

Lithuania’s Port of Klaipėda is supplied by the national electricity grid, operated through multiple substations by ESO (distribution) and LITGRID (transmission), with supply reliability and capacity being essential due to uneven daily and seasonal load fluctuations as well as growing electrification demands. The port increasingly relies on green electricity, with 43.66% of power sourced from renewables, and current infrastructure supports both conventional terminal needs and future projects such as shore power (OPS), green hydrogen production, and local energy storage.

Polish ports remain at an early stage in leveraging digital and AI tools for energy transition, but growing EU and national subsidies, successful international benchmarks, and new pilot projects are setting the stage for future expansion, especially in forecasting and integrated infrastructure management.

Poland is rapidly evolving from a newcomer to the Baltic Sea's leading offshore wind market, with total technical potential as high as 33 GW — over half of the country's current electricity consumption could be met through renewables in the coming decades.

Offshore wind energy is transforming Poland's power sector through large-scale investments, strategic international partnerships, local supply chain growth, and landmark infrastructure projects. The first green electricity from Polish offshore farms will flow in 2026, with massive expansion and investment continuing through 2030 and beyond.

Technical & Theoretical Potential by Source:

- Offshore Wind: Technical estimates of the Baltic Sea's Polish sector offers a potential Energy output between 7.7–18 GW based on current technologies and suitable sea space. Wind conditions (9–10 m/s) and seabed characteristics are favourable, with actual projects targeting 5.9 GW installed by 2030 and 18 GW by 2040.
- Solar (Photovoltaics): Poland's solar capacity exceeds 21,8 GW (projects above 50 MW nearly half), with rapid expansion in all regions; theoretical maximum is several times this, but technical/economic limits remain under study.
- Tidal: The technical potential in the Baltic is modest given low tidal amplitudes, with no commercial developments yet. The focus remains on research and pilot demonstrators.
- Wave: Theoretical wave energy potential along Poland's coast is estimated at around 6 GW, with the Baltic Sea as a whole offering up to 24 TWh per year. Technical potential for wave converters at wind farm sites ranges from 262–1,880 MW depending on technology (WaveBob, WaveDragon, WaveStar).
- Marine Biomass: There is significant theoretical potential, especially via biogas/biomass plants in the region (e.g., Szczecin has 76 MW biomass), but marine-sourced biomass remains largely untapped in commercial-scale energy.

Table 6. Overview of Existing and Planned Renewable Energy Capacities in the Baltic Sea

Energy source	**Technical Potential (MW)**	**Seasonal variabilility**	**Diurnal (24h) Variability**	**Planned availability timeline**

Offshore wind	Baltic Power (1,140–1,200 MW), Bałtyk 2 & 3 (1,440 MW), Baltica 2 (1,500 MW), BC-Wind (500 MW); target 5.9 GW by 2030 and 18 GW by 2040; total project pipeline around 98 GW	High year-round (typical winds 9–10 m/s)	24h	Baltic Power (around 2026), Bałtyk 2 & 3 (around 2028), Baltica 2 (around 2027), BC-Wind (around 2028), Nordlicht 1 & 2 (about 1.6 GW by 2026) and Beta (about 2.5 GW by 2030), plus multiple further projects towards and beyond 2030
Solar PV	Limited deployment in ports so far; Ports of ZMPSi: about 0.28 MW total (around 0.05 MW internal, 0.232 MW by external operators)	High (summer peak), low (winter)	Day time, peak at midday	Only limited expansion planned in ports due to space constraints
Marine biomass	Around 76 MW regional biomass capacity in Szczecin area; marine biomass largely unused	Stable year-round	24h	Regional biomass development ongoing, marine-based use still in research phase
Wave energy	About 0.3–1.8 GW technical potential (around 262–1,880 MW depending on technology)	Seasonal variability	24h	Research and pilot phase, not yet commercialised
Green hydrogen	No firm capacity yet; technical documentation in preparation; Emerging option for heavy port equipment and vessels	Flexible production, storable year-round	24h	Preparatory infrastructure and pilot applications under development
Tidal energy	Around 0.5 GW technical potential	Predictable but limited in Baltic	Tidal predictable, wave weather-dependent	Research-only due to low tidal range and limited economics

Renewable Energy Use in Ports/Terminals

- ZMPSiŚ (Szczecin & Świnoujście):
    - In-house photovoltaic installations: 0.05 MW installed.
    - External operators within the ports: 0.232 MW solar capacity.
    - Preparation for hydrogen-based solutions underway; technical documentation prepared for future green transition based on hydrogen technologies.
- Regional Overview (West Pomerania):

  - Electricity from renewables is 122.7% of the region's consumption, the highest in Poland.
  - Breakdown in leading municipalities:
    - Szczecin: 76 MW biomass, 15.5 MW waste-to-energy.
    - Darłowo: 258.4 MW wind.
    - Golczewo: 101.9 MW solar.
    - Złocieniec: 2 MW biogas.Manowo: 3.3 MW hydro.

Percentage Already Used / Planned in Ports

- Port installations are still in early phases:
  Solar and biomass are present, but total port/terminal-specific capacities are below 1 MW per site. Offshore wind, hydrogen, and biogas are in planning/documentation status only. Marine wave/tidal technologies and marine biomass are not yet used commercially in Polish ports.

Challenges in Adopting Alternatives:

- Limited physical space for renewable installations within port areas.
- High upfront investment requirements for grid upgrades, hydrogen, or new generation.
- Regulatory, environmental, and planning constraints remain significant obstacles.
- Equipment readiness: port operation technology and cargo handling equipment are often not suited yet for alternative energies.
- Need for local supply chain and manufacturer adaptation.

Acceptance among Stakeholders:

- Terminal Operators/Service Providers: Prefer wind, solar, and biomass due to proven economics and easier integration; hydrogen is attractive in plans but not yet widely adopted.
- Policymakers: Strong support for offshore wind, solar, and energy storage; incentivizing hydrogen and bioenergy through EU and national programs. Wave/tidal technologies receive research focus, not large-scale acceptance.
- State Incentives: CEF Transport's AFIF grants (EU) provide funding for hydrogen, electrification, and alternative fuels in port infrastructure, with €1 billion available for 2024–2026. National programs heavily subsidize energy storage systems (up to 65% costs for SMEs), prosumer solar/wind, and large-scale installations.

Differences and Special Incentives:

- Offshore wind and solar receive the bulk of investment and policy backing because of higher scalability and proven grid impact.
- Energy storage receives special incentives (grants/loans up to 65% project cost) to stabilize renewables integration.

- Hydrogen and alternative fuels infrastructure in ports have dedicated CEF and national support — port authorities can apply for substantial EU funds for hydrogen bunkering, electrification, and shore-side power solutions (e.g., ZMPSiŚ preparing AFIF application now).
- Wave/tidal and marine biomass are supported through R&D projects, not yet commercialized at scale.

Table 7. Overview of Estimated Technical Potential of Renewables in the Baltic Sea

Source	Technical Potential (GW)	Theoretical (GW)	Port Uptake (2025)	Main Challenges	Accepted By	Incentives
Offshore Wind	7.7–18	up to 33	None yet; planned	Grid, cost, space, supply chain	All stakeholders	High (EU/national)
Solar PV	17+	Much higher	<1 MW in ports	Grid, space, imports	Operators/state	High (subsidies/R&D)
Tidal	<0.5	3–4	None	Low amplitude, tech maturity	Researchers	R&D focus
Wave	0.3–1.8	6	None	Low energy, tech cost	Researchers	R&D focus
Biomass	76+ (region)	Higher	Some (Szczecin)	Supply chain, scalability	Operators/state	Moderate
Hydrogen	(planned)	(planned)	Doc/prep phase	Cost, infra, technology	Planners/policy	High (EU/national)
Storage	n/a	n/a	Growing	Funding, technical standards	All	Very high (special grants)

Poland’s renewable transition in ports is led by wind and solar, with gradual expansion to hydrogen and energy storage, supported by EU incentives. Wave, tidal, and marine biomass remain largely in the experimental phase. Investments and adoption will grow as infrastructure, regulations, and technology mature over the coming years.

Swedish ports and terminals are increasingly exploring the use of digital and artificial intelligence (AI) tools to support the forecasting and design of energy transition demand, although adoption is still in relatively early stages compared to some other European ports.

These digital tools primarily focus on enhancing operational efficiency, optimizing energy use, and supporting strategic planning for decarbonization efforts.

Sweden's offshore wind strategy places emphasis on floating wind farms to better exploit deeper waters and reduce visual and ecological impacts. The government supports these ambitions by commissioning up to six offshore grid connection points, aiming to facilitate the integration of up to 10 GW of offshore wind power into the national grid. This infrastructure will relieve developers from building their own expensive transmission lines and is crucial for timely deployment.

Marine renewables such as wave and tidal power remain at an earlier stage of development and are mostly confined to pilots and research projects. Sweden faces challenges including complex and lengthy permitting processes, environmental and biodiversity protections (e.g., Natura 2000), and occasional local opposition often related to defense and radar concerns. These factors can delay project approvals and require careful marine spatial planning to balance environmental stewardship with renewable energy ambitions.

Financial investments are substantial, with billion-euro scale funding flowing into offshore wind projects and their associated infrastructure. Public-private partnerships and government-led initiatives drive innovation, especially in floating wind technologies. The nation aims to progressively achieve a fossil-free electricity system by leveraging its extensive coastline and maritime resources.

Overall, the current situation of deployment of AI tools shows growing demand for a dedicated digital tool within the DeCoInter project. The demand emerges from the increasing complexity, scale, and interdependency of energy transition processes in maritime port systems across the SBA. As demonstrated throughout the chapter, ports are no longer isolated logistics nodes but are evolving into multi-functional energy hubs that must simultaneously integrate renewable generation, manage fluctuating demand, comply with regulatory frameworks, and coordinate with a diverse ecosystem of stakeholders. This transformation fundamentally exceeds the capabilities of traditional planning approaches, thereby creating a clear and urgent need for advanced digital decision-support solutions.

At the core of this demand lies the inherent variability and intermittency of blue renewable energy sources, particularly offshore wind and solar power. While offshore wind provides a relatively stable year-round energy supply, its seasonal fluctuations and short-term variability introduce significant challenges for operational planning and infrastructure sizing. Solar energy further complicates the system due to its pronounced diurnal and seasonal patterns, while emerging energy carriers such as hydrogen introduce additional temporal flexibility but also new layers of system complexity. The report clearly illustrates that energy availability is not constant but dynamically changing across hours, days, and seasons, requiring continuous balancing between supply and demand. Without a digital tool capable of modelling these temporal dynamics in high resolution, ports are unable to optimize energy usage, storage strategies, or investment decisions effectively.

In parallel, the rapid scale-up of renewable energy capacity in the SBA intensifies the need for integrated planning tools. Offshore wind alone is projected to reach tens of gigawatts across the region, far exceeding the direct electricity demand of individual ports. This creates a structural shift in the energy system, where the primary challenge is no longer resource scarcity but rather the efficient integration, distribution, and utilisation of abundant renewable energy. Ports must determine how to align their infrastructure development, such as shore power systems, hydrogen production facilities, and electrified terminal operations, with this evolving supply landscape. A dedicated digital tool is therefore essential to simulate different integration scenarios, evaluate infrastructure bottlenecks, and identify optimal pathways for aligning port demand with regional renewable energy flows.

Another critical driver of demand is the increasing electrification of port operations and maritime transport. The deployment of Onshore Power Supply systems, the electrification of cargo handling equipment, and the introduction of hydrogen-based fuels for heavy-duty applications significantly increase the complexity of port energy systems. As highlighted in the report, even single components such as shore power can already generate electricity demand in the order of several gigawatt-hours annually, with future expansions expected to multiply this figure substantially. At the same time, future port expansions, such as the planned development zones in Klaipėda with projected demands of up to 200 MW, illustrate the scale of upcoming energy requirements. Managing these evolving demand profiles requires a tool that can integrate infrastructure data, forecast consumption patterns, and assess the impact of different technological configurations under varying operational conditions.

