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PORT ELECTRICITY COMMERCIAL MODEL (PROJECT PILOT)

Final Report

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1 MANAGEMENT SUMMARY

The urgent need for achieving climate neutrality by 2050 demands a substantial reduction in greenhouse gas (GHG) emissions from all modes of transportation, including maritime. To reach this climate ambition as well as the energy policy targets, the pivotal role of ports in electrification and transition to low-carbon and renewable energy vectors emerges as a significant avenue for decarbonization. While several European ports have initiated clean energy solutions, many still grapple with hurdles in their decarbonization journey. Challenges persist, ranging from securing funding for electrification and port infrastructure to delays in electricity grid capacity expansion and difficulties in defining viable business models. Hence, the study's primary objective is to offer pivotal insights and guidance to decarbonize European ports. The study aims to delineate economically viable energy business models, aligning with the European Union's policy frameworks and advancing the objectives of the European Green Deal and REPowerEU. Our specific goals encompass the analysis of feasible clean energy business models based on electrification or other low-carbon solutions. Additionally, we aim to evaluate the potential and requirements of ports concerning Offshore Renewable Energy Sources (ORES) and the implementation of the revised Trans-European Networks for Energy (TEN-E) regulation, ensuring our findings align with the European Union (EU)'s policy trajectory.

The management summary encapsulates the key findings and insights derived from the project, focusing on several scope tasks critical to advancing clean energy transitions within European ports. These facets collectively contribute to a comprehensive overview intended to guide and inform policymakers, stakeholders, and port authorities in charting a sustainable, energy-efficient course for European ports in alignment with the EU's ambitious climate and energy objectives.

1.1 Clean energy business models and their replicability

The study delineated five clean energy business model categories, with each one subsequently matched to a specific model(s) at one of the front-runner ports for detailed analysis. The results regarding the viability of each model are demonstrated through their socio-economic benefits, derived from the output of the Cost-Benefit Analysis (CBA); their replicability potential has been presented and further confirmed in a workshop involving representatives of port authorities that were not part of the assessment.

Onshore Power Supply (OPS)

The implementation of Onshore Power Supply (OPS) in the Ports of Marseille, Kristiansand, and Gothenburg, is primarily driven by environmental regulations and pollution reduction in port/city areas. OPS installation significantly reduces CO_2 emissions and pollutants such as NOx, SOx, and Particulate Matter by approximately 80%, compared to berthing without OPS.

The analysed OPS cases exhibit both notable similarities in technical solutions and operational models, yet there are also distinct differences. These divergences encompass the types of vessels served, ranging from cruises and ferries to cargo ships, as well as variations in equipment ownership, involving the port, terminal owner, or a new entity often formed through a collaboration between the port and an electricity supplier. Another crucial distinction lies in the entities investing in the OPS system. In most instances, the port authority played a role in contributing to grid equipment investments.

The common system is a standard OPS crane that supplies auxiliary power to a single ship. However, some ports are considering more powerful installations with the ability to charge batteries for fully electric vessels. Certain ports impose an additional fee for the electricity supplied. Notably, these ports are exploring diverse solutions to minimize peak demand and reduce the need for extensive grid extensions. Strategies include scheduling ships at different times, with potential extra costs during peak hours or incentives such as discounts for suitable time slots, and the implementation of local storage solutions.

The success of this mature technology relies on its economic performance and environmental benefits. These ports engage in long-term contracts with ship operators – investing, installing, and operating most OPS systems as part of concession agreements. However, a major hurdle lies in electricity grid reinforcement, crucial for OPS deployment. As confirmed during the workshop on replicability of business models, this does not need to be the case for all ports but remains the most pressing issue. Predictable electricity consumption due to regular ship services allows for well-planned infrastructure development and use by the Port Authority (PA), and most OPS systems to avoid major grid upgrades.

The potential for CO_2 savings through Onshore Power Supply (OPS) across these ports is significant. In Gothenburg and Marseille, the yearly emission reduction potential for OPS could range from 38-43 ktonnes CO_2 equivalent. While Kristiansand also presents similar CO_2 savings potential, the challenge lies in sustaining these reductions over time due to the escalating electricity demand. This is especially due to a relatively large group of smaller vessels, as they contribute to a high peak demand.

Cost-Benefit Analysis (CBA) highlights positive outcomes for the 3 OPS cases when considering environmental and societal costs and benefits. However, our CBA indicates the Kristiansand case with limited calls per year only shows better results than the business-as-usual (BaU) case if ship investments are not taken into consideration.

Replicability for other ports relies on funding recovery, grid capacity, and possible subsidies. The investment economics depend on funding accessibility and partnerships for OPS installations. For an OPS system, a significant investment element is the 50Hz/60Hz frequency converter, crucial for connecting vessels, which gives ship operators flexibility over managing their fleets, especially for cruises. This poses challenges despite most EU countries operating on a 50 Hz network, as ships prefer port-side converters for flexibility without on-board conversions. The European Maritime Safety Agency's (EMSA) Guidance on Shore-Side Electricity[1] provides additional information.

Expectations lean towards replicating OPS models with either open-access systems managed by a Port Authority (PA) or regular ship services under long-term contracts with terminal operators. Challenges arise for some ports in container and cruise segments due to existing electricity grid limitations. This is particularly true for cruise ships with extensive infrastructure needs and irregular traffic (with high fluctuations during a short high season). These limitations have so far hindered the pursuit of OPS in this segment and compliance to the mandatory alternative fuels infrastructure regulation (AFIR) for the ports that fall under its scope, resulting in either delayed investment decisions or, particularly for cruises, considerations to ban their traffic altogether until the cruise segment evolves to accommodate more regular traffic. At the same time, the Fuel EU Maritime Regulation (Regulation (EU) 2023/1805) mandates the use of onshore power supply for container and passenger vessels, including cruises, unless alternative zero-emission technology is used, practically guaranteeing future OPS deployment.

Decarbonisation of terminal's operation

Within the scope of our study, this category specifically focuses on the container terminal, exploring the rubber-tired gantry cranes **(RTG) electrification business model**, exemplified in the Port of Valencia. The electrification study revealed substantial benefits, including a 65% reduction in CO_2 emissions, a 50% decrease in maintenance costs, and a 60% cut in energy costs. These improvements contribute to a more efficient system and an enhanced working environment. The positive CBA reaffirmed its viability due to lower maintenance costs and higher energy efficiencies compared to diesel RTGs. Despite mature technology and proven investment cost recovery through increased productivity, further large-scale electrification depends on additional electricity grid capacity and local constraints. Grid limitations hinder the fast expansion of terminal electrification for 2030 despite successful projects in Valencia.

Under this category many business models can show high **replicability** potential, provided a secure electricity supply is ensured. Additionally, the integration of renewable energy resources with conventional generation and energy storage in

[1] https://www.emsa.europa.eu/electrification/sse.html

ports enhances electricity system reliability and facilitates energy system integration, playing a crucial role in optimizing energy vectors' linkages.

New businesses

In the category New Businesses, the **renewable hydrogen production and use model**, a prototype hydrogen reach stacker at the Port of Valencia, is in a testing phase, hence it lacked real data collection. Despite technological immaturity and uncertain investment costs, the model shows potential to decarbonise terminal operations without heavy reliance on electricity grid developments. The emphasis is on onsite renewable hydrogen production, significantly reducing electricity costs that would need to come from the grid and achieving nearly 100% CO_2 emissions reduction by transitioning from diesel engines to hydrogen propulsion using H_2 fuel-cells or H_2 internal combustion engines. However, the initial prototype's higher investment costs and ongoing tests without market-ready solutions create uncertainties, requiring future reassessment with effective project results for a clearer business case.

As for new business ventures, uncertainties persist due to the immaturity or lack of market-ready technologies required. Despite the widespread use of reach stackers in ports, the replicability potential is relatively low due to technological immaturity of hydrogen technology.

Examining the deployment of renewable hydrogen production, the **replicability** potential is limited and largely dependent on the size of the port and availability of complementing industrial off-takers. Conversely, onsite renewable electricity production seems more replicable, contingent on each port's potential to install solar photovoltaic (PV), wind turbines and wave energy in a combined system with batteries, balancing output with local consumption.