The demand for the tool is further reinforced by the fragmented and multi-layered nature of data currently available to port stakeholders. As evidenced throughout the report, relevant information on energy capacity, availability, demand, and infrastructure is distributed across different institutions, formats, and levels of granularity. While this report consolidates much of this information into a coherent analytical framework, the absence of a unified digital platform limits its practical usability for ongoing decision-making. A dedicated digital tool would act as a central integrative environment, enabling stakeholders to combine datasets, test assumptions, and generate actionable insights in a consistent and transparent manner.

In addition, regulatory and spatial constraints introduce another layer of complexity that necessitates digital support. Maritime spatial planning, environmental protection requirements, and grid connectivity limitations all significantly influence the feasibility of renewable energy projects and port infrastructure developments. These constraints are often dynamic, context-specific, and interdependent, making them difficult to assess using static methods. The report highlights how factors such as Natura 2000 protections, grid bottlenecks, and permitting procedures can delay or reshape projects, underscoring the need for a tool that can incorporate these constraints into scenario modelling and feasibility assessments. Such a tool would allow stakeholders to move beyond theoretical potential and evaluate realistic, implementable solutions.

Moreover, the increasing importance of cross-sectoral and cross-border coordination amplifies the need for a shared digital platform. The SBA involves multiple countries with different regulatory systems, energy strategies, and levels of technological maturity. Ports must coordinate not only with national authorities and grid operators but also with international partners, energy developers, and private operators. The absence of a common analytical framework risks inconsistencies, inefficiencies, and suboptimal investment decisions. A dedicated digital tool can facilitate harmonisation by providing a standardized environment for data exchange, scenario analysis, and collaborative planning across regions and stakeholders.

Finally, the emergence of digitalisation and artificial intelligence in port energy management further strengthens the case for such a tool. The report documents early applications of AI-driven forecasting, digital twins, and smart grid management systems in ports such as those in Mecklenburg-Vorpommern and Denmark. These developments indicate a clear technological trajectory toward more data-driven and automated decision-making processes. However, without a structured and project-specific digital platform, these innovations remain fragmented and limited in scope. The DeCoInter digital tool can serve as a unifying framework that integrates these advanced technologies into a coherent system tailored to the specific needs of port energy transition.

In conclusion, the demand for a dedicated digital tool within the DeCoInter project is not merely an enhancement but a fundamental requirement arising from the complexity of modern port energy systems. The convergence of variable renewable energy supply, rapidly growing and diversifying demand, infrastructural and regulatory constraints, and the need for cross-border coordination creates a decision-making environment that cannot be effectively managed through conventional approaches. A digital tool capable of integrating datasets, modelling scenarios, and supporting strategic and operational decisions is therefore essential to enable ports in the South Baltic region to fulfil their role as key moderators of the energy transition.

4 Variability and availability of marine renewables for port users

The availability schedule of alternative energy solutions at Danish ports and terminals reflects the nature of each renewable source, seasonal and daily variability, and client demands. The AFIR (Alternative Fuels Infrastructure Regulation) directive guides Danish ports' implementation actions, ensuring alignment with EU-wide targets.

Offshore Wind
- Availability: High and relatively stable year-round, with stronger winds in autumn and winter months. Diurnal variability is low, but short-term fluctuations can occur.
- Clients: Primarily feeds electricity into the national grid supporting shore power infrastructure for cruise ships, container vessels, and other port operations.
- Notes: Offshore wind is considered the backbone for green electricity supply at ports, providing consistent power to meet vessel and terminal energy demands.

Solar Power
- Availability: Peaks in the summer months with long daylight hours and clear skies; low availability during winter and at night.
- Clients: On-site port facilities, administrative buildings, and auxiliary services. Currently, solar's role in direct vessel supply is limited due to variability.
- Notes: Surplus solar energy must be fed into the public grid; direct on-port consumption is regulated by Danish port law.

Tidal and Wave Energy
- Availability: Tidal energy has predictable cycles aligned with lunar patterns, offering reliable but intermittent generation. Wave energy is dependent on wind and weather, showing variability on hourly and seasonal scales.
- Clients: Currently limited deployment; potential future use for port electrical needs or hydrogen production.
- Notes: Still in developmental stages and subject to regulatory and environmental assessments under AFIR.

Marine Biomass (e.g., Biomethane)
- Availability: Generally stable year-round, as biomass processing can be managed independently of weather conditions.
- Clients: Complementary fuel source for port vehicles, equipment, and potentially for shipping applications.
- Notes: Production delays persist due to regulatory and market challenges, but biomass fuel is a reliable alternative, reducing fossil fuel dependency.

Implementation Guidance under AFIR

- Danish ports focus on integrating these alternative energy sources with shore power systems, enabling vessels to plug in and reduce emissions while berthed.
- Seasonal and diurnal availability considerations influence energy storage solutions and backup grid connections to maintain reliable supply.
- AFIR mandates installation of necessary refueling and recharging infrastructure by a set timetable, influencing port upgrade schedules and client service offerings.

In summary, offshore wind provides a stable base load of green electricity, supplemented by solar in daytime and summer periods, with emerging tidal/wave and biomass options developing to enhance supply diversity. These sources serve different client groups — from cruise and container ships to port internal services — under regulatory frameworks including AFIR to ensure availability meets operational demands.

Table 8. Overview of Existing Capacities of Marine Renewables in the Denmark

Energy source	**Technical Potential (MW)**	**Seasonal variabilility**	**Diurnal (24h) Variability**	**Planned availability timeline**
Offshore wind	Kriegers Flak 1 (600 MW); Energy Island Bornholm (3–3.8 GW + 1.5 GW option); Kriegers Flak 2 (up to 3.5 GW planned)	High year-round (stronger in autumn–winter)	24h	In operation and under expansion, Energy Island Bornholm in phased development until 2028
Solar power	Political target to quadruple current capacity	High (summer peak), low (winter/night)	Day time, peak at midday	Expansion currently slowed due to low electricity prices
Marine biomass (biomethane)	Complementary fuel source for port and transport	Stable year-round		Projects at Vordingborg (SAF, biomethane) planned, facing delays over off-take agreements
Wave energy	No concrete capacity installed	Weather- and wind-dependent		Activities permitted in principle, but no current commercial projects

Tidal energy	Predictable lunar cycles, intermittent		Limited deployment potential	Early development stage, possible future use for port electricity supply

An availability schedule of alternative energy solutions in Mecklenburg-Vorpommern ports and terminals reflects the seasonal and diurnal variability of renewable energy sources, their integration capability, and client demand patterns.

Table 9. Overview of Availability of Usage of Marine Renewables in Mecklenburg-Pomerania

Alternative Energy Source	Seasonal Availability	Diurnal Availability	Typical Clients Served	Notes on Variability and Use
Offshore Wind	High: Autumn to Spring	High: Day and Night	Terminal operations, vessel charging, hydrogen production	Wind speeds higher in cooler months; fairly consistent day/night, enabling stable supply and grid integration
Onshore Wind	Moderate-High: Fall to Spring	High: Day and Night	Local terminal power, support to grid	Similar profile to offshore; influenced by local terrain and atmospheric conditions
Solar PV (on-site floating and rooftop)	High: Late Spring to Summer	Peak: Midday	Terminal lighting, auxiliary loads	Solar peaks midday with declining availability in winter; often complement wind availability
Hydrogen (electrolyzer)	Dependent on wind and solar availability	Can store energy for use anytime	Fuel for vessels, heavy equipment, backup power	Hydrogen production mainly day-time, can be stored and used on demand
Marine Biomass	Year-round (harvest cycles)	Stable	Supplementary power, heating for facilities	Biomass supply depends on harvesting and processing, generally stable but limited in scale
Tidal and Wave Energy	Predictable tidal cycles	Predictable tidal cycles	Experimental clients, research vessels	Tidal predictable, but low energy density limits large-scale supply; wave energy seasonal and weather-dependent

Mainstay of port renewable electricity is wind energy (Offshore/Onshore) with its strong availability during autumn, winter, and spring and its reliable diurnal variation supporting continuous operations and hydrogen production. This is seasonal complemented by solar energy with its high availability in summer daytime hours; used primarily to power auxiliary port services and reduce grid draw. Hydrogen as a strategic energy carrier produced mostly when wind/solar peaks, stored for constant availability meeting fuel demand of vessels or terminals. Marine Biomass provides steady, though small-scale, energy supply to ports; challenged by limited resource base. Tidal and Wave produced energy is mostly an experimental or niche use due to spatial and energy density constraints but offers predictable energy cycles aligned with tides.

This schedule assists terminal operators, shipping companies, and port energy managers in aligning energy supply with operational needs and planning fuel mixes that maximize renewable use while ensuring reliability.

Klaipėda Port is implementing and operating several advanced green energy solutions, focusing on Onshore Power Supply (OPS), green hydrogen, and renewable electricity integration. Below are the planned operation dates, availability, capacity, and client groups, supplemented by latest project updates and financing sources.

OPS (Onshore Power Supply):

- **Ro-Ro and Ro-Pax vessels** (CKT & KCT terminals): OPS facilities will be operational starting April 2026, with continuous year-round availability according to terminal operations. Peak demand will occur during daytime docking and cargo operations; main users are Ro-Ro/Ro-Pax vessel operators.

- **Cruise vessels** (old and new terminals): OPS systems for cruise ships are scheduled for full operation in 2027. Eight connection points (total 16 MW) will be provided, mainly for the April–October cruise season, with demand highest in summer daytime. Main clients are cruise vessel operators.

Green Hydrogen:

- **Production and refuelling station** (Nemuno g. 40, Klaipėda): Operations will commence in April 2026, with continuous, year-round hydrogen output up to 530 kg/day (127 tonnes/year). The system uses a Proton Exchange Membrane (PEM) electrolyser powered by renewables and a 3 MW plant. Refuelling will serve port service vessels (e.g., waste collection), heavy vehicles, port equipment, and public transport, integrating with Klaipėda’s municipal fleet. The hydrogen is compressed for marine, road haulage, and public transport uses, and the project benefits from about €6 million in EU/NextGenerationEU funding, with a total value of €12 million.

Green Electricity from RES:

- **Rooftop solar PV**: Several tenants actively generate power from rooftop PV, mainly self-consumed by the businesses involved. Production peaks during summer daylight hours, dropping in winter and at night.

- **Certified green electricity from the grid / AEI cluster**: Green electricity is available year-round without daily/seasonal limitations. Port companies and terminal operators routinely purchase certified green electricity from suppliers for operations.

- **Renewable Energy Cluster (planned 200 MW hybrid park)**: Under analysis, this project would supply wind, solar, and battery energy to secure stable, long-term electricity at fixed prices for port and tenant consumption, supporting load balancing and resilience. Decision to participate remains pending.

OPS, hydrogen, and renewable electricity projects demonstrate Klaipėda's focus on sustainable, reliable, and flexible energy strategies for maritime, land transport, and industrial use, with EU and national support financing the green transition. The ongoing Port Electrification Study (2025–2026) at Klaipėda Port focuses on integrating the port's growing electricity demand with the broader city energy system, aiming for coordinated infrastructure development to meet the combined needs efficiently.

Availability schedule for alternative energy solutions at Polish ports/terminals, organized around seasonal and diurnal variations of renewable resources and aligned with decarbonization mandates such as OPS by 2030 under EU regulations (AFIR, FuelEU Maritime, ETS). This schedule also reflects which client groups will benefit most.

Table 10. Alternative Energy Availability Schedule at Polish Ports

Energy Source	Seasonal Availability	Diurnal Variability	Client Groups Benefiting	Notes
Offshore Wind Power	High availability year-round, stronger in autumn/winter due to Baltic wind patterns	Generally stable, slight dips during calm periods at night	All port users, especially shipping lines requiring OPS; terminal equipment	Offshore wind provides the backbone of green OPS electricity, with high reliability despite diurnal variation.
Onshore Solar PV	Peak availability late spring–summer (April–September); low in winter	Strong daytime peak, zero at night	Daytime cargo handling operators, admin buildings, electric vehicles charging	Solar supplements port electricity mainly during daytime operational peaks; storage required for night use.