Energy hubs

The **renewable electricity generation model** based on Port of Valencia is highly promising in aiming to install as much and as diverse generation as possible. It involves solar PV, onshore wind and wave energy. These installations combined could cover more than 65 % of Port of Valencia's electricity needs, based on current consumption levels. However, to optimally integrate the self-generated electricity into its system, the port would need to install an advanced Smart Energy Management System (EMS).

The **replicability** of this business model in other ports is, however, conditional upon the careful assessment of unique local dynamics. While the template of utilising port space for renewable energy generation is transferable, its ultimate viability necessitates a thorough feasibility study, considering regional climatic variations, available space, energy demands, and existing infrastructure, to ensure that the model can be effectively applied to other port locations.

The **renewable hydrogen economy model** and its development in the Port of Rotterdam are in the early stages, indicative of the overall immaturity of the renewable hydrogen economy. While numerous ambitious projects have been announced, only a few have progressed to the final investment decision (FID) stage, making it challenging to assess replicability potential. As an alternative, the report identified key requirements for ports aspiring to facilitate renewable hydrogen development, based on Rotterdam's example:

- High renewable energy sources (RES) availability or import facilities: Ports situated near substantial offshore wind energy farms are more likely to attract renewable hydrogen producers. Additionally, ports should possess the capacity to receive hydrogen in specialized terminals.
- Large industrial base: Ports with a substantial industrial presence, including refineries and chemical industries, can play a pivotal role as initial off-takers for renewable hydrogen and derivatives. This involvement contributes to the decarbonisation of their operations.
- Export capability: Ports like Rotterdam, which are centrally located in a large natural gas network (including pipelines or import/export terminals for liquified hydrogen and its derivates) or near the planned hydrogen backbone, have the advantage of being able to supply hydrogen further. In the case of Rotterdam, it can supply

hydrogen to the rest of Netherlands and neighbouring countries such as Germany. In contrast, ports that lack connectivity to gas networks may miss out on the opportunity to establish themselves as significant hydrogen hubs.

Smart Grids

Energy Management Systems (EMS) in ports aim to efficiently manage energy demand, supply, flows, and storage using Smart Energy Management Systems like Smart Grids or Microgrids. These systems reduce reliance on external electricity grids by aligning energy demand with available supply based on energy prices, grid tariffs, and technical constraints. They cater to various equipment within ports, drawing energy from utility grids and onsite renewable sources like solar and wind energy. In a couple of ports, they have been applied in pilot projects employing field devices with sensors – acting as intelligent agents making localized decisions, coordinating with peers, and communicating with control centres.

Replicating Smart Systems and Grids in European ports is necessary to enable information and power exchange between various stakeholders, leveraging advancements in intelligent communication, monitoring, and management systems. Yet, full deployment requires operational experience, information and communication technology (ICT) competence, and a shift from experimental exercises to widely applied solutions.

1.2 Evolution of electricity demand and impact on electricity infrastructure

The replicability of clean energy business models in most cases are conditioned by the availability of energy infrastructure in each individual port and access to electricity supply via the grid and/or own onsite generation.

In most large deployment projects, in view of significantly decarbonising the port operations, the current electricity grids do not fit the new needs and challenges, such as the need for electrification and the transition to renewable energy sources. The deployment of variable (non-dispatchable) electricity generation sources poses challenges to balancing responsible parties (BRPs) and both distribution and transmission system operators (DSOs and TSOs) as well. Efforts to integrate renewable energy sources, such as solar PV installations, wind turbines, and potentially wave energy systems, aim to reduce dependency on the grid. However, the surplus of renewable power at certain times poses challenges, requiring investments in local energy storage systems (e.g. batteries) or agreements with grid operators to inject the surplus electricity into the grid.

Most ports expect a substantial growth in their electricity demand from the implementation of these models (for instance, electricity demand is expected to quadruple by 2030 in the Valencia and Rotterdam ports). In some ports, this is not a major issue due to the high availability of low-carbon grid electricity. While for other ports the implementation of electrification projects will be conditioned by the deployment of renewable electricity production and back-up generation or storage capacity, where appropriate, to ensure a reliable electricity supply to the port site.

The OPS systems stand out as the most demand-driven electrification project, and concurrently are the preferred choice for berthing decarbonisation. Medium-sized ports like Gothenburg or Marseille can be estimated to have annual OPS electricity demand ranging from 55 to 61 GWh between 2030 and 2050, while smaller ports like Kristiansand from 22 to 23 GWh, potentially doubling or tripling their current requirements. Meanwhile, the larger ports like those of Valencia and Rotterdam are forecasted to demand around 150 GWh and nearly 300 GWh by 2050 respectively. With exception of Kristiansand, in all other cases this poses challenges to grids and electricity supply.

Ports employ various solutions to deal with the issue of congested grids and power demand peaks. Although there is a significant electrical infrastructure present in all ports, most grids are used at full capacity. Strategies to manage power peaks involve deploying spare batteries for machinery, employing smart planning methods to reduce voltage disturbances, and exploring alternative power sources like ship auxiliary engines, bi-directional shore side electricity systems or optimising energy usage in non-critical areas. Digital tools for forecasting electricity supply and demand play a crucial role in optimising charging times for electric equipment and maximizing the consumption of locally produced electricity.

The combination of new energy resources like energy storage with conventional generation, e.g. onsite Combined Heat and Power (CHP) and energy storage allows to improve the reliability of the electricity system. Ports can play a key role in the energy system integration by facilitating the optimal linkages between local production, transport, storage, and use of the different energy vectors (electricity, heat, renewable gas), including providing transport services for CO_2 and waste heat recovered from industrial processes.

1.3 Barriers and challenges

A significant barrier is the need for electricity grid capacity upgrades to provide sufficient power for large ships and the local port grid due to electrification, particularly in remote areas with limited infrastructure. Overcoming this barrier requires the reinforcement and extension of the electricity grids, enabling a reliable power supply for ports and shipping companies. Local electricity production, such as solar and wind energy, can be part of the solution, although high investment costs and intermittent production may pose challenges.

Another major barrier is the energy infrastructure investment costs. These costs are associated with building new substations and transformers, adding transmission lines, OPS, and electrification equipment, such as electric cranes. Ports often make investments which have a high societal value for the surrounding communities and national interests, but do not generate adequate return on investments. Based on the “polluter pays principle“, it seems appropriate to pass on the costs to the polluter (shipping companies). Currently this is considered by some ports to weaken the competitive position of the port. After 2030, once OPS use by maritime vessels is mandated in the Fuel EU Maritime Regulation, this specific barrier will become less relevant. The extension of ETS scope to include maritime transport in 2024 and the requirements in the Fuel EU Maritime Regulation to reduce the greenhouse gas intensity of fuel used by ships calling EU ports as from 2025 will provide incentives for the use of OPS by ships and will therefore contribute to an increase in demand for OPS in the first mover ports that have already deployed OPS infrastructure prior to the legislative deadline of 2030.

Limited funding or budget constraints can make it harder to allocate resources for grid development and equipment purchases. Combining business models such as OPS, electrification, onsite energy generation, etc. and strategic planning for the long term can increase funding options, allow for synergies, optimise resource usage (e.g .”dig only once”) and improve return on investment. Capital support (subsidies or grants) is an important mitigation measure, for supporting both the greening of port equipment and the rollout of alternative fuels infrastructure and OPS. However, given the limited amount of public funding available and considering the diverse nature, characteristics, needs and strategies of each port, the appropriate support (among those available) should be sought. Financing support also through blending instruments should be considered and may be more appropriate for larger ports with higher volume projects and high traffic volumes.

Current electricity price levels and grid tariff structures are not favourable for equipment with high peak demand, such as OPS used by large cruise or passenger vessels. In addition, the complexity of electricity markets can pose challenges in mitigating the barrier. Electricity procurement costs are influenced by various factors, including supply and demand dynamics, irregular renewable energy generation, transmission and distribution costs, and regulatory policies in particular regarding network tariffs. Navigating these market complexities, securing favourable power purchase agreements (PPAs) with electricity suppliers, and ensuring stable and predictable electricity prices requires careful consideration from the ports. Collaboration with local utilities, regulators, and 3rd party electricity providers to agree on terms and tariffs appropriate for these new port needs is essential. The proposed reform to the Electricity Market Design

(2023) includes provisions for facilitating more stable long-term contracts such as PPAs which can help address this issue.[2]

As more electrification and clean fuel technologies are implemented by ports and other industries for their decarbonisation efforts, the lack of skilled workforce will become more evident and competition for these workers will increase, leading to ports facing a risk of a lack of skilled personnel. Actions, such as port training programmes to facilitate the transfer of knowledge and skills and new vocational education programmes, must be taken now to prevent the knowledge and skill gap.

For clean fuels, the availability of space, including safety distances, can be an important barrier affecting local renewable hydrogen production and storage (as well as bunkering activities). Hydrogen needs considerable space to store at the surface in gaseous form, or considerable energy to liquefy and for some ports, safety distances overlap with residential areas, which makes it almost impossible to import green ammonia for end-use either as ammonia or reconversion to hydrogen. Mitigations are port specific and not all ports will be able to implement hydrogen production (and derivatives) and storage onsite, especially on a large-scale. The mitigations mainly include planning by the ports and Member States to identify suitable ports and locations for hydrogen and other clean fuel projects.

The second most prominent barrier for low-carbon fuels, and more specifically hydrogen, is permitting. For most Member States, the regulatory framework to authorise hydrogen projects is lacking, making hydrogen project development lengthy, uncertain, and costly. To resolve the permitting barrier, the best action is the clarification and streamlining of legislative and regulatory frameworks at the EU and Member State levels for hydrogen production, conversion, transport, storage, and usage. The Clean Hydrogen Alliance has presented in June 2022 its report identifying barriers to the permitting of hydrogen projects, describing good and bad practices and making policy recommendations. Further steps have meanwhile been taken, specifically for PCI/PMI (Projects of Common Interest and Projects of Mutual Interest). The Commission will evaluate the permit granting process (Art. 21 of TEN-E Regulation) by end June 2027.

1.4 Implementation of business models in two ports

In order to assess and better comprehend the implications of clean energy business models, a set of two representative ports, model ports, was used: 1) the transport port and 2) the industrial port. The typical transport port used in the analysis is based on the Port of Valencia and the typical industrial port is based on the Port of Rotterdam. The combination of the business models was used for each port.

The yearly costs of the transport model port are higher than those of the industrial model port, primarily due to a larger representation of OPS capacity, e-RTGs, and H_2 reach stackers in the transport model. The industrial model port has higher renewable capacity. These differences arise from assumptions based on the forecasts of the ports of Valencia and Rotterdam, with the scale factor reflecting their representativeness. On average for 2030-2050, the transport model port incurs 27% higher costs than the industrial model port. The net economic benefits of the two model ports are comparable in 2030 (1.9 MEUR/year) and are growing to 3.2 MEUR in 2050 for the industry port and 4.0 MEUR/year in the transport port.

1.5 Ports as industrial hubs for ORES and TEN-E implementation

Ports and surrounding areas are pivotal for the EU's TEN-E policy as well as for the ORES policy, aimed at bolstering energy infrastructure for a secure, sustainable, and well-connected energy network across Europe. They can serve as key nodes in interconnecting energy networks between regions and countries through infrastructure like high-voltage interconnectors or connection points to future hydrogen pipelines, thus increasing the integration of the European backbone network and enhancing supply security. Ports can also play a role in building and operating CO_2 transport

[2] https://www.consilium.europa.eu/en/press/press-releases/2023/10/17/reform-of-electricity-market-design-council-reaches-agreement/

pipelines to connect industrial plants or energy production facilities that capture CO_2 with other industrial plants that use CO_2 or with offshore and onshore storage and sequestration facilities. Moreover, ports can become hubs for innovation in energy technologies, hosting research and test facilities for new energy technologies. The expansion of energy-related port infrastructure can drive job creation and local economies in adjacent regions, aligning with the broader objectives of the TEN-E regulation and the ORES policies. Ports can become a key element in advancing the EU's energy transition and infrastructure development ambitions. At the same time, the business models considered have a positive effect on the implementation of the EU Climate and Energy policies, including REPowerEU. This is a result of the ports' increased focus on relevant aspects of their goals. These include better integration of renewable energies into the system through improvements to the ports' own grid infrastructure and local electricity production and storage. These improvements can, in turn, have a positive impact on the energy supply and grid stability, while reducing dependence on fossil fuels.

In the business models, a host of **energy-related infrastructures** is considered. Energy storage systems were found to be relevant as an additional and complementary infrastructure in all the cases considered. Especially in the case of onshore power supply (OPS), the possibility of adding hydrogen-based power systems (stationary or on barges) offers a promising option when it comes to additional infrastructure for ports. Looking beyond concrete business model cases, a variety of other promising options were identified for ports, including, e.g., waste-to-energy or waste-to-resource facilities, logistics and supply chain innovation centres, or the use of electrolyser by-products (heat, oxygen).

For **hydrogen and derivatives**, larger ports, especially those that are already part of an energy or industry cluster, are well-positioned to play a significant role in the value chain. This is contingent on the availability of sufficient space and a sufficient distance from urban agglomerations to account for fuel-specific risk characteristics. Ports' strategic locations and (in parts) already existing infrastructures make them pivotal nodes for the production, storage, conversion, transportation, import/export, and distribution of hydrogen and its derivatives (methane, ammonia, power-to-liquids) including CO_2 as a feedstock for synthesised electrofuels (e-fuels). This applies for use cases limited to the port area itself, such as the bunkering of vessels, as well as for use cases directed at the wider area of the port and its hinterland. On the production front, electrolysis facilities (a key process for power-to-hydrogen processes using renewable energy sources, such as wind or solar) in or nearby ports present a compelling case in principle. Their proximity to these renewable arteries minimises transmission costs and losses, thus improving the economic efficiency of hydrogen production and supply. Storage, a critical link in the hydrogen value chain, plays an important role as well. The spatial expanse and infrastructural readiness of ports make them suitable locations for operational storage facilities (limited volumes, short period times). However, safety and security considerations may impact the implementation and scale of such facilities, especially in the vicinity of populated areas.

In terms of the transportation and distribution of hydrogen, ports can serve as energy hubs and facilitators in the shipment of hydrogen and its derivatives across regional and international corridors, leveraging the extensive networks of maritime, road, and rail routes and pipelines. Port energy hubs are a crucial element in the future mix of clean energy from both domestic sources and imports. With their established customs and inspection structures, and where there is sufficient space available, these ports are ideally suited to handle hydrogen and its derivatives at scale. Whether it's smaller port production sites or larger import and export hubs, all scales contribute to balancing supply and demand across the surrounding area and the wider hinterland, respectively. This contributes to the integration of the broader European energy network.

1.6 Key findings

This section presents the key findings for the main stakeholders involved in port electrification and decarbonisation: Port Authorities and terminal owners. All considered types of clean energy business models can in practice provide positive net benefits. The effects largely depend on the specific characteristics of the port, its physical environment, the actual energy prices and emission costs, and local and national regulations. In the report we focused on the most relevant clean energy business models. As the energy landscape rapidly evolves, ports should remain vigilant for emerging alternatives and yet immature technologies, that may prove more suitable to the current clean energy business models.

Suitable measures can enhance and accelerate Onshore Power Supply (OPS) implementation

OPS shows in general a positive business case when the environmental and social costs and benefits are also considered.

To optimize the adoption of OPS, strategic investment is paramount. Collaborative efforts between ports, electricity suppliers, grid operators, and ship companies should focus on refining ship berth scheduling and on ensuring reliable shore-power availability at competitive terms. Engaging in long-term contracts with ship operators and electricity suppliers enhances economic viability while minimizing the overall risks for ports. Cooperation of ports with electricity suppliers and grid operators can ensure reliable shore-power availability at competitive terms. Good long-term planning can optimise resource use and reduce disturbance, when for example cable laying interventions already anticipate future developments in the port and thus there is no need to “dig up the terminals again”.