Energy Source	Seasonal Availability	Diurnal Variability	Client Groups Benefiting	Notes
Hydrogen (Green)	Seasonal independence if produced via electrolysis using renewable power; potentially stored	Constant availability if stored, used as fuel when needed	Heavy-duty cargo equipment, docks, and ship bunkering (hydrogen-capable vessels)	Hydrogen acted as dispatchable energy, compensating for solar/wind intermittency; critical for decarbonizing fuel types not easily electrified.
Battery Energy Storage (BESS)	Year-round; buffers renewable generation peaks and demand	Supplies power during low renewable generation (night, low winds)	All port systems requiring continuous power; critical for OPS when renewable output falls	Storage essential for balancing solar/wind and delivering reliable OPS power 24/7.
Marine Biomass & Biogas	Seasonal variation linked to supply chain (agricultural/molasses waste), more constant in colder months	Relatively stable, used as continuous fuel source	Local energy consumers and smaller terminals, supplementing green baseload	Limited scale currently, but useful for stable base load and heat generation.

Seasonal variation is most pronounced in solar, with high summer output supporting peak daytime energy demand. Offshore wind is the most reliable renewable source currently planned, with strong potential to cover base and peak loads year-round for OPS systems. Green hydrogen and battery storage are key to delivering flexible, dispatchable energy to ports and ships, smoothing out solar and wind intermittency and facilitating 24/7 OPS compliance. Clients include shipping vessels (shore-side electricity and hydrogen bunkering), terminal and cargo handling operators (electric and hydrogen fuel), administrative and service buildings (solar and storage), and potentially truck fleets and other port transport. This schedule enables strategic targeted investments in renewable infrastructure and storage to meet decarbonization requirements, maximize renewable utilization, and ensure reliable alternative energy supply for all port users throughout the year.

In Swedish ports and terminals, the availability of alternative energy solutions is closely tied to the natural variability of renewable resources, which affects when and how different energy sources can be utilized throughout the year and across daily cycles. Given Sweden's northern latitude and maritime climate, this variability requires careful management to ensure reliable energy supply for port operations and their clients.

Offshore wind energy, the backbone of Sweden's marine renewables, generally offers high availability year-round, with peak wind speeds typically occurring during autumn and winter months. This seasonal robustness makes offshore wind highly reliable for powering a wide range of port activities, including ship shore power, cargo handling equipment, and terminal services. Its relatively stable production profile across day and night, despite occasional lulls, allows ports to plan for continuous energy supply, supplemented if necessary by energy storage or backup systems. Clients benefiting most from offshore wind availability include maritime vessels requiring shore-side electricity and terminal operators seeking to decarbonize operations.

Solar photovoltaic (PV) installations, increasingly deployed on port rooftops and surrounding areas, follow a pronounced diurnal and seasonal pattern, with high generation during long summer days and little to no production during winter. This makes solar power a valuable energy source for daytime port operations and administrative functions, providing clean energy during periods of peak activity. However, its seasonal limitations mean solar energy must be complemented by other sources or storage solutions to meet annual demand effectively.

Hydrogen technologies, anticipated as a key energy carrier for heavy-duty equipment and vessel fuelling in Swedish ports, offer the advantage of temporal flexibility. Hydrogen can be produced during periods of excess renewable electricity generation (often during windy or sunny times), stored safely, and later used on demand. This makes hydrogen available round-the-clock regardless of the weather, particularly benefiting clients with high and variable energy needs such as heavy cargo handling equipment and ships equipped for hydrogen fuel bunkering.

Battery energy storage systems (BESS) play a critical role in smoothing diurnal and short-term variability of renewables by storing surplus energy during high production periods and discharging it during low generation periods or peak demand times. These systems ensure a reliable supply of electricity for continuous port operations and enhance grid stability.

Other marine renewable energies like wave and tidal power, while still largely in pilot phases, are expected to provide complementary, relatively predictable sources of energy once matured, potentially augmenting the energy mix in future years.

Alternative energy availability in Swedish ports is seasonal and diurnally dynamic: offshore wind provides consistent year-round power; solar PV complements with daytime summer generation; hydrogen offers dispatchable, on-demand fuel; and battery storage ensures supply stability. Different client groups — vessels, terminal operators, and administrative facilities — benefit according to their specific energy consumption profiles and operational schedules. Integrating these sources strategically supports Sweden’s commitment to a resilient and decarbonized port energy system.

5 Spatial, environmental and regulatory feasibility in the coastal–port interface

There are several constraints and enablers limiting and supporting renewable energy projects development in Danish ports.

Constraints:

- Space limitations within port premises restrict the scale and types of energy facilities that can be installed, particularly for solar panels or biomass plants which require significant surface area.
- Grid connectivity is a major challenge since ports need reliable and sufficiently dimensioned grid access to integrate large-scale renewable energy production or shore power systems. Grid reinforcements can be expensive and lengthy to implement.
- Environmental permitting processes in Denmark are complex, time-consuming, and require compliance with stringent regulations designed to protect marine biodiversity and ecosystems, which can delay project development.
- Danish Port Law restricts ports' commercial activities; for example, ports are generally not allowed to sell surplus energy production (such as solar power) directly to tenants or users within the port. Instead, any surplus must be fed into the public distribution grid.
- These regulatory and legal limitations narrow the business models available to ports for energy production and resale, reducing financial incentives for investment in on-site renewables.

Enablers:

- Denmark's strategic spatial planning provides dedicated offshore wind zones and supports integration of renewable energy projects, including port-related infrastructure, facilitating coordinated development.
- Growing political and financial support at national and EU levels, such as CEF funding and green transition policies, encourage ports to invest in sustainable energy solutions.
- Ports have the possibility to collaborate with energy utilities, grid operators, and technology providers to overcome grid connection challenges.
- Flexibility to participate in permitted green activities such as hosting wave energy projects or collaboration on biomethane can help diversify port energy portfolios.
- Increasing pressure from policymakers and the market to reduce maritime emissions incentivizes ports to innovate and adopt shore power and renewable energy projects despite constraints.

While ports face regulatory, spatial, and infrastructural hurdles, strong enabling frameworks in spatial planning and funding, combined with environmental safeguards, shape a challenging but promising environment for port-based energy harvesting in Denmark.

Danish ports generally do not have direct grid connections to renewable electricity production facilities located outside their premises, primarily due to regulatory limitations governing grid operations and energy distribution. Renewable energy generation such as offshore wind farms and large-scale solar installations typically feed electricity into the national grid rather than directly supplying individual ports. This means that ports rely on the broader electricity network to access renewable energy rather than having dedicated lines from production sites.

However, some ports are actively exploring new models to bridge this gap and enhance local renewable energy integration. For example, the Port of Aalborg is involved in a pilot project investigating the concept of a local energy community. This initiative aims to combine multiple renewable energy production sources with consumption sites within a defined area, facilitating a more integrated and flexible approach to energy sharing. Such local energy communities have the potential to strengthen the link between renewable generation and port demand, enabling ports to become more self-sufficient and sustainable energy hubs.

Overall, while direct access to renewable energy production sites remains limited, evolving regulatory frameworks and innovative projects signal growing opportunities for Danish ports to connect more closely with marine and other renewable energy resources in the near future.

Within the approximately 50 km influence zone of Danish ports, several blue renewable energy projects are either operational or planned:

- The Port of Rønne is located within 50 km of the Energy Island Bornholm offshore wind parks. While this proximity offers potential access to large-scale offshore wind power, the port itself and its current customers consume power at levels far below the capacity generated by these wind farms. Therefore, the direct impact on port energy sourcing is expected to be limited in the near term.

- The Port of Vordingborg lies within about 50 km of the Kriegers Flak offshore wind zones. This closer proximity is significant for Vordingborg, especially considering the planned sustainable aviation fuel (SAF) production facility at the port, which will require substantial electricity input. The short distance to Kriegers Flak presents a promising opportunity to establish a direct grid connection or landing zone at the port premises, potentially facilitating efficient and reliable access to green offshore wind energy for the energy-intensive SAF production process.

Overall, while these renewable energy projects support the regional green energy transition, their influence on individual ports depends on factors such as power demand scale, grid connection options, and project design. Ports like Vordingborg with higher energy needs stand to benefit more directly from nearby offshore wind resources compared to smaller or lower-demand ports like Rønne.

Key constraints and enablers for energy harvesting in Mecklenburg-Vorpommern's marine and port regions include regulatory, ecological, technical, and social factors that strongly shape project planning and renewable energy deployment.

Constraints:

- **Spatial Planning:** Strict marine spatial plans control the location and expansion of offshore wind and other energy facilities, prioritizing shipping, fishing, and tourism zones while limiting available space for energy harvesting.
- **Marine Biodiversity Concerns:** Environmental protections for Baltic Sea marine habitats (e.g., Natura 2000 sites, migratory bird corridors, fish spawning areas) restrict project siting and require rigorous impact assessments that can delay or reduce project scope.
- **Grid Connectivity:** Grid capacity constraints can hinder connection of new offshore installations, especially in remote port areas, prompting the need for grid upgrades and smart management to handle fluctuating supply.
- **Local Opposition:** Community protests and stakeholder resistance ("Not in my backyard" attitudes) pose challenges for wind and solar installations, often resulting in lengthy permitting processes and adjustments to mitigate concerns.
- **Technical Barriers:** Wave and tidal technology remain at a low maturity level in the southern Baltic, and marine/biomass projects face cost, reliability, and scaling challenges.

Enablers:

- **Integrated Marine and Port Planning:** Alignment of port infrastructure investments and energy zoning with regional economic and environmental goals supports efficient siting and multi-purpose use of marine spaces (e.g., combining wind farms with aquaculture or shipping lanes).
- **Grid Investments:** Major grid expansion projects and digitalization initiatives improve connection reliability and facilitate higher renewable integration.
- **State and EU Incentives:** Attractive investment subsidies, R&D support, and priority grid access for renewables provide critical financial and regulatory backing for new projects.

- **Technological Innovation:** Advancement in turbine design, floating solar pilots, power-to-gas infrastructure, and smart grid technologies enhance harvesting efficiency and address intermittency challenges.
- **Environmental Monitoring and Adaptive Management:** Adoption of robust monitoring programs and adaptive mitigation strategies allows project development in sensitive areas with minimized biodiversity impacts.

Mecklenburg-Vorpommern's energy harvesting is shaped by a delicate balance of environmental stewardship, advanced technical planning, community acceptance, and policy-driven support mechanisms.

Table 11. Proximity of German Ports to Marine Renewables in the Baltic Sea

Port	Closest Renewable Resource	Notes
Rostock	Offshore Wind (Baltic Eagle, Arkona)	Major hub for offshore wind and hydrogen
Sassnitz-Mukran	Offshore Wind	Maintenance and hydrogen-linked projects
Wismar	Offshore and Onshore Wind, Solar	Coastal proximity to wind farms
Stralsund	Offshore Wind	Supports renewables logistics
Greifswald	Onshore Wind, Solar	Small scale projects
Wolgast	Onshore Wind, Solar	Potential for renewables integration

In Mecklenburg-Vorpommern, several ports are in close proximity to key marine renewable energy resources, particularly offshore wind zones, with some emerging potentials for solar and marine energy complements:

- **Port of Rostock:** The largest and most significant port, located near several active and planned offshore wind farms in the Baltic Sea (e.g., Baltic Eagle). Rostock is also a hub for hydrogen projects linked to renewable electricity from offshore wind. Its location on the coast provides immediate grid connection opportunities to wind zones.
- **Port of Sassnitz-Mukran:** Closely situated to offshore wind areas in the northern Baltic, Sassnitz-Mukran participates actively in pilot renewable projects and is important for servicing turbines and hydrogen production infrastructure.
- **Port of Wismar:** Located near the southwestern Baltic offshore wind zones; Wismar supports onshore wind and solar investments and benefits from expansion plans of offshore wind farms further offshore.

- **Port of Stralsund:** Near designated offshore wind priority areas; Stralsund engages in renewables logistics and maintenance, with potential for expanding solar and wind integration locally.
- **Smaller Ports (e.g., Greifswald, Wolgast):** These ports have limited direct offshore wind access but are involved in supporting renewable infrastructure through service ports and smaller scale projects, including potential for solar PV on-site.