Successful OPS integration requires active participation from ports in crucial decisions and depends on vessel types and their power needs, equipment ownership, and investment options. This involvement is essential for tailoring OPS solutions to properly align with the unique characteristics of each port, fostering a more effective and sustainable approach to shore-power implementation. Port Authorities have an essential role as initiator and facilitator of OPS systems and often as co-investor in the required basic electricity infrastructure. Sufficient grid capacity and availability of low/zero-carbon electricity are key prerequisites for a positive business case. Onsite power generation coupled with battery storage, can reduce the investment needs for grid reinforcement and improve the business case of OPS.

Promoting terminal electrification is an essential element on the path towards sustainable operations

Electrification of container terminal operations generally have a short payback period and a substantial emissions reduction potential (especially for ports with suitable areas for onsite renewable electricity generation and/or connected to an electricity distribution system with a low emission factor). Ports with mostly dry/liquid bulk throughput are not likely to benefit as much from the electrification of their operations compared to container terminals.

To accelerate the reduction of CO_2 emissions, ports could implement incentives aimed at encouraging terminal operators to adopt electrification. For most terminal's equipment currently operating on diesel, such as RTGs, vehicles, and various horizontal and vertical machinery, proven electrification alternatives exist. These alternative options do not only decrease local emissions but provide increased productivity and energy cost savings as well.

To facilitate this transition, ports are advised to incorporate electrification projects into future concession agreements with terminal operators. By including these projects into contractual arrangements, ports can actively contribute to a more sustainable and eco-friendly operational landscape while fostering long-term collaboration with terminal operators.

Ports that operate as Energy Hubs can accelerate the energy transition by facilitating renewable energy generation and hydrogen generation and use

Ports, especially those with high land availability, are well positioned to implement onsite renewable energy generation such as solar PV and wind energy to increase energy independence and alleviate local electricity grid capacity issues. These types of ports can also serve as points of energy import (e.g. landing of electricity from offshore wind energy farms) and transmission to the hinterlands as well as points of energy import/export (e.g. hydrogen and derivatives). There is a large number of potential hydrogen applications and use cases for which ports can play a facilitating role. For ports acting as energy hubs, spill-over effects can be identified and valued.

To facilitate the green transition, ports should consider the role of hydrogen for their own energy needs and as bunker fuel and identify synergies with hydrogen applications beyond the port premises (e.g. fuel cell-electric trucks for logistics[3]).

To facilitate the deployment of electrolyser systems within or near port areas, ports should also assess the possibility of capturing by-product heat from electrolysers for use in local/regional heating systems. Additionally, they should consider the use of by-product oxygen, although this may have more limited potential demand.

To facilitate the handling of hydrogen and its derivatives, port authorities should cooperate with each other and with regulators at both the national and international levels. They should work together to develop specific standards for hydrogen and derivative assets. Where necessary, they should define or adapt safety conditions and requirements for the bulk handling and use of ammonia as an energy vector. This should be done within the methodological framework of a comprehensive technology assessment, which also includes security considerations.

Ports will be facilitators to interconnect energy networks and markets

The focus of ports that operate as energy hubs at the interface of sea and shore is set to change substantially from incumbent biomass and fossil fuels to renewable energy sources including electricity from solar and wind energy, power-to-hydrogen and derivatives, heat, O_2 and CO_2 (including building and operating networks within the port) – thus linking global, regional, and local energy systems. By serving as hubs for energy exchanges, ports can facilitate an efficient transfer of renewable energy between world regions and countries. Furthermore, at the local level, ports can integrate with surrounding areas, forming cohesive energy (and possibly CO_2) networks that benefit both the port and its adjacent regions.

Port authorities should support and facilitate the implementation of smart energy systems

Multiple ports are experimenting with building blocks of smart energy systems aiming to efficiently manage energy demand, supply, flows, and storage. These systems reduce reliance on external electricity grids by aligning local energy demand with available supply based on the actual energy prices, grid tariffs, and technical constraints.

Ports aiming to engage in onsite renewable electricity generation, possibly coupled with local storage, should prioritize the implementation and optimization of a Smart Energy Management System (EMS). This involves a comprehensive approach to integrating various energy systems like solar PV, wind and wave energy, covering a substantial portion of the local electricity demand. However, a successful implementation requires a meticulous assessment of local dynamics through thorough feasibility studies.

Smart Energy Management coupled with renewable energy generation and/or supply and potentially also local storage, not only allows to reduce dependence on conventional energy sources but also contributes to emission reduction, cost savings, and improved efficiency in renewable energy utilization and mobility. To ensure interoperability of the different system components, the adherence to established technical requirements and standards is imperative to facilitate this transition.

The environmental benefits and financial viability of electrification business models are significantly influenced by the emission intensity of the national electricity system and the capacity for onsite renewable energy generation

The financial and environmental benefits of OPS and e-RTGs business models will be relatively low in ports located in countries with a high grid emission factor. There, ports will likely benefit more from deploying onsite renewable energy capacity where suitable areas are available. As all EU countries are at present decarbonising their electricity supply

3 For road transport applications, the competitiveness of hydrogen compared to battery-electric solutions remains uncertain, particularly given current market conditions. However, hydrogen may find favour in heavy-duty and/or long-distance transport applications, while battery-electric powered vehicles could be preferred for light-duty and/or shorter distances.

system, the national grid emission factors will further decrease. Hence, the environmental benefits of switching port operations from fossil fuels to electricity will gradually increase.

Ports should consider cooperating with local electricity DSOs and TSOs

The analysis of the business cases showed that after electrification, the electricity demand of ports and port related activities might grow by 300 to 500%. Catering this demand will require a substantial expansion and redesign of the electricity network. Onsite electricity generation, possibly coupled with storage, can substantially reduce the investment needs for grid reinforcement and provides better grid quality services as well. Hence, it should be considered where technically feasible.

Ports should cooperate with local DSOs and TSOs to plan for future electricity capacity needs, avoiding potential long lead times that would decelerate electrification. Long-term planning will help DSOs and TSOs to upgrade the grid in time.

Ports should consider cooperating for providing training to ensure availability of adequately skilled workforce

Recognizing the potential skilled workforce gaps, ports should align on national or international level with educational institutes, national and European authorities, and with each other to design and implement adequate training programs addressing the skills needed for the transition to clean energy technologies at ports and operational experience transfer. Collaboration with educational institutions and vocational programs will ensure a skilled workforce capable of operating and maintaining clean energy infrastructure. A mobility program of workers between ports could promote youth participation, reinforcement of the quality of informal and non-formal learning processes, and development of the clean energy business models more rapidly and widely.

2 INTRODUCTION

2.1 Objectives of the project

The urgent need for achieving climate neutrality by 2050 demands a substantial reduction in greenhouse gas (GHG) emissions from all modes of transportation, including maritime. A number of European ports already have taken actions towards decarbonisation of their activities by putting in place clean energy solutions in line with the EU legislation (notably the Clean Energy Package). However, most of the European ports still face decarbonisation challenges such as securing funding for electrification and other port infrastructure investments, electricity grid capacity expansion delays, lack of adequate business models, and (national/local) electricity supply or provision rules that do not properly take into account the specificities of ports.

Therefore, the main objective of this study is to provide insights and guidance to the European Commission on economically viable energy business models for European ports that are in line with the European Union's policy frameworks and contribute to the objectives of the European Green Deal and REPowerEU.

The study has two specific objectives that contribute to the main objective of providing insights in economically viable electricity-based business models for ports:

- The first specific objective is to analyse techno-economically feasible clean energy business models for ports based on electrification or other low-carbon solutions. The models themselves will be quantitative, but they will be complemented with qualitative inputs, such as solutions to overcome barriers and overviews of available commercial models and operations of energy management in ports. The economic value of the different business models will be central to this assessment, as the environmental and other societal benefits should outweigh possible negative effects.
- The second specific objective is to assess the potential and need of ports with respect to ORES and the implementation of the revised TEN-E regulation to make sure findings of the study are aligned with the EU's policy trajectory. In addition, aspects from REPowerEU will also be considered in this study, amongst others the recent European energy supply disruption and its impact on energy flows into European ports.

There are many different technological pathways possible to decarbonise ports. Electrification of ports and surrounding industries has an important potential, but also comes with major challenges, including the increasing flexibility needs resulting from the deployment of variable renewable energy sources and the fact that electrification will not be feasible for all end-uses. This project identifies and analyses the following categories of solutions (identified as clean energy business models):

1. **Onshore Power Supply (OPS)** with focus on onshore power connections and the adjustments needed to the energy infrastructure.
2. **Decarbonisation of port operations including energy efficiency measures** with focus on electrification of terminal operations other than OPS. This covers decarbonisation of freight handling equipment, lighting, mobility within terminals but also other solutions, e.g. hydrogen.
3. **Ports as energy hubs** with focus on onsite renewable energy production as well as processing, storing, importing and exporting energy.
4. **New business models** with focus on other opportunities related to the energy transition outside the traditional Port's activities, such as transformation (hydrogen production and use and other Power-to-X), industrial activities such as construction and assembly of (parts of) wind turbines, equipment for tidal operations, mobility (electric charging

stations for trucks and forklifts) and provision of flexibility services such as demand response and storage (e.g. batteries).

5. **Smart grids** with a focus on integration of renewable energy sources and flexibility of the energy system and its management.

2.2 Overview of Relevant EU Legislation, Policies, Standards and Guidance

The 'Fit for 55' package contains a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring that EU policies are in line with the energy and climate goals to reach climate neutrality by 2050. The initial step requires a minimum 55% reduction of EU GHG emissions by 2030. Each proposal has a set of goals, for example, the FuelEU Maritime regulation sets reduction goals and limits for the yearly average GHG intensity of the energy used on board ships. During a reporting period the average GHG intensity should be reduced by 2% from January 2025, by 6% from January 2030, and by 80% from January 2050. Table 2-1 provides a summary of main regulations and policies affecting clean energy business models for ports.

Table 2-1: Summary of Regulations applicable to ports/maritime activities

Regulation	Objective	Applies to
Regulation on Alternative fuels infrastructure (AFIR)[4]	Provide OPS to reduce the carbon footprint of maritime transport and local air pollution in port areas.	Ports that have at least: • 50 port calls by large passenger vessels (>5,000 gross tonnage (GT)) • 100 port calls by container vessels (>5,000 GT), or • 25 port calls by cruise vessels (>5,000 GT).
FuelEU Maritime Regulation[5]	Promote the use of renewable and low-carbon fuels (RLF) and OPS.	All vessels above 5,000 GT travelling to, from or at berth in ports in the EU. • 100% of energy used at berth in an EU port. • 100% of energy used for intra-EU voyages. • 50% of energy used for international voyages. From 2030, the requirement for Zero-Emission at berth (OPS or alternative zero-emission technologies) will be compulsory for all container and passenger vessels.
Regulation on Trans-European Networks – Energy (TEN-E)[6] (PCI status)	Foster the development of cross-border energy infrastructure in EU.	Eleven energy transport priority corridors. Three priority thematic areas, including CO_2 transport networks and smart grids. Priority corridors include electricity corridors, offshore grid corridors and hydrogen corridors. EU funding is available via Connecting Europe Facility (CEF).
Regulation on Trans-European transport network (TEN-T)[7]	Development of coherent, efficient, multimodal, and high-quality transport infrastructure across the EU.	Short sea shipping routes and roads linking urban nodes, maritime and inland ports. Ports exceeding a total annual cargo volume of 500,000 tonnes and contributing to diversifying EU energy supplies and accelerating the deployment of renewable energy.

Table 2-2 provides a summary of Directives and Acts applicable to the maritime sector that affect port business models. Directives are part of EU's secondary law and unlike Regulations, Directives must be transposed into national law

[4] REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council, https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559

[5] REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562

[6] REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on guidelines for trans-European energy infrastructure and repealing Regulation (EU) No 347/2013, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:824:FIN

[7] Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU, http://data.europa.eu/eli/reg/2013/1315/2023-07-09

before they are applicable in Member States. Directives generally must be adopted within 2 years and the transposition is mandatory. The national transposition of Directives can result in minor differences between Member States' national legislation, i.e. the transposition may not be identical in all Member States, and if not transposed within the set deadline, it could lead to delays in implementation by ports and other affected entities.

Table 2-2: Summary of Directives and Acts applicable to maritime activities

Directive/ Act	Objective	Applies to
Energy Taxation Directive (ETD)[8] (proposed revision)	• Align with current EU climate and energy objectives. • Incentivise investment in clean technologies. • No longer favour fossil fuels. Improve clarity and legal certainty for Member States.	• Fuels sold to international shipping. • All bunker fuels sold within the EU and all bunker fuels used on voyages within the EU. • Electricity used in ports and sold to shippers.
EU-ETS Maritime[9]	Ensure that the maritime transport sector fairly contributes to the EU's increased ambition for CO2 emission reduction.	• GHG emissions from large ships (above 5000 GT), regardless of the country they are registered in. • GHG emissions from ships calling at an EU port for voyages within the EU (intra-EU) as well as 50% of the emissions from voyages starting or ending outside of the EU (extra-EU voyages). • All GHG emissions that occur when ships are at berth in EU ports.
Energy Efficiency Directive[10]	Sets the binding EU energy efficiency target of 11.7% reduction in energy consumption by 2030 compared to the projections made in 2020.	Energy consumption in domestic maritime (excluding international maritime bunkers).
Renewable Energy Directive III[11]	Promoting renewable energy development. Sets the EU binding renewable energy target at 42.5% for 2030 with aspiration to reach 45%.	Member States with maritime ports shall endeavour to ensure that as of 2030 the share of renewable fuels of nonbiological origin in the total amount of energy supplied to the maritime transport sector is at least 1.2%.
Delegated Acts on renewable hydrogen[12] [13]	Facilitate the scaling up of hydrogen production and ensure its contribution to the Fit for 55 and REPowerEU objectives.	Hydrogen, hydrogen-based fuels, and other energy carriers. Greenhouse gas emissions savings calculations.

[8] COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Accompanying the document Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0641&qid=1706184538113

[9] Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May 2023 amending Regulation (EU) 2015/757 in order to provide for the inclusion of maritime transport activities in the EU Emissions Trading System and for the monitoring, reporting and verification of emissions of additional greenhouse gases and emissions from additional ship types, http://data.europa.eu/eli/reg/2023/957/oj

[10] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast), http://data.europa.eu/eli/dir/2023/1791/oj

[11] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, http://data.europa.eu/eli/dir/2023/2413/oj

[12] Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, http://data.europa.eu/eli/reg_del/2023/1184/oj

[13] Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels, http://data.europa.eu/eli/reg_del/2023/1185/oj

Finally, Table 2-3 provides a summary of guidance/standards on Onshore Power Supply (OPS) in ports. The standards address ship safety and high/low voltage connection systems. The high- and low- voltage standards do not apply to electrical power supply during docking periods, including dry docking and maintenance and repair activities when the ship is out of service. Furthermore, national or local authorities, ship operators, or shore supply/distribution system owners may impose additional or alternative requirements based on their jurisdiction or operational considerations.

Table 2-3: Summary of guidance and standards on Onshore Power Supply in ports

Guidance	Objective	Applies to
Ship safety standards for Shore-Side Electricity (SSE) or Onshore Power Supply (OPS)[14]	Assist in the planning and development of SSE options, starting with project decision-making and development of infrastructure elements, definition of responsibility frameworks and construction of control measures to assist in operation.	Port Authorities and Administrations, operators and other stakeholders involved in OPS development/operation.
IEC/IEEE 80005-1[15]	Standards for the design, installation, and testing of HVSC systems used to supply ships with electrical power from shore.	High-voltage shore connection (HVSC) systems: • HV shore distribution systems, • shore-to-ship connection and interface equipment • transformers/reactors • semiconductor/rotating frequency converters, • ship distribution systems • control, monitoring, interlocking, and power management systems.
IEC/IEEE 80005-3[16]	Standards for the design, installation, and testing of LVSC systems used to supply ships with electrical power from shore.	Low-voltage shore connection (LVSC) systems: • LV shore distribution systems • shore-to-ship connection and interface equipment • transformers/reactors • semiconductor/rotating converters • ship distribution systems, • control, monitoring, interlocking, and power management systems.