Wave and tidal energy potential remain limited in the Baltic, so no ports currently have direct tidal or wave resource access of significance, though ongoing research continues. Rostock and Sassnitz-Mukran lead in proximity and direct integration with offshore wind and marine renewable projects, supported by Wismar and Stralsund with growing contributions from smaller regional ports.

Several blue renewable energy projects are operating or planned within approximately 50 km of major ports in Mecklenburg-Vorpommern, reflecting the region's strategic focus on offshore wind and emerging marine energy technologies:

- **Offshore Wind Farms:** The **Baltic Eagle Offshore Wind Farm** (over 300 MW) is under construction near the island of Rügen, within about 30 km of the Port of Sassnitz-Mukran. It is a key project supplying renewable power that supports regional port energy demand and hydrogen production initiatives. The **Arkona Offshore Wind Farm** (approximately 385 MW) is operational and located about 45 km northeast of the Port of Sassnitz-Mukran, serving as a major clean energy source integrated in the regional grid. The **Wikinger Offshore Wind Farm** (350 MW) near the island of Rügen is operational and within range of Rostock and Sassnitz ports, contributing to local renewable power supply and export.
- **Hydrogen Projects Linked to Blue Energy:** At the Port of Rostock, large-scale hydrogen electrolysis plants are either operational or in commissioning phases, using offshore wind power to produce green hydrogen, thus linking marine renewables with port industrial processes and transportation decarbonization.
- **Marine Biomass and Tidal/Wave Pilots:** While no large-scale tidal or wave projects exist near these ports due to the Baltic's limited wave and tidal energy potential, pilot projects for marine biomass (algal cultivation) are at research or pilot levels, generally within proximity of coastal scientific institutions or port-served test sites.

Table 12. Projects in Mecklenburg-Pomerania on Renewable Energy Development

Project Type	Specific Project/Area	Approximate Distance to Port	Notes
Offshore Wind	Baltic Eagle	~30 km from Sassnitz-Mukran	Under construction
Offshore Wind	Arkona	~45 km from Sassnitz-Mukran	Operational
Offshore Wind	Wikinger	<50 km from Rostock	Operational
Hydrogen (electrolysis)	Rostock Port	Within port area	Operational/planned scale-up
Marine Biomass (pilot)	Various research sites	Nearby coastal zones	Experimental stage
Tidal/Wave	No large projects	N/A	Baltic Sea low wave/tidal potential

Uninterrupted supply is indispensable for Klaipėda port operations, especially as demand from shore power, hydrogen stations, and storage rises. OPS, set for full deployment by 2028, will require major upgrades, including new high-voltage grid connections and backup storage to ensure ships can use clean electricity at berth and vessels equipped with hydrogen-electric propulsion. Battery and hydrogen-based energy storage solutions are planned to handle peak demand and prevent operational instability. Continuous cooperation with ESO and LITGRID includes monitoring substation load data and modeling future scenarios in a comprehensive electrification study underway (2025–2026).

Klaipėda Port's electrification efforts will expand with more shore power stations (OPS) for RoRo, cruise, and container vessels by 2026–2028, all supplied by certified green electricity from wind and solar. Green hydrogen infrastructure is being developed from 2025 onward, with a planned electrolyzer capacity of 1.27–2.25 MW and a target of 127 tons annually for fueling ships, equipment, and vehicles. Port's sustainability and infrastructure projects are co-financed through major EU programs (Connecting Europe Facility), reflecting high prioritization of clean energy supply for maritime operations.

Ongoing studies and investments focus on enhancing reliability, distribution capacity, high-voltage links from LITGRID, and resilience for growing energy needs. Stakeholder collaboration underscores the port's proactive approach in embracing renewables, with plans reflecting both current usage and projected growth in OPS and hydrogen applications.

The Port of Klaipėda is supplied via the national electricity grid with multiple 110/10 kV substations managed by ESO (DSO) and LITGRID (TSO), ensuring reliable service for critical operations but facing significant challenges from rising OPS (Onshore Power Supply), hydrogen production, and energy storage needs as demand and load fluctuations increase. Around 43.66% of electricity consumption already comes from renewable sources (solar PV and green contracts), with ongoing work to model future demand scenarios in cooperation with grid operators.

Supply comes through several substations, with the Lithuanian transmission network well connected to neighboring grids and prepared for long-term upgrades. Reliability is a top priority, since vital port functions (cargo, cold storage, safety systems) all depend on uninterrupted power. Daily and seasonal load fluctuations, especially cargo handling and vessel consumption, require dynamic grid management. OPS systems and hydrogen production are driving the need for network reinforcement, new high-voltage LITGRID connections (110-330 kV), and robust backup storage (batteries, hydrogen). Electrification of quays for RoRo, container, and cruise ships is underway and will require sourcing power from renewable suppliers; full deployment is targeted by 2028, with partial EU funding. A new hydrogen production facility (1.27–2.25 MW electrolyzer capacity, 127 tons annual output) will be installed, fueled by green electricity and integrated into the port's energy system by 2026.

The Port Authority works closely with ESO and LITGRID to obtain detailed load/substation data and prepare accurate, future-oriented demand scenarios, coordinated through a port electrification study in progress (2025–2026). Local energy storage projects are planned to help balance peak loads and enhance operational stability as electricity demand from clean fuels and electrified infrastructure rises. Klaipėda Port's approach exemplifies strong cooperation with grid operators, robust supply security, and readiness for future electrification and renewable integration, supported by EU investment and modern infrastructure planning.

The Port of Klaipėda does not have direct access to offshore renewable energy zones. The nearest offshore renewable projects are the planned Lithuanian offshore wind parks in the Baltic Sea, located approximately 30 to 36 kilometers off the coast near Palanga, well outside the immediate port area.

Lithuania is developing two major offshore wind farms totaling approximately 1.4 GW capacity, expected to produce up to 6 TWh of green electricity per year. These projects are part of Lithuania's National Energy Independence Strategy and are scheduled to be operational around 2035. While these wind farms will contribute significantly to Lithuania's electricity supply, covering up to half of current demand, they are not physically connected to the Port of Klaipėda but are designed to feed electricity into the national grid.

The Port of Klaipėda is preparing its infrastructure to support these offshore wind developments by dredging and upgrading berths to enable assembly, processing, and storage of wind turbine components. By the end of 2026, Klaipėda aims to become a key logistical hub for offshore wind farm construction and maintenance.

In summary, Klaipėda Port supports and facilitates offshore wind energy logistics but does not have direct access to renewable energy generation from these offshore zones; rather, it relies on grid connections supplied by these national projects located offshore some 30+ kilometers away from the coast.

Currently, there are no active blue renewable energy projects — such as wave, tidal, or marine biomass — within a 50 km radius of the Port of Klaipėda. At the national level, Lithuania is actively developing two major offshore wind farms in the Baltic Sea as part of its ambitious renewable energy expansion plans. One of these, the Curonian Nord offshore wind farm, is located about 37 km from the Lithuanian coast, which translates to roughly 50 km from the Port of Klaipėda. This project, alongside the first offshore wind farm already under development, represents a combined planned capacity of approximately 1.4 GW, aiming to supply up to 6 TWh of green electricity annually — enough to cover about half of Lithuania's current electricity demand. The Curonian Nord project is now progressing through the planning and preparation phases, supported by competitive tender processes and stakeholder consultations.

The Port of Klaipėda faces several important spatial, regulatory, and technical constraints regarding the integration and expansion of renewable energy infrastructure within its area. Spatially, the port area is fully occupied or leased to various port users, leaving no available land for large-scale solar or wind farms. Additionally, the port aquatory is unsuitable for wave or tidal energy projects due to intensive navigation activities, shipping corridors, and sedimentation challenges, which complicate the installation and operation of such marine energy systems.

From a regulatory perspective, the port is subject to strict safety and security frameworks, including compliance with the ISPS code and fire safety regulations. These rules effectively limit the possibility of deploying large-scale energy facilities near quays or within cargo handling zones. Furthermore, Lithuania's legal framework for green hydrogen remains under development, generating uncertainties around permitting, hydrogen storage, and operational conditions, which pose challenges for project developers and port authorities aiming to scale green hydrogen technologies.

Technically, the existing electricity infrastructure — comprising substations and distribution networks — was originally designed to meet historical demand levels, which are significantly lower than what future projects require. The arrival of large-scale Onshore Power Supply (OPS) systems and green hydrogen production plants demands substantial grid reinforcement and modernization. At present, the port lacks installed energy storage solutions, such as battery or hydrogen storage systems, which are critical to balancing variable renewable electricity supply and peak demand, especially under OPS and hydrogen load profiles. The Port Electrification Study underway in 2025–2026 is actively examining these infrastructure gaps and potential investments needed to overcome technical barriers.

Despite these challenges, Klaipėda Port is making significant strides in renewable energy integration. It has initiated infrastructure upgrades, including quay reconstructions to support offshore wind logistics, is advancing the installation of OPS stations for vessels (with initial stations operational from April 2026), and is constructing the Baltic region's first green hydrogen production and refuelling facility. These efforts reflect Klaipėda's commitment to sustainable development as well as alignment with national and EU decarbonization goals, supported by strategic investments and funding under Lithuania's Recovery and Resilience Plan and EU NextGenerationEU programs.

Key constraints and enablers for energy harvesting in Polish ports and terminals cover a wide set of technical, regulatory, spatial, and environmental aspects. The current transition focuses on collecting data about port equipment demand, analyzing spatial and infrastructural feasibility, integrating with the grid, and complying with environmental and biodiversity requirements.

Constraints:

- Spatial Planning: The vast majority of Poland's territory is restricted for wind farm development due to required buffer zones from settlements (usually 1000–2000 m). This limits available sites to less than 7% of total land area and is often even more constrained on a local level. In port areas, suitable space for large-scale installations is particularly limited.
- Marine Biodiversity/Environmental Protection: Renewable energy projects (especially offshore wind and coastal solar) must comply with stringent environmental regulations, including Natura 2000 protections and restrictions on ecologically sensitive zones. Cumulative biodiversity impacts require careful assessment and can necessitate project redesign or relocation.
- Grid Connectivity: Poland faces nationwide grid bottlenecks, with thousands of renewable energy connection applications being rejected each year due to lack of transmission/distribution network capacity. Port-based facilities are especially affected because existing infrastructure was not designed for large new power sources. Integration of renewables requires substantial grid modernization (e.g., 400

kV line upgrades, smart grid rollout), with connection times stretching into years in some areas.

- Stakeholder Adaptation: Existing port handling and storage equipment is mostly not ready for zero-emission fuels. Adapting or replacing it is capital-intensive, and real energy demand data must be gathered for hydrogen or electrification planning.
- Legal and Planning Procedures: Development is slowed by lengthy permit processes, local public consultation requirements, and multi-level governmental decision-making — especially for projects that may impact the visual landscape or biodiversity.

Enablers:

- Energy Demand Assessments: Data collection and modeling (as ongoing at various ports) enable targeted decisions for fuel switching and infrastructure investment, especially for hydrogen-powered handling equipment.
- Strategic Spatial Mapping: National and regional governments actively designate "renewable energy zones" to streamline development, prioritizing areas with lower ecological risk and available infrastructure.
- Grid Investment Programs: Poland is investing in large-scale grid upgrades, including smart grids and new 400 kV lines in the northwest, designed both to accommodate offshore wind/port renewables and to improve regional grid stability and capacity.
- EU and State Policy Incentives: Robust financial, regulatory, and technical support for alternative fuels and grid integration, including grants, subsidies, pilot programs, and regulatory reforms to facilitate new connections and distributed energy adoption in ports.
- Technology Pilots: Demonstration projects in the use of hydrogen for port equipment, the introduction of renewable-powered charging/refueling infrastructure, and active research on integrating alternative energies with port operations.

Ports are using stakeholder consultation, technical modeling, environmental compliance, and alliance with new policy instruments to move from energy demand assessment toward implementation — despite substantial spatial, regulatory, environmental, and technical constraints.

The following ports in the region have direct access or close proximity to marine renewable energy resources:

- Świnoujście Port
  Located very close to significant offshore wind zones in the Baltic Sea, particularly on the Oder Bank where several large offshore wind projects, including ORLEN Neptun developments, are situated. This port benefits from proximity to offshore wind farms

(planned and under construction) providing potential direct access to green power and offshore wind energy infrastructure.

- Szczecin Port
  While located inland on the Oder River, Szczecin is closely connected via waterways and logistics hubs to the offshore wind zones and the coastal port of Świnoujście. It has access to renewable energy infrastructure, including solar PV installations and biomass plants within the region, that support port operations and energy demands.

- Gdańsk Port
  Directly adjacent to major offshore wind development areas in the central Baltic Sea, including Pomeranian concessions under Poland's offshore program. The port serves as a key logistics hub for wind turbine assembly, installation vessels, and maintenance operations, with access to regional green energy grids and planned hydrogen infrastructure.

- Gdynia Port
  Strategically positioned near Gulf of Gdańsk offshore wind zones, supporting deployment and servicing of Baltic wind projects through specialized terminals like OT Port. It connects to emerging renewable supply chains, including shore power electrification and proximity to Pomeranian wind farms under construction.

- Elbląg Port
  Situated on the Elbląg River with access to the Vistula Lagoon and broader Baltic offshore zones, this port supports regional logistics for wind energy components via inland waterways. It benefits from proximity to Warmian-Masurian renewable projects, including planned solar expansions and grid connections for green energy supply to port operations.

Offshore wind farms (5+ GW planned along Oder Bank and Słupsk Bank) are the dominant marine renewable resource near these ports. Solar photovoltaic installations and biomass plants are widely distributed inland, particularly near Szczecin, supporting regional energy needs. The regional Energy Performance Sheet indicates strong regional production of renewable electricity, with West Pomerania leading Polish provinces in renewable electricity share (over 120% of consumption).

Ports in West Pomerania (particularly Świnoujście and Szczecin), Pomerania (Gdańsk and Gdynia), and Warmian-Masurian (Elbląg) regions along the Polish Baltic coast have direct or logistical access to significant renewable energy resources, especially offshore wind farms situated in the Baltic Sea right off the coast. This proximity offers opportunities for ports to integrate marine renewable energy directly into their operations and connect to regional green electricity infrastructure, supporting decarbonization goals and energy transition strategies.

There are currently no blue renewable energy projects such as marine biomass, tidal, or wave pilots operating within a 50 km radius of the ports of Szczecin, Świnoujście, Gdańsk, Gdynia, and Elbląg. At the same time, ORLEN is advancing a major offshore wind program in the Ławica Odrzańska area, with an estimated total potential of 17.5 GW across four concessions in the Baltic Sea. These projects form part of Poland's offshore wind support framework, with three of the five concessions expected to be launched by 2035 and full implementation targeted for 2040.

This scale of development creates a direct need for onshore port infrastructure upgrades, especially in Szczecin and Świnoujście. In Świnoujście, where final assembly for the offshore wind projects will take place at the Offshore Terminal, Onshore Power Supply (OPS) will be essential to reduce emissions from construction and service vessels while improving port sustainability. At the same time, the expected growth in offshore wind logistics will require a gradual transition of terminal equipment in both Szczecin and Świnoujście toward electric or low-emission systems, including cranes, handling vehicles, and auxiliary port machinery.

Gdańsk and Gdynia will continue to support installation and maintenance logistics for wind farms in the Pomeranian zone, but the scale of the Ławica Odrzańska pipeline makes Szczecin and Świnoujście particularly important as enabling infrastructure hubs. The 17.5 GW potential therefore not only strengthens Poland's offshore wind outlook, but also justifies targeted investments in OPS and terminal decarbonization to support the operational demands of this long-term buildout.

As part of the energy transformation strategy, a detailed study to identify the optimal locations for renewable energy installations within the port areas shall be prepared. For the Port of Szczecin, potential sites include Ostrów Meleński for onshore wind turbines, as well as rooftops on port buildings and warehouses for photovoltaic solar panels. The contractor will also assess whether amendments to the municipal spatial development plan are necessary to accommodate the planned renewable technologies. In Świnoujście, the focus is on locating optimal areas for renewable energy sources to support the port's transition to green energy, while Gdańsk, Gdynia, and Elbląg will conduct similar analyses for container terminals, wharves, and storage areas. This strategic planning will significantly contribute to the new development strategy, effective until 2027, ensuring that all ports take concrete measures to maximize the use of renewable energy sources moving forward.

Figure 4. Map of Polish Baltic sea offshore wind parks;

There are spatial and regulatory constraints within the port areas along Poland's Baltic coast—including West Pomerania (Świnoujście and Szczecin), Pomerania (Gdańsk and Gdynia), and Warmian-Masurian (Elbląg)—that limit marine renewable energy integration, especially wind power.

- Local Spatial Development Plans: Under Poland's 2016 Wind Power Act, wind farm locations depend exclusively on local plans, requiring amendments where construction is currently prohibited to align with regional land use and urban priorities.
- Mandatory Distance Setbacks: Turbines must sit at least 10 times their height (ground to blade tip) from residences—for instance, 1,500 meters for a 150-meter tower—severely restricting options near urban edges of these ports.
- Natura 2000 Areas: EU biodiversity rules block development in protected ecological zones adjacent to port lands and waters.
- Port Infrastructure Limits: Safety buffers around existing cranes, roads, and operations shrink viable space for new installations.

These spatial and regulatory factors represent important hurdles in integrating marine renewables within port zones, demanding careful planning, stakeholder engagement, and potential amendments to local development plans to enable projects compliant with safety, environmental, and community standards.

The development of marine renewable energy in Sweden faces several key constraints and enablers related to spatial planning, marine biodiversity, and grid connectivity. Spatial planning constitutes a significant challenge due to the need to balance the extensive offshore wind ambitions with other maritime uses and environmental protections. Sweden's marine spatial plans are designed to allocate areas for offshore wind while safeguarding shipping routes, fishing zones, and sensitive ecological habitats. However, the permitting processes remain complex and time-consuming, with detailed environmental impact assessments required to comply with national regulations and EU directives such as Natura 2000. These protections, while crucial for preserving marine biodiversity, often delay project approvals and necessitate careful site selection to minimize impacts on protected species and habitats.

Grid connectivity also presents both a constraint and an enabler. On the one hand, integrating large-scale offshore wind and other marine renewables into the national grid requires substantial infrastructure investments, especially in offshore grid connection points and onshore reinforcement. To address this, Svenska Kraftnät, Sweden's national grid operator, is proactively developing multiple offshore grid hubs designed to connect up to 10 GW of offshore wind capacity. This strategic investment reduces the burden on individual developers to build costly transmission lines and facilitates smoother grid integration. Still, coordinating the timing of grid upgrades with project development is vital to avoid bottlenecks.

Moreover, local stakeholder engagement and opposition related to environmental and societal concerns can affect project timelines and site approvals. Although Sweden has a strong environmental governance framework, balancing renewable energy expansion with societal acceptance remains an ongoing challenge.

In Sweden, several ports benefit from direct access or close proximity to significant marine renewable energy resources, primarily offshore wind zones, which are the most developed and promising form of blue energy in the region. Key ports such as Gothenburg, Stockholm, and those along the east coast, including ports near the Baltic Sea and the Gulf of Bothnia, are positioned advantageously near designated offshore wind areas identified through national marine spatial planning.

The Port of Gothenburg, Sweden's largest and a pivotal maritime hub, is located near growing offshore wind zones in the Kattegat and Skagerrak seas, providing opportunities for direct green power supply once associated wind farms become operational. Similarly, ports serving Stockholm and the surrounding archipelago can leverage proximity to floating offshore wind projects planned in the Baltic Sea, such as the large-scale floating wind farms proposed southeast of the capital.

While offshore wind dominates, solar energy installations are increasingly deployed at port facilities across Sweden to supplement local energy demand, especially during the long daylight periods in summer. Wave and tidal energy potentials are more limited and experimental, but coastal research centers and pilot projects exist near some ports on Sweden's west and east coasts.

The strategic location of Sweden's key ports near maritime renewable energy resources facilitates integration of clean electricity into port operations, supporting ambitious national decarbonization targets and promoting ports as hubs of sustainable energy transition in the Nordic region.

Several blue renewable energy projects are either already operating or planned within the influence zones of key ports, generally within a 50-kilometer radius. Offshore wind farms are the primary form of blue energy currently active or under development near major Swedish ports. For example, the coastal waters around Gothenburg and Stockholm host several proposed and developing offshore wind projects, leveraging the strong wind resource and deep waters suitable for floating wind turbine technology.

While operational offshore wind capacity near ports is still in its early stages, large-scale projects scheduled to commence construction in the late 2020s are expected to be directly connected to nearby port infrastructure for assembly, maintenance, and grid integration. For instance, projects like the Deep Wind Offshore's 1.4 GW wind farm in the Bothnian Sea will be relatively close to northern ports, supporting regional energy transition needs.

Marine biomass projects are less common within immediate port areas but benefit from the proximity to marine harvesting zones and local industrial uses of biomass for heating and energy in port hinterlands. Tidal and wave energy technologies remain mostly in pilot or research stages in Sweden, with some demonstration projects conducted in research institutions and coastal sites, often located further from major commercial port activities.

Spatial and regulatory constraints significantly influence the use and integration of marine renewable energy within port areas. It is limited by environmental protections, spatial competition among maritime uses, safety and legacy infrastructure considerations, and regulatory approval processes. These constraints necessitate comprehensive planning and coordination to ensure sustainable and safe deployment of renewables in port areas.

6 Port energy system baseline: demand, existing renewables and infrastructure readiness

Energy-related feasibility work and transition planning in Denmark is currently strongest around shore power (OPS) roll-out, port electrification, and the enabling national hydrogen/PtX infrastructure. At port level, large initiatives are typically backed by structured project documentation (often linked to EU funding), tendering, and grid connection planning. Examples include Copenhagen Malmö Port's cruise OPS programme in Copenhagen (Langelinie/Oceankaj) and the Port of Aarhus' pathway toward CO_2-neutral port operations by 2030, both centred on electrification and the scaling of shore power as a core decarbonisation measure. In parallel, national system operators provide planning inputs that ports depend on, such as Energinet's feasibility work for hydrogen transmission infrastructure in Jutland with a cross-border connection toward Germany, supporting future port-adjacent PtX clusters and bunkering/logistics concepts.

Comparable "total port area energy demand" figures are not always published in a single, harmonised format across Danish ports. However, OPS-related electricity demand is quantified in credible studies and provides a concrete baseline for the scale of near-term electrification loads. A scientific assessment by Aarhus University (DCE) based on 2023 port-call data estimates on-board electricity consumption at quay (i.e., the electricity ships would draw when using OPS instead of running auxiliary engines) at 27,620 MWh/year for Copenhagen (cruise + ferries, total) and 3,962 MWh/year for Aarhus (cruise + ferries, total). These values capture ship-at-berth loads rather than the full tenant/industrial consumption, but they illustrate that OPS alone already reaches the few-to-tens of GWh per year range for major hubs. In principle, Denmark's offshore wind build-out is large enough for marine renewables to cover these electricity needs; in practice, the limiting factors are typically local peak capacity, grid reinforcement timelines, and procurement/contract structures that ensure renewable supply is both reliable and credibly "green."

Ports in Mecklenburg-Vorpommern, particularly the Port of Rostock and Sassnitz-Mukran, currently use renewable energy and have concrete plans to expand its use across various operations.

- **Shore Power:** Ports provide renewable shore power connections for vessels, reducing diesel emissions while docked. These shore power systems increasingly draw from local offshore wind energy, ensuring a green electricity supply for ships and terminal equipment.
- **Terminal Operations:** Terminals integrate wind and solar power directly into their electricity consumption, optimizing onsite renewable generation to power lighting, cargo handling, and administrative buildings.

- **Hydrogen Production:** At the Port of Rostock, hydrogen production plants shall use offshore wind power via electrolysis to create green hydrogen, which serves as fuel for port vehicles, industrial processes, and as export product. Expansion of these plants is planned to increase capacity significantly by 2027–2030.