2.3 Key Stakeholders

In the following section, the key stakeholders and their potential roles within the decarbonisation of ports are described. Depending on the Member State the roles of different parties may deviate based on legal provisions, strategy, funding, etc. The intent of this section is to provide an overview, not an exhaustive list, of the key stakeholders concerned with port decarbonisation and the possible roles they may play.

[14] Shore-Side Electricity (SSE), https://www.emsa.europa.eu/electrification/sse.html

[15] IEC/IEEE 80005-1:2019/AMD2:2023 Amendment 2 - Utility connections in port - Part 1: High voltage shore connection (HVSC) systems - General requirements, https://webstore.iec.ch/publication/73907

[16] IEC/IEEE Draft International Standard - Utility Connections in Port - Part 3: Low Voltage Shore Connection (LVSC) Systems - General Requirements, https://standards.ieee.org/ieee/80005-3/5934/

Distribution System Operator (DSO)

The DSO is responsible for the distribution of electricity from the high-voltage transmission grid to end consumers, such as ports and other facilities. In the context of shore power, the DSO would be involved in transporting electricity from the TSO to the port infrastructure. Often ports have their own closed distribution grid and are operating and responsible for the grid. The availability of sufficient grid capacity is key, especially to enable the connection and injection of an increasing number of renewable electricity production installations and to facilitate decarbonisation activities like electrification of equipment, heating and transport.

Energy Suppliers

Energy suppliers provide electricity or other forms of energy to end-users. They are responsible for supplying electricity to the port facilities. Subject to EU and national energy legislation, port authorities or terminal operators may be legally allowed to also supply electricity to third parties, in particular if they own and operate onsite electricity generation facilities connected to the port's grid. In this case, they may need to also take balancing responsibility to ensure that the supply (injection) profile matches demand (offtake) at any moment.

Local, regional and national Governments

They collaborate with relevant stakeholders, including port authorities, terminal operators, energy network operators (TSO, DSO) and energy and services suppliers, to plan and implement projects related to shore power provision and alternative fuels infrastructure. They also work towards providing the necessary support and incentives to encourage the implementation of sustainable practices in ports, such as onshore power supply and renewable fuels usage.

Port Authority (PA)

The port authority is an administrative body responsible for managing and overseeing the operations of a port. Its role includes infrastructure development and funding, port planning, and ensuring the smooth functioning of port activities. Depending on national regulation and EU legal provisions, the port authority could take the role of DSO on its territory and operate the port's own electricity distribution network. According to the provisions of Regulation 2017/352 (the Port Services Regulation) the PA or a competent authority indicated by a national administration has important role in determining the conditions under which port services (which OPS is a part of, like bunkering) are provided in the port, by for example having the option to define minimum requirements and introducing limitations. The PA may provide a port service itself (as internal operator) or tender out to one (or more) third parties.

Port authorities can invest themselves or call for 3rd party investments in onsite production of renewable energy, energy storage, transport networks for heat and CO_2, refuelling stations for clean fuels, and in charging and exchange stations for battery containers, develop projects for shore power supply to docks, and request quotes for shore power equipment for seagoing vessels. The appetite for such investments depends on regulation, strategy, funding, and other considerations and differs between Member States.

Shipping Companies

Shipping companies own or lease and operate merchant ships for transporting goods or passengers. They are responsible for operating these different vessels and complying with the regulations and requirements set by the EU, national and port authorities. They are expected to gradually reduce greenhouse gas emissions from their ships by switching to renewable and low-carbon energy sources, with legislation providing guidance towards that goal. For example, shipping companies are obligated to use onshore power supply or alternative zero-emission solutions for all energy needs of large container and passenger ships while moored at the quayside in major EU ports by 2030. To that end, proactive collaboration with port authorities and terminal operators will ensure the availability and utilisation of onshore power infrastructure. Shipping companies with sufficient level of operations in a port or who operate their own terminals may consider investing in the OPS installation themselves.

Onshore Power Supply (OPS) Provider /Shore-side Electricity (SSE)

EU Regulation 2017/352 (Port Services Regulation) includes in its scope the provision of shore-power as a port service. The OPS provider is responsible for providing electrical power to ships at berth and for the operation, maintenance, and the equipment. Depending on the port, a number of different arrangements are possible with regard to the provider of OPS. The European Maritime Safety Agency's (EMSA) Guidance on Shore-Side Electricity[17] provides additional information.

Terminal Operators
Terminal operators are entities responsible for operating and managing terminals within a port. Terminals operators may be the port authority or another entity under a concession. They handle the loading, unloading, and storage of cargo or passengers. Within ports they have a role in facilitating the implementation of sustainable practices, including onshore power supply and electrification of equipment.

Transmission System Operator (TSO)
The TSO is responsible for the high-voltage transmission of electricity across a country or region. In the context of shore power, the TSO would play a role in ensuring the availability and transmission of electricity from the main power grid to the port facilities.

2.4 Approach of the project

The main tasks to be performed in the project are:

- **Select ports and clean energy business model selection**. This chapter includes a summary of the selection process of ports and clean energy business models, the short list of selected ports and clean energy models and its update. The list of ports is presented in Appendix C.
- **Collect and assess evidence on clean energy models**. The results of the eight clean energy models are presented in chapter 5.
- **Analyse cost and benefits of clean energy business models**. The results of the analysis of six clean energy business models are presented in chapter 5 in the sections costs and benefits.
- **Assess the evolution of electricity demand and OPS potential to scale**. To understand the electricity demand as well as overall energy on the maritime side, ship operations were assessed in greater detail. Based on today's number of port calls and time at berth from AIS data (Vessel traffic data, or Automatic Identification System) and expected changes in number of port calls until 2050, energy demand and CO_2 emission reduction potential were estimated. The results for the ports of Marseille, Gothenburg, Kristiansand, Rotterdam and Valencia are presented in Chapter 3.
- **Identify and assess barriers**. The project team assessed the barriers and challenges to successful implementation of the clean energy business models in ports and provided recommended mitigation actions. The results are presented in Chapter 6.
- **Assess impact of the implementation of clean energy models in two average ports** covered an integrated view of the cost and emission reduction of the combined clean energy business models for a typical average industrial port and an average container port in 2030-2040-2050. The draft results are presented in chapter 7.
- **Analyse the role of ports as industrial nexus for offshore renewable energy and TEN-E implementation**. Here we aim to assess how business models and developments within ports can serve as a nexus for ORES and TEN-E implementation, i.e., how ports can facilitate and support cost-efficient implementation of these policies. The results are presented in chapter 8.

[17] https://www.emsa.europa.eu/electrification/sse.html

2.4.1 Port and clean energy business model selection

Objective

The main objective of the clean energy business models' assessment is to describe and analyse best practices of front-runner ports in such a way that they can support other ports in their journey to reduce emissions in their respective port areas.

Approach

The assessment is based on:

1. Pre-selection of front-runner ports based on operational experience (years of practice) and diversity criteria of general port segmentations like type, location and size. The final selection includes the ports of Marseille, Gothenburg, Kristiansand, Valencia and Rotterdam.
2. Description of clean energy business models: mainly based on interviews with representatives of port authorities, and assessment of supporting documentation and literature.
3. Cost Benefit Analysis (CBA). The CBA is based on current fuel type and fuel prices, standard depreciation period of 20 years and a standard interest rate of 6%. 2023 is the reference year for the energy prices. For other general assumptions on prices and electricity mixes used please refer to Appendix D.

Via literature review, interviews with maritime experts from the consortium partners and discussions with the Commission, ten clean energy business models spread over five ports (Kristiansand, Gothenburg, Marseille, Rotterdam and Valencia), were selected from a long list of 30 European ports. Criteria for the selection of business models and ports were established in two steps:

- A port's operational experience with a clean energy business model, listing the ports and business models by number of years of their practice.
- General segmentation of seaborne ports like type of port, size, geographical location and industrial activities.

The selection process and the longlist of selected ports were presented in the inception report. The ports are introduced in Chapter 3 and the short list of selected business models is presented in Chapter 4.

2.4.2 Collect and assess evidence on clean energy models

Objective

To collect and assess evidence that can serve a dual purpose: first, to highlight and describe existing business models adopted by different ports. Second, to act as a foundational resource for analytical framework, providing crucial insights and assumptions necessary for constructing and populating the CBA analyses.

Approach

The information on the clean energy business models collected during the inception phase and received from the ports was analysed and transferred to the agreed business model description. Besides public sources, experts working at Port Authorities were the most important information sources. Data was collected via e-mails and interviews with port representatives, terminal owners, shipping companies and maritime experts of DNV.

2.4.3 Cost Benefit Analysis

Objective

To systematically evaluate and quantify the economic viability and potential benefits of implementing various clean energy business models within port settings.

Approach

The CBA (Cost-Benefit Analysis) methodology is a systematic approach used to evaluate the economic feasibility of a potential investment considered with the purpose to decarbonise operations in ports. CBA provides decision-makers with a comprehensive framework to assess the net present value of the clean energy business models.

It involves identifying and quantifying the costs and benefits associated with the business model and comparing them with the business-as-usual (BaU) alternative (no decarbonization project takes place) to determine whether the alternative is worth pursuing. CBA takes into account relevant stakeholders and considers both short-term and long-term effects. In the calculations undertaken in this study costs such as grid reinforcement costs and investment costs incurred by other stakeholders such as the retrofitting of ships for OPS were also included.

The process involved estimating the initial investment costs, operational expenses, and potential risks or uncertainties. Clear benefits of electrification and other decarbonisation options that were estimated include reduced GHG emissions, acid and particle matter emissions. Either local or global benefits were estimated if the sourced electricity is mainly based on renewables. Such projects will have clear socio-economic benefits on different areas such as reduced dependence on (imported) fossil fuels, improved health of citizens, reduced noise from ships in berth, better climate and preserving biodiversity. The environmental and other societal benefits of reduced emissions of greenhouse gases such as CO_2 and indirect greenhouse gases like SO_x and NO_X on global warming, health, and biodiversity were documented in other analyses and not monetized further. The benefits of improved biodiversity and health were not included in the calculations, and a monetisation of these factors would improve the decarbonisation business case versus BaU.

Each respective section in Chapter 5 presents and analyses the outcomes of the CBAs.

Key assumptions crucial to the analysis include:

- A projected 20-year depreciation period for all projects, aligning with their anticipated operational lifetimes.
- The CBA analysis grounds itself on prevailing fuel types and associated prices. Electricity pricing references the year 2023 in the corresponding countries, relying on the average day-ahead wholesale market price as a medium scenario. The low and high electricity price scenarios have been defined as well, but the medium scenario has been taken as a basis for the analysis with a subsequent sensitivity analysis (see explanation below).
- All essential assumptions pertaining to financial inputs, electricity and fuel prices, as well as electricity mixes utilised, are detailed in Appendix D for further reference.

Sensitivity analysis

In the study, we employed sensitivity analyses to comprehensively assess the robustness of our findings and the potential influence of uncertainties on the results obtained from the CBA and electrification models within port environments. By systematically altering key parameters such as fuel prices, electricity prices, and project CAPEX, we sought to evaluate the sensitivity of our models to these variations, thus enhancing the reliability and validity of the results. This process aids in better understanding the range of potential outcomes and the factors that significantly influence the effectiveness and economic viability of different electrification strategies within port operations.

For all OPS models, a sensitivity analysis was performed to calculate the impact of a 20% increase and decrease in the CAPEX, electricity price, CO_2 price and bunker fuel price on the annual costs for the both the OPS case and BaU case.

For the other three business models (RTG, H2 production and Renewable electricity generation), sensitivity analyses were performed to calculate the impact of a 20% increase or decrease in the CAPEX, electricity price, CO_2 price and fuel price on the annual costs for both cases.

The tornado graphs are employed to visually represent the sensitivity of the OPS and BaU models concerning the respective variables mentioned.

2.4.4 Evolution of electricity demand and Onshore power supply (OPS) potential

Objective

The objective of the evolution of electricity demand and Onshore Power Supply (OPS) potential assessment is to provide an "outside-in"[18] estimate of the shore power demand of seagoing vessels and the respective CO_2 emission savings in the five selected ports (Gothenburg, Marseille, Kristiansand, Valencia and Rotterdam) for the time period 2023-2050.

Approach:

The estimate was based on four main steps:

1. Port traffic analysis: Determined today's number of port calls and time at berth (AIS data) for each ship type, model change in number of port calls until 2050, and introduced two scenarios: scenario 1) all ships >5,000 GT (gross tonnage) and scenario 2) all ships >400 GT.
2. Ship data analysis: For each ship type, provided an estimate for the auxiliary engine (A/E) setup installed and the auxiliary engine utilisation at berth. Auxiliary engines are the predominant source for electrical power onboard ships today.
3. Energy demand estimate: Calculated the energy demand of ships at berth provided by auxiliary engine and derive the OPS demand of ships at berth, considering OPS utilisation and time to (dis-)connect the ship. The term 'OPS utilization' combines the minimum requirements outlined in the FuelEU Maritime Regulation with the current and projected usage of OPS, as reported by the respective ports. All ports do and plan to further overachieve targets stated in the FuelEU Maritime Regulation.
4. CO_2 emission reduction estimate: Calculate the CO_2 emission reduction potential, assuming full availability of "green" power[19] replacing ships' auxiliary engines as applicable.

To understand the energy demand on the maritime side, ship operations were assessed in greater detail by an analysis of AIS data and the use of DNV's MASTER model. AIS data can be used to map the ship operations in the port with respect to most ship types related to frequency, length of stay, and occupancy rate of berths in the five selected ports.

Assumptions and shore power demand results presented in this study serve as a high-level estimation of the ports' shore power demand. The estimation was based on external data sources and not on detailed port data. Results cannot be used as a basis for, e.g., electricity grid design. The assumptions are presented in Appendix E.

2.4.5 Implementation of business models in two ports

Objective

The objective of this analysis is to analyse and evaluate the net benefit (e.g. monetary, emissions) of combining the business models in two scaled model ports: an average European transport port and an average European industrial port.

Approach

In order to analyse the impact of implementing multiple business models in a port, a set of two indicative ports, model ports, was used: the transport port and the industrial port. The typical transport port used is based on the Port of Valencia. The typical industrial port used in the analysis is based on the Port of Rotterdam.

The combination of the business models is non-exclusive. Hence, all the different business models were combined in both the model transport port and the model industrial port. To evaluate the impact of decarbonisation business models

[18] The terms „outside-in" relates to the fact that no data provided by the ports has been used for the OPS electricity demand estimate.

[19] The assumption of "green" power, i.e. the provision of electricity with a footprint of 0 gCO2/kwh seems valid as Gothenburg and Marseille confirmed the use of green electricity. No information is available for Kristiansand; however, as the Norwegian electricity mix is dominated by renewable sources, the assumption the green electricity for Kristiansand seems valid.

on two model ports, a scaling factor was employed to transform the relatively large ports of Rotterdam and Valencia into representative "average" industrial and transport ports, considering cargo tonnage and container metrics. This scaling process is detailed in Appendix F. The assessment covers the years 2030, 2040, and 2050, using data from both Rotterdam and Valencia as a basis, with scaling factors applied to OPS supply, e-RTGs, H_2 reach stackers, and renewable capacity for these years. The quantification of the associated costs and benefits of implementing each business case was calculated based on the real investment costs from the ports and estimated EU average grid emission factors, energy and emission prices in 2030, 2040 and 2050. The use of unweighted EU averages facilitates the comparison of the results of the two ports.

2.4.6 Barriers

Objective

The objective of this analysis is to evaluate the barriers and challenges and subsequent mitigating actions that relate to the three categories of business models: onshore power supply (OPS), port electrification, and deployment of clean fuels.