Ports are developing plans to scale up renewable energy capacity with upgraded shore power infrastructure, larger electrolyzers for hydrogen production, and integrating battery storage to stabilize supply. Investments include digitization and AI for better energy demand forecasting and management, allowing optimal use of variable renewable resources within port operations. Future timelines target significantly higher shares of renewable electricity use in port operations by 2030, aligned with Mecklenburg-Vorpommern's broader climate and energy goals.

Mecklenburg-Vorpommern's ports are adopting blue renewable energy solutions and plan to deepen this integration to meet environmental, operational, and regulatory aims. In Mecklenburg-Vorpommern, ports such as Rostock and Sassnitz-Mukran currently use renewable energy and have concrete plans to expand its application. Renewable shore power supplied largely from offshore wind farms is already available for vessels to reduce emissions while docked. Terminal operations incorporate wind and solar power for onboard energy needs, including lighting and cargo handling. At Rostock, green hydrogen production utilizing offshore wind electrolysis is operational and slated for significant capacity expansion by 2027–2030, fueling port vehicles and industrial processes. Planned developments include enhanced shore power infrastructure, larger electrolyzers, battery storage, and AI-driven energy management to optimize the variable renewable supply. These initiatives align with Mecklenburg-Vorpommern's climate goals and position its ports as leaders in blue renewable energy adoption and integration.

The core infrastructure supporting renewable energy integration in Mecklenburg-Vorpommern ports includes high-capacity substations, dedicated grid access points, and energy storage systems. These infrastructures are critical for managing the increasing renewable influx, supporting hydrogen projects, and enabling the ports to serve as regional energy hubs.

In Mecklenburg-Vorpommern, energy-related feasibility studies and transition planning are most visible in two practical tracks:

1. Shore power/electrification.
2. Hydrogen hub development.

For shore power, feasibility and business-case work has been developed in the wider Baltic context through the Green Cruise Port initiative, including a dedicated business case for Rostock (Warnemünde) that addresses investment needs, cost structures, and grid/tariff-related barriers that strongly influence port-side viability. Complementing this, Rostock-Warnemünde's shore power system for cruise shipping has moved beyond planning into operation, providing an applied reference point for further scaling and replication to additional berths and segments.

For hydrogen and system integration, "Energy Port Rostock" roadmaps and associated projects (including HyTechHafen concepts) outline staged development toward large-scale electrolysis capacity, linking port demand (industry/logistics/maritime) with renewable supply and potential waste-heat integration. At the offshore wind system level, feasibility and transition planning is strongly institutionalised through TSO and federal planning artefacts: 50Hertz' grid connection projects (e.g., Ostwind 2 and Baltic grid connection planning) define how offshore generation is integrated onshore (notably toward the Lubmin area), while the Federal Maritime and Hydrographic Agency (BSH) provides strategic environmental assessment and environmental reporting for offshore wind site development in the Baltic Sea. Together, these planning layers form the practical backbone for how MV ports can align shore-side infrastructure and future energy carriers with the expanding offshore renewable system.

Publicly comparable, "whole-port-area" energy demand figures are not always available in a single consolidated dataset; however, shore power demand provides a robust, quantifiable slice of port electrification needs. For Mecklenburg-Vorpommern, a concrete datapoint is the DNV/Green Cruise Port business-case assumptions for Rostock–Warnemünde: assuming ~60% of cruise port calls use OPS, annual electricity consumption is estimated at ~5.7 GWh; the calculated annual electricity consumption potential for the terminal is ~9.5 GWh, depending on utilisation assumptions and traffic levels. These values reflect cruise-at-berth demand (not the full tenant/industrial load), but they indicate the order of magnitude for near-term electrification measures that ports can directly influence.

In terms of supply, the regional offshore wind resource is already at multi-TWh annual output, meaning that — technically — marine renewables could cover a significant share of port electrification loads (OPS, e-mobility and parts of terminal demand), provided grid access is available. 50Hertz reports that Baltic Sea offshore wind farms fed ~5,400 GWh into its eastern German extra-high-voltage grid in 2025, and notes wind yields of ~4,900 GWh (2024) and ~4,300 GWh (2023) from the Baltic offshore build-out — several orders of magnitude above the single-digit GWh demand of cruise OPS in Rostock–Warnemünde. In practice, the "realistic" coverage is therefore less constrained by the offshore resource itself and more by local grid capacity and reinforcement timelines, connection costs and tariff structures, and operational peak-load management at the port/terminal level.

The Port of Klaipėda is proactively upgrading its infrastructure to serve as a critical logistics and assembly hub for these offshore wind farms. Key upgrades include the reconstruction and deepening of the Smeltė quay to facilitate the handling and storage of large wind turbine components, as well as berth adaptations to accommodate installation vessels and maintenance operations. These strategic investments position Klaipėda Port as the primary base for Baltic offshore wind farm construction and servicing, supporting Lithuania’s goal of energy independence and green transition. The developments complement broader EU and national efforts by leveraging the port’s favorable location and industrial capacities.

The Port of Klaipėda is actively advancing its transition to renewable energy through multiple initiatives that underscore its commitment to sustainability and energy efficiency. The Port Authority is currently installing a 35 kV solar power plant on the Fleet Base buildings, enhancing on-site renewable energy generation to reduce dependency on external sources. Since July 1, 2025, the Port Authority has committed to purchasing exclusively electricity generated from renewable sources, a practice certified by official documentation, ensuring that its energy consumption supports clean power objectives.

Looking ahead, the Port Authority is evaluating the possibility of joining a Renewable Energy Cluster currently developing a 200 MW hybrid park combining wind, solar, and battery storage technologies. This initiative aims to provide a stable, long-term green electricity supply to the port and its users, though a final decision is still pending following ongoing analyses.

Complementing these energy initiatives, Klaipėda Port is also investing in broader infrastructure upgrades to support offshore wind farm projects, positioning itself as a vital hub for renewable energy in the Baltic region. These efforts align with the port’s strategic vision to increase energy independence, reduce emissions, and contribute to regional sustainability goals.

Recent developments also highlight the completion of the first quay electrification project at the Fleet Base, including installation of an onshore power supply station that will serve the port authority’s green-powered vessels, marking the start of a green transition in port operations. These initiatives underscore Klaipėda’s strategic commitment to sustainable, modernized energy infrastructure, positioning the port to meet growing electrification requirements and environmental targets.

In Lithuania, a significant Port Electrification Study is currently underway, running through 2025–2026. This comprehensive analysis aims to assess the present and future electricity demand of the Port of Klaipėda and its users, alongside evaluating the capacity of the local grid operated by ESO (Distribution System Operator) and LITGRID (Transmission System Operator). The study encompasses a detailed examination of alternatives such as grid reinforcements, integration of remote renewable energy generation, and potential energy storage solutions. Its expected output includes the development of two to three plausible electricity supply scenarios, a thorough investment needs analysis, and proposed measures for CO_2 reduction aligned with Lithuania's and the EU’s climate goals.

Prior to securing EU funding support, thorough feasibility and technical-economic assessments were conducted for the green hydrogen production plant and connected refuelling stations planned in Klaipėda. These assessments confirmed project viability and led to their approval, with construction and implementation actively progressing. The hydrogen facility is expected to play a pivotal role in port logistics and local green energy ecosystems by producing up to 2.25 MW of green hydrogen, supporting decarbonisation of port operations and adjacent transport modes.

Similarly, for the Onshore Power Supply (OPS) projects, initial technical and economic studies paved the way for approval under the EU's Connecting Europe Facility (CEF) funding scheme. The project focuses initially on supplying Ro-Ro vessels with four connection points totaling around 6 MW capacity, with construction underway and operations expected to begin in April 2026. An expansion phase targeting cruise vessels with eight connection points and 16 MW capacity is planned from 2027, aiming to enable shore power usage as a key method for eliminating vessel emissions at berth.

Altogether, these concerted efforts form part of Lithuania's strategic approach to port electrification and green energy transition, setting Klaipėda Port as a frontrunner in adopting advanced sustainable energy infrastructures in the Baltic region. They are closely integrated with national goals for renewable energy growth, CO_2 emissions reduction, and hydrogen economy development, supported by European structural funds and investment programs.

In 2024, the port companies in Klaipėda consumed a total of approximately 60.5 GWh of electricity annually, based on a recent survey. Of this, around 43.66% was sourced from renewable energy, including rooftop solar PV installations on port facilities and certified green electricity purchased from suppliers. Currently, several projects are in progress or planned to support the port's growing energy needs. The OPS (Onshore Power Supply) system for Ro-Ro and Ro-Pax vessels, which is scheduled to become operational from April 2026, will require a capacity of around 6 MW. Additionally, an OPS system for cruise vessels with a projected capacity of 16 MW is planned for launch from 2027. The port further anticipates a demand of approximately 15 MW for OPS services for container vessels.

Complementing these, a green hydrogen plant with an installed capacity of 2.25 MW is under construction and scheduled to operate from April 2026. This hydrogen capacity will support decarbonizing port logistics, vessel refuelling, and potentially other transport and industrial activities.

Looking ahead, the Port Authority is developing a new territory of approximately 100 hectares, where the electricity demand could rise substantially — up to 200 MW — depending on the scope and scale of the new activities planned. This expansion will significantly increase the port's overall electricity needs, especially as OPS solutions are extended to larger vessels including containers.

Regarding the potential to meet this escalating demand from renewable sources, currently there are no direct blue energy resources such as wave, tidal, or marine biomass located within or near the port area. The closest large-scale projects are the Lithuanian offshore wind farms planned for the Baltic Sea, with a combined capacity of about 1.4 GW. These offshore wind farms will feed into the national grid, and depending on grid capacity and distribution infrastructure, they could partially meet the port's future electricity demand.

This strategic development aligns with Lithuania's broader goals to increase the share of renewable energy, and expand port infrastructure for sustainable maritime operations.

Currently, major Polish ports along the Baltic Sea, including Szczecin, Świnoujście, Gdańsk, and Gdynia, are utilizing renewable energy sources primarily through photovoltaic (solar) installations. At the ports of Szczecin and Świnoujście, managed by ZMPSiŚ, the total installed capacity of solar power systems directly operated by the port authority amounts to 0.05 MW, with an additional 0.232 MW provided by external operators within the port areas. In Gdańsk, associated solar projects contribute around 4.8 MW of capacity, while the Port of Gdynia features 1.2 MW of operating PV installations, supplemented by smaller systems such as a 50 kW setup at OT Port facilities.

Looking ahead, Polish seaports along the Baltic coast are preparing technical documentation and investment programs to accelerate their energy transition — particularly with regard to hydrogen technologies, shore power systems, and integrated renewable infrastructure. These initiatives form the foundation for future hydrogen production, storage, and distribution capabilities, reflecting a nationwide port strategy aimed at expanding the use of clean energy in maritime operations, cargo handling, and port-related services.

In summary: Ports currently use solar photovoltaic installations totaling approximately 0.28 MW in port operations. Technical and strategic planning is underway to integrate hydrogen technologies as part of a wider renewable energy transition. These efforts will enable expansion of renewable energy use across shore power, terminal operations, and hydrogen production in the near future.

This transition aligns with broader EU and national goals for decarbonization of port and maritime activities.

The current infrastructure in the port to support renewable energy integration includes a robust network of power stations and transformers designed to manage and distribute electrical power effectively. Specifically:

- There is 1 high-voltage (WN) substation operating at 110 kV, which serves as the main connection point for high-voltage grid access to the port.

- Additionally, 72 medium-voltage (SN) and low-voltage (nN) substations are in operation. These include SN, SN/nN, and nN substations that handle regional distribution within the port area.

- The port is equipped with 122 transformers, collectively providing a total transformation capacity of 96.5 MVA. This transformer capacity enables effective voltage conversion and power distribution to various port systems and potential renewable energy installations.

This existing electrical infrastructure forms a solid foundation for integrating renewable energy sources such as photovoltaic solar power and offshore wind, along with future technologies like hydrogen energy systems. The combination of high-voltage access, numerous medium- and low-voltage substations, and a substantial transformer capacity ensures flexibility and reliability in managing variable renewable power flows within the port.

The estimated total energy demand of the port area — covering Szczecin and Świnoujście — amounted to approximately 25,650,251 MWh in 2024. This figure represents the overall annual energy consumption, including baseline port operations and facilities.

To accurately assess the potential to cover this demand with marine renewable energy sources, Ports are currently conducting a detailed feasibility study focused on the energy transition of transshipment and storage equipment. The study involves gathering data through consultations with terminal service operators to understand fuel consumption patterns of individual transshipment units, translating fuel usage into equivalent electrical energy demand that would be necessary to replace fossil fuels and calculating the hydrogen demand required to support zero-emission fuel alternatives for equipment currently powered by fuel.

This comprehensive energy balance will integrate the total port energy consumption plus the projected energy requirements of electric and hydrogen-powered transshipment equipment. It will serve as a basis for the next stage of planning aimed at estimating the amount of renewable energy, particularly from marine sources such as offshore wind, that is realistically needed and can be harnessed to achieve carbon neutrality for port operations.

Total annual energy consumption in the port region in 2024 was roughly 25.65 million MWh. An ongoing energy balance study is quantifying energy needs related to transshipment and storage equipment, including hydrogen demand. The study's outcomes will guide how much marine renewable energy is needed to realistically cover the port's energy demand for a zero-emission transition. This data-driven approach enables precise planning for integrating renewable energy sources aligned with operational realities and climate goals.

Swedish ports are increasingly adopting renewable energy sources and have clear plans to expand their use in the near future. Currently, some ports utilize solar photovoltaic (PV) installations on terminal buildings and surrounding facilities to supply clean electricity for administrative operations and low-load activities. Offshore wind power, while not yet extensively integrated directly at ports, is expected to become a significant source of shore power and operational energy as nearby offshore wind farms come online and grid connections improve.

Additionally, several Swedish ports are actively exploring hydrogen as a key element in their energy transition strategies. Pilot projects focus on hydrogen production and refueling infrastructure to supply heavy-duty port equipment and hydrogen-capable vessels. These initiatives align with Sweden’s national hydrogen strategy and broader goals to achieve carbon neutrality in maritime transport and port operations.

The strategic integration of renewable energy in Swedish ports aims to decarbonize shore power supply, reduce greenhouse gas emissions from cargo handling equipment, and enable cleaner vessel fueling options. Plans typically include expanding solar capacity, upgrading grid connections to support offshore wind power, and developing hydrogen production and storage facilities on port premises.

Swedish ports have evolving electrical substations, improved grid access supported by national transmission upgrades, pilot-scale energy storage, and emerging hydrogen infrastructure. These elements collectively form a growing platform to enable the scale-up of renewable energy integration in support of sustainable port operations and shore power provision. Sweden is advancing its blue renewable energy sector with a strong emphasis on offshore wind power, complemented by emerging marine renewables like wave and tidal energy. Current and near-term projects (2025-2026) include major offshore wind farms such as Deep Wind Offshore’s Olof Skötkonung (1.4 GW) in the Bothnian Sea and floating wind projects like Simply Blue Group’s Skidbladner (2 GW) and Herkules (2.75 GW). These projects leverage floating technology to exploit deeper waters and minimize environmental impact. The Swedish government is expanding marine spatial plans to accommodate up to 90 TWh of offshore wind and investing in grid infrastructure, including up to six offshore grid hubs, to support integration of up to 10 GW of offshore wind capacity.

Wave and tidal energy remain primarily in pilot stages due to technological and economic challenges, while marine biomass is utilized regionally but not extensively in ports. Challenges include lengthy permitting processes, biodiversity protections under EU regulations, local opposition, and grid capacity constraints. Sweden addresses these via centralized permitting, grid investments, public-private partnerships, and innovation funding, fostering a transition toward a large-scale offshore wind industry and emerging marine renewables.

The country’s vast technical offshore wind potential (around 70–100 GW) positions it as a leader in marine renewable energy in Northern Europe, with ambitious plans extending well beyond 2030. Investments are significant, backed by public and private funding, focusing on reducing fossil fuel dependence and enhancing energy security through sustainable maritime resources. This progressive approach aims to balance environmental stewardship, social acceptance, and energy needs in Sweden's blue economy.

Swedish ports' energy-related studies reveal a robust commitment to green transition, characterized by careful technical, economic, and environmental evaluations. These processes have laid solid foundations for forthcoming investments in offshore wind integration, hydrogen infrastructure, solar and storage deployment, and systemic decarbonization of port operations, supporting national climate targets and sustainable maritime growth.

The estimated energy demand of Swedish port areas varies depending on the size and activity level of each port, but larger ports such as Gothenburg and Stockholm typically consume several hundred thousand to over a million megawatt-hours (MWh) annually. This demand encompasses terminal operations, cargo handling equipment, shore power for vessels, administrative facilities, and associated logistics.

Realistic coverage of this energy demand by marine renewables, primarily offshore wind, is promising due to Sweden's significant offshore wind potential and ongoing projects. With planned offshore wind farms nearing gigawatt-scale capacities located near major ports, a substantial portion of port energy needs could be supplied by clean, renewable electricity. Estimates suggest that as offshore wind capacity expands and grid connections improve, up to 60-80% of port-related electricity consumption could be covered by offshore wind power over the next decade.

Solar PV installations, while contributing smaller shares due to seasonal variability, can supplement daytime energy use in port facilities. Emerging technologies such as hydrogen produced via marine renewables and stored on-site may supply a significant fraction of energy needs related to heavy equipment and vessel refueling, potentially covering 10-20% of the overall energy demand depending on uptake and technology maturity.

7 Governance, stakeholder ecosystem, integration with cities, pilots and gap analysis

To improve synergies between port infrastructure and city planning while sharing costs, several integrated strategies are recommended:

1. Multi-Use Charging Infrastructure

   Develop public charging stations at the port that serve multiple user groups: electric trucks serving the port, tourist vehicles including cars with caravans, and port machinery such as cranes. This 24/7 multi-use approach maximizes utilization of charging assets, spreading capital and operational costs across diverse clients and reducing per-user expenses.

2. Collaborative Partnerships

   Invite commercial operators with expertise in e-mobility services to invest in, operate, and maintain such charging stations. This reduces upfront costs and operational risks for the port authority. Public-private partnerships can also facilitate integration with municipal electric mobility plans, ensuring alignment of goals and resource sharing.

3. Connectivity and Accessibility Planning

   Align charging station location and design with city traffic patterns, ferry routes, and public transport hubs to optimize accessibility for both port-related and general public users. Coordinate with city planners on traffic management, signage, and safety measures to support expanded EV use without disrupting port operations.

4. Shared Energy and Grid Services

   Explore opportunities for shared renewable energy generation — such as solar panels on port buildings — that can supply power for both the port and adjacent city charging infrastructure. Coordinate grid connection upgrades that benefit both port and city users, sharing reinforcing costs for higher capacity and resiliency.

5. Flexible Use and Future Proofing

   Design installations with modularity to adapt to evolving needs, such as scaling charging capacity or integrating vehicle-to-grid (V2G) technology to support local grid stability. Plan for integration with emerging technologies and alternative fuels as port and city sustainability strategies evolve.

6. Collaborative Funding and Incentives

   Identify co-funding opportunities from state and EU programs supporting green transport infrastructure that cover both port and urban mobility aspects. Joint planning strengthens applications for subsidies or grants by demonstrating broader impact and efficient resource use.

These recommendations aim to transform ports and urban areas into interconnected, sustainable mobility ecosystems. By fostering multi-user facilities, partnerships, and shared infrastructure investments, costs are distributed more effectively while enhancing service offerings for commercial, public, and industrial stakeholders. This integrated approach advances both port competitiveness and city environmental goals.

Stakeholders involved in energy planning and port development in Denmark typically include port authorities/operators and terminal operators, municipalities and city development agencies (especially where urban port areas are closely integrated with city infrastructure), and the national grid/hydrogen actors led by Energinet alongside relevant regulators and ministries. On the demand side, shipping lines and ferry operators are central for OPS utilisation and future fuel uptake, while technology providers (OPS suppliers, grid contractors, energy management solutions) shape implementation. Finally, energy developers and PtX actors (offshore wind developers, hydrogen/e-fuels producers and offtakers) increasingly influence port-side infrastructure requirements and investment roadmaps, particularly where ports are expected to become nodes in regional energy and fuel value chains.

To integrate port infrastructure and city planning effectively in Mecklenburg-Vorpommern and improve synergies while sharing costs, several strategic recommendations can be made focusing on coordinated development, shared resources, and mutual benefits. Proactive coordination between port authorities and municipal planners will be essential to capitalize on blue energy transitions and create wider socio-economic and environmental gains from shared infrastructure and planning frameworks.

Ports like Rostock and Sassnitz-Mukran are actively piloting microgrids, green hydrogen production, integrated battery storage, and digital energy management platforms. Test fields for offshore wind (Rostock-Warnemünde) and cross-border energy infrastructure pilots (e.g., Bornholm Energy Island, Hansa Power Bridge) are underway. Research sites and demonstration projects for marine biomass, offshore solar, and digital “Energy Port” solutions are ongoing or in development.

In Lithuania, the key stakeholders involved in energy planning and port development collaborate closely to support the country’s clean energy transition and modernize port infrastructure. The Port Authority of Klaipėda (KVJUD) plays a central role, overseeing and coordinating all port infrastructure projects and renewable energy initiatives such as Onshore Power Supply (OPS) systems, the green hydrogen production plant, and the Port Electrification Study nearing completion in 2026. The Authority is aggressively investing in sustainable infrastructure, with plans to spend over €300 million on modernization and energy projects, positioning Klaipėda as a leading maritime and green energy hub in the Baltic region.

Complementing the Port Authority’s responsibilities, ESO (Lithuanian Distribution System Operator, DSO) and LITGRID (Transmission System Operator, TSO) provide expertise and operational capacity to ensure reliable grid connectivity, sufficient distribution capacity, and system stability for the port’s expanding electricity needs. These organizations work closely with the port to reinforce grid infrastructure and integrate growing renewable energy and hydrogen demand.

At the governmental level, the Ministry of Energy formulates and oversees energy policy and legal frameworks impacting the port’s renewable projects and broader national energy transition efforts. The Ministry is actively involved in supervising major clean energy projects, aligning Lithuania’s climate goals with EU directives and funding mechanisms.

Private port tenants and terminal operators are vital contributors, undertaking investments in rooftop solar PV systems and procuring certified green electricity from the market, thus advancing the shared goal of decarbonizing port operations. Collaboration among these stakeholders fosters an integrated approach toward energy resilience, environmental sustainability, and economic competitiveness, ensuring Klaipėda Port’s future readiness and leadership in green maritime logistics and innovation.

The Port of Klaipėda is actively implementing a green hydrogen production project alongside its Onshore Power Supply (OPS) systems. The hydrogen project involves a polymer electrolyte membrane (PEM) electrolyser with an installed capacity of about 2.25 MW, which will produce around 127 tons of green hydrogen annually once at full capacity. This facility is scheduled to begin operations in early 2026 and is the first of its kind in the Baltic region. The hydrogen produced will be used not only for refuelling port service vessels but also heavy-duty vehicles and public transport, supporting decarbonization within the port and the city. The project is partly financed by the EU’s NextGenerationEU program, with a budget of approximately €12 million, half of which is EU-funded.

In addition, the Port is progressing with OPS infrastructure, installing stations that supply green electricity directly to berthed Ro-Ro, Ro-Pax, and cruise vessels. This integration of clean technologies aims to significantly reduce emissions from shipping activities while improving energy efficiency.

Further complementing these initiatives, the ongoing Port Electrification Study (2025–2026) is exploring additional energy storage solutions, like batteries and hydrogen, as well as smart microgrid applications to balance the variable load and supply associated with OPS and hydrogen production. These efforts demonstrate Klaipėda's commitment toward a sustainable, low-carbon maritime future by integrating advanced renewable energy systems and infrastructure innovations.

The integration of renewable energy in Lithuania, particularly concerning the Port of Klaipėda, faces several significant gaps and challenges that need to be addressed to accelerate progress.

Regulatory aspects present a notable barrier, as the legal framework for green hydrogen production, storage, and use remains under development. This generates uncertainties around permitting, operational safety, and compliance requirements for hydrogen projects, which slows down investment and implementation initiatives. Meanwhile, Lithuania is actively working on transposing EU clean energy legislation, including RED III targets, to create a clearer and more supportive policy environment for hydrogen and other renewable technologies.

Financing is another critical challenge. Onshore Power Supply (OPS) and green hydrogen projects require substantial capital investment; ongoing support from EU funds (such as NextGenerationEU) and national programs is essential to maintain momentum. Given the scale of modernization and infrastructure expansion required — estimated at over €300 million for modernization efforts in Klaipėda Port alone — continued financial backing is crucial.

Grid capacity limitations also hinder renewable integration. The current electricity infrastructure was designed for lower, centralized fossil fuel-based demand and struggles to accommodate the increasing loads from OPS, hydrogen production, and the envisaged 200 MW demand in the port's expanding territory. Significant reinforcements to ESO's (DSO) and LITGRID's (TSO) networks and new grid connections are necessary to ensure reliable supply and system stability.

Furthermore, knowledge and practical experience with next-generation energy solutions such as large-scale hydrogen technologies and energy storage remain limited in Lithuania. The port, along with national stakeholders, recognizes the importance of building expertise and testing innovative technologies to overcome technical and operational challenges.

Institutional collaboration and stakeholder engagement are critical to the success of these efforts. The Port Authority (KVJUD) actively seeks stronger involvement from energy institutions, policymakers, and port users to foster coordinated action, share knowledge, and accelerate the energy transition. Strengthening public-private partnerships and regional cooperation will be essential to leverage resources efficiently and implement innovative solutions.

Overall, while Lithuania has made strategic advances in renewable energy development and sets ambitious decarbonization targets, addressing regulatory uncertainty, financing needs, grid constraints, technical readiness, and multi-stakeholder coordination remains vital to fully unlock the potential of renewables, particularly in maritime and port sectors.

To improve synergies and share costs between port infrastructure and city planning in Poland, several strategic recommendations are pertinent for ZMPSiŚ and its cooperation with municipal authorities, given their reporting to the Ministry of Infrastructure and their current coordination primarily around local spatial planning matters:

Early and Joint Spatial Planning: Establish formal coordination platforms between port authorities and city planners at the earliest stages of development projects, ensuring port expansion and urban land use are harmonized. This reduces conflicts, optimizes land allocation, and integrates transport connections, minimizing costly retrofits.

Shared Multi-Use Infrastructure: Design infrastructure (roads, rail links, energy grids, digital networks) as shared assets serving both port activities and urban needs. For example, road upgrades or electrification projects serving port terminals could accommodate city traffic and public transport, splitting investment and operational costs.

Integrated Energy Systems: Develop joint renewable energy projects (solar parks, wind installations) and energy storage systems that can supply both port facilities and urban areas, distributing cost benefits among stakeholders and facilitating grid stability.

Funding Coordination: Leverage combined funding applications for EU and national infrastructure grants that recognize integrated urban-port development benefits. Joint proposals increase competitiveness and ensure coherent project design aligned with broader regional development goals.

Mobility and logistics hubs: Coordinate the development of multimodal logistics hubs that serve both port freight handling and city-based distribution, enhancing efficiency, reducing congestion, and enabling shared facility costs.

Environmental Impact and Social Licensing: Collaborate on joint environmental assessments and public consultations, sharing responsibilities for biodiversity protection and community impact mitigation. This integrated approach reduces duplicated efforts and improves stakeholder acceptance.

Digital Infrastructure and Data Sharing: Establish platforms for joint digital planning and data exchange on traffic flows, energy use, and environmental monitoring. Shared data analytics can optimize infrastructure use and maintenance costs while supporting smart city and port synergy initiatives.

A formalized, strategic partnership framework between ports and city planners beyond ad hoc spatial planning consultations can drive better integrated land use, infrastructure development, and energy systems. Combining resources for shared infrastructure investments, joint funding, and cooperative environmental and digital strategies will reduce overall costs, streamline development, and strengthen the port-city interface's resilience and sustainability. This approach supports Poland's broader infrastructure modernization and sustainable urban and coastal development policies under the Ministry of Infrastructure guidance. To improve synergies and share costs between port infrastructure and city planning, it is recommended that ZMPSiŚ and local city planners establish formalized, early-stage coordination mechanisms. This would harmonize land use and optimize access routes to the port, minimizing costly redesigns. Shared use of infrastructure — such as roads, rail links, energy grids, and digital networks — should be designed to serve both port operations and urban needs, enabling investment and operational cost sharing.

Joint development of renewable energy installations and storage systems can supply both ports and city areas, distributing benefits and improving grid stability. Coordinated applications for EU and national infrastructure funding can increase competitiveness while ensuring integrated regional development. Developing multimodal logistics hubs serving both freight and urban distribution helps reduce congestion and allows shared facility costs.

Environmental assessments and public engagement should be conducted jointly to streamline compliance and enhance stakeholder acceptance. Digital platforms for shared data on traffic, energy use, and environmental monitoring can optimize operation and maintenance costs and support smart city-port synergies.

Key Stakeholders Involved are Port Authority (ZMPSiŚ), Private Operators and Terminal Lessees, Municipalities and Local Authorities and Initiatives like Szczecin Port Stakeholders Council (Rada Interesantów Portu Szczecin as well as Energy Utilities/Infrastructure Providers and National and EU Regulatory Bodies. These bodies set policies, funding frameworks, and environmental standards that shape energy transition and port development strategies. Funding applications and compliance reporting often involve coordination with these institutions. Together, these stakeholders form a collaborative ecosystem that guides the port's energy transition and development trajectory in line with legal, economic, and environmental objectives.

Poland's main gaps are slow, complex permitting and high upfront costs for hydrogen-ready infrastructure, plus limited operational experience with marine renewables in port settings; long-term plans focus on OPS readiness by end-2029, hydrogen-centric equipment decarbonisation, grid upgrades, and EU-cofinanced implementation roadmaps for Szczecin and Świnoujście. Together with national port alliances and the Świnoujście offshore terminal build-out, these plans aim to align port operations with EU alternative-fuels and electrification requirements while de-risking first-of-a-kind deployments.

Sweden remains challenged in fully matching demand due to variability in renewable generation and energy storage needs, but ongoing investments in offshore grid infrastructure, port electrification, and hydrogen infrastructure are expected to progressively increase the share of marine renewables in port energy mixes. Wave and tidal energy remain primarily in pilot stages due to technological and economic challenges, while marine biomass is utilized regionally but not extensively in ports.

Summary

The decarbonisation of the maritime sector has become a central priority within global climate policy and energy transition strategies. As international shipping and port activities contribute significantly to greenhouse gas emissions, increasing attention has been directed toward the integration of renewable energy sources within maritime infrastructure. Recent literature highlights the strategic role of ports as hubs for energy transition, particularly through the development and integration of blue renewable energy systems such as offshore wind, marine biomass, wave energy, and hydrogen production (Notteboom & Haralambides, 2020; IRENA, 2022). Within this context, the Baltic Sea region has emerged as a key area for renewable maritime energy development due to its favourable geographic conditions, established port infrastructure, and supportive policy frameworks.

Offshore wind dominates as the most mature and scalable source, with Denmark's Energy Island Bornholm at 3-3.8 GW (expandable by 1.5 GW), Kriegers Flak up to 4.1 GW, Poland targeting 5.9 GW by 2030 and 18 GW by 2040 (including 17.5 GW in Ławica Odrzańska), Lithuania at 1.4 GW, and Mecklenburg-Vorpommern exceeding 2.5 GW technical potential. Solar, tidal, wave, and biomass play supplementary roles, often at pilot scales (e.g., wave potential in Poland ~6 GW theoretical, but limited by Baltic conditions), with ports adopting shore power, electrolyzers, and rooftop PV for immediate use.

Ports drive transition via infrastructure like Rostock's 100 MW hydrogen electrolyzer (scalable to 1 GW), Klaipėda's 2.25 MW green hydrogen plant and OPS systems up to 37 MW, and Copenhagen Malmö's 48 MVA shore power by 2028. EU funding (CEF, NextGenerationEU) and policies (AFIR) enable progress, though digital tools like AI forecasting and digital twins are emerging mainly in Denmark and Germany.The region boasts substantial green energy potential, led by offshore wind exceeding 35 GW across planned and technical capacities (e.g., Poland 18+ GW long-term, Denmark ~8 GW Baltic projects, Germany MV >2.5 GW, Lithuania 1.4 GW, Sweden's pipeline toward 10 GW+). Adding minor contributions from solar (stalled but expanding), wave/tidal (low GW-scale demos), and biomass yields a conservative total technical potential of over 40 GW, sufficient to cover regional electricity needs multiple times over and position ports as energy hubs.

Research on marine renewable energy consistently identifies offshore wind as the most mature and scalable technology in maritime energy systems. Offshore wind has experienced rapid technological advancement and cost reduction, enabling large-scale deployment across European maritime regions (IEA, 2023). The Baltic Sea is particularly suited for offshore wind development due to its relatively shallow waters, moderate wave conditions, and proximity to energy-intensive coastal economies

Several Baltic Sea countries have adopted ambitious offshore wind development strategies. Denmark, for example, is widely recognised as a pioneer in offshore wind technology and infrastructure, with large-scale projects such as the Energy Island Bornholm initiative projected to deliver between 3 and 3.8 GW of capacity, with further expansion potential. Similarly, Poland has outlined extensive offshore wind plans, targeting approximately 5.9 GW by 2030 and up to 18 GW by 2040. These initiatives reflect a broader regional trend toward large-scale marine energy deployment aimed at supporting both national decarbonisation goals and European energy security.

Lithuania and Germany also demonstrate growing offshore wind capacity in the Baltic Sea. Lithuania plans to develop approximately 1.4 GW of offshore wind capacity, while the German state of Mecklenburg-Vorpommern is estimated to have technical offshore wind potential exceeding 2.5 GW. Sweden has also announced major offshore wind expansion projects targeting up to 90 TWh of additional energy production in the coming decades. Collectively, these developments highlight the Baltic Sea region as a major emerging centre for marine renewable energy production.

Although offshore wind dominates the current energy landscape, other forms of blue renewable energy remain under development. Solar energy installations on port infrastructure, as well as marine biomass and wave energy systems, are increasingly explored as complementary energy sources. However, many of these technologies remain at pilot or demonstration stages due to technical constraints and the relatively low wave energy potential of the Baltic Sea compared to Atlantic coastal regions.

Despite significant progress, the integration of blue renewable energy within maritime systems faces several challenges. One of the most prominent barriers is the complexity of maritime spatial planning, particularly in regions with competing interests such as shipping lanes, fishing grounds, and environmental protection zones. Environmental concerns also play an important role, as offshore energy infrastructure can potentially affect marine biodiversity and ecosystems. As a result, project development often requires extensive environmental impact assessments and stakeholder consultations.

Technical challenges also remain, particularly in relation to grid connectivity and energy storage. Large-scale offshore wind projects require substantial grid infrastructure and interconnection capacity to transmit electricity from offshore generation sites to onshore consumers. Additionally, financing large-scale maritime energy infrastructure remains capital-intensive, requiring long-term investment commitments and public-private partnerships.

Finally, coordination among diverse stakeholders—including port authorities, regional governments, energy companies, and private operators—can present governance challenges. Effective collaboration frameworks are therefore essential for implementing successful energy transition strategies in maritime regions.

In conclusion, the South Baltic Region holds at least 40 GW of blue renewable potential, predominantly offshore wind, enabling ports to moderate the energy transition toward decarbonization, energy security, and economic growth by 2030. Ports will likely play a central role in this transition by functioning as energy hubs that integrate renewable generation, hydrogen production, and clean shipping infrastructure. Through continued policy support, technological innovation, and cross-sector collaboration, maritime ports in the Baltic Sea region can significantly contribute to regional decarbonisation, energy security, and economic development.

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