Approach

This task has been informed by a detailed review of relevant literature followed by individual port interviews and a broader stakeholder workshop. The information gathered by these three means was categorised and then analysed using a framework based on DNV's risk matrix, to indicate the probability of a barrier occurring and its possible impact. Mitigation actions were then identified and analysed with the same technique to provide a final understanding on the magnitude of impacts and complexity to mitigate, and thus the effects the barriers will have on port decarbonisation.

The main external and internal barriers and potential mitigation solutions were identified and assessed via literature review, interviews with the five selected ports and an online workshop with over 60 representatives from Port Authorities, shipping companies, terminal owners, industry and local governments. The potential impact of EU legislation was also taken into account in the analysis.

2.4.7 Ports as industrial nexus for ORES and TEN-E implementation

Objective

The objective of this task is to describe potential roles and required infrastructures of ports to become industrial nexus for ORES and TEN-E implementation, i.e. facilitating the energy transition and decarbonisation.

Approach

Opportunities for port developments resulting from an improved implementation of the TEN-E and the ORES policies were identified, how additional infrastructure can improve the business models described in the preceding tasks, and potential roles and infrastructures of ports with regard to hydrogen and derivatives.

The approach starts with an analysis of the ORES and TEN-E policies, describing key elements and main features. This part is covered only shortly, as it rather serves as an introduction. This introductory part is followed by an analysis of how the implementation of the TEN-E and ORES can be enhanced through the integration of ports in this domain. Along with an initial high-level view, this is described in more detail in a second step by looking at the concrete business cases in connection with the ports and how they can foster the implementation of these policies.

We then considered additional/complementary infrastructure in ports, and possible synergies related to the deployment of hydrogen and its derivatives in connection with the further development of the ports' business cases. As for the question on additional infrastructure, the approach consists of three steps: first the identification of additional infrastructure related to the business cases analysed before, secondly the assessment of the relevance of the identified additional infrastructure for the business, and finally additional infrastructure independently from the business cases analysed but potentially interesting for ports in general.

The chapter finishes with a special focus on hydrogen and its derivatives. It describes the role ports could play in the different hydrogen-based value chains with a focus on the production and supply side as well as possible uses cases, including indications concerning the scale that would go along with the different use cases.

3 CLEAN ENERGY PORTS

3.1 Introduction to clean energy ports

In our exploration of clean energy adoption within ports, a crucial preliminary step before delving into business models involves gaining a comprehensive understanding of the ports themselves. To achieve this, an analysis of front-runner ports—Gothenburg, Kristiansand, Marseille, Valencia, and Rotterdam—is provided in this Chapter 3. The aim is to unravel the unique dynamics and energy systems of these ports, essential for comprehending the subsequent discussions on cleaner business models.

Beginning with Section 3.2, trends and drivers towards adopting cleaner business models are presented. Section 3.3 takes a closer look at selected ports, offering a glimpse into their energy systems and assumptions regarding future electricity demand. These insights predominantly stem from interviews conducted with Port Authorities, setting the stage for subsequent discussions.

Recognising the dearth of consistent and comprehensive data specific to future electricity demand in individual ports, Section 3.4 focuses on analysing the primary drivers projected to wield substantial influence on future electricity demand within ports: Onshore Power Supply (OPS), drawn from DNV's analysis of AIS. Insights gleaned through interviews, affirm that OPS is the major force steering forthcoming demand trends. Section 3.5 presents possible impacts on port's energy infrastructure, collectively providing a view of the evolution of clean energy within port environments.

3.2 Trends and drivers towards clean business models for ports

The decarbonisation potential of ports is intertwined with the transitions that will take place in and around them. The ongoing energy transition and associated trends also affect the clean energy trends observed at ports and their surrounding areas. For example, electrification of industry and vehicle fleets, and fuel switching are general trends that also impact ports due to proximity, similarities in operations, and synergies. These transitions create opportunities for decarbonisation strategies for ports if they are coordinated, intentional, and accompanied by the right policies. The following paragraphs discuss energy-related trends and drivers that support and promote clean energy business models for ports.

Decarbonisation of port activities and equipment is a trend observed in numerous European ports. Activities well-suited for electrification include logistics, freight handling (cranes and vehicles), cold ironing, cold storage, service vessels (tugboats and pilot boats) and buildings. One of the activities experiencing an increase in electrification is the retrofitting or replacement of existing diesel-powered equipment such as rubber-tired gantry cranes (RTGs) or mobile harbour cranes (MHC) and port vehicles, like forklifts or terminal tractors. This approach allows for reduction in local emissions in a cost-effective manner. For equipment that is harder to be fully electrified, hybrid diesel-electric solutions also provide a significant reduction in emissions compared to diesel-only fuelled operations. A lesser implemented approach is the switch from diesel to low-carbon fuels such as hydrogen or ammonia. This is due to the need for further technology maturity of these technologies. However, pilot projects such as hydrogen fuelled cranes, tugboats and even ships running on ammonia exist, and the expectation is that low-carbon fuels will become effective solutions for equipment with longer periods of operations or where electrification is harder to be implemented. Electrification of port activities and equipment is driven by carbon emission reduction goals set forth by policies or legislation such as the Energy Taxation Directive (yet to be approved), the Renewable Energy Directive, and other proposals under the 'Fit for 55' package aiming to ensure that EU policies are in line with the climate goals to reach climate neutrality by 2050.

Onshore Power Supply (OPS) installations provide vessels with electricity to power their on-board activities while a ship is berthed. Currently, most ships rely on onboard diesel generators to power their needs during these times but legislation such as FuelEU Maritime is now mandating the use of OPS by ships, which will create a different situation as regards OPS demand than what exists today. OPS can be either a grid connected/stationary installation or mobile. OPS at ports is driven by regulation, namely through the Alternative fuels infrastructure regulation (AFIR) that require ports with specific vessel traffic to provide OPS. Other drivers include the environmental benefits for local air quality, pollution reduction, and noise mitigation, which are especially important for ports located in or near urban areas. When the electricity provided is 100% green, OPS provides the greatest emissions reduction especially for large vessels, like cruise ships, that remain berthed for longer periods of time and have a high electricity demand while at port. Some Member States have a temporary permit to apply a reduced rate of taxation to OPS electricity for ships. The proposed revision of the Energy Taxation Directive would also make it easier for electricity provided by OPS to be exempt from taxation, an additional driver for OPS.

Decarbonisation efforts at various parts of the economy include **onsite renewable energy generation**, such as solar and wind energy. Ports are progressively deploying such installations, which are technologically mature and cost-competitive, to increase onsite clean energy production, and reduce electricity grid reliance and costs as well as GHG emissions. Rooftop solar PV on terminals and office buildings are becoming commonplace and small onshore wind turbine plants have also seen an increase on port land. Tidal and wave energy are still maturing technologies, but they can become significant resources for future energy generation. Drivers for the increase of onsite renewables include compliance with EU legislation and policies such as the Renewable Energy Directive (RES Directive) and international climate change mitigation agreements, such as the Paris Agreement. Additionally, onsite clean energy generation allows for increased energy security and resiliency during times of peak demand or outages, and lower electricity costs by self-generation (and peak shaving if combined with energy storage) or the potential for electricity sales to the local utility/3rd parties. National, local, or port emissions reduction goals are another driver for onsite renewable generation, as are business development opportunities for ports that could attract new businesses/industries by providing Guarantees of Origin of locally produced renewable electricity.

Together with onsite renewables, **integration of offshore wind** at the greater port area is gaining traction. Offshore wind energy is projected to become one of the fastest growing renewable energy markets and current ports with energy hubs or ports aspiring to create energy hubs are predicted to be a part of the offshore energy strategy. The ports would act as the intermediary between sea and land for offshore wind, by distributing the energy that is generated at sea, through the port to the end users. The largest growth is expected in the North Sea where the relatively shallow sea and strong and consistent wind speeds are favourable conditions. At ports with industrial clusters, coupling offshore wind with **industry decarbonisation and electrification** efforts is also an opportunity to consume the generated electricity locally, either via direct electrification or via electrolysers using renewable energy to produce hydrogen for industrial processes or hydrogen derived fuels such as ammonia. These activities can be revenue generating activities for applicable ports. The 2020 EU strategy on offshore renewable energy has been acting as a driver for the development of at least 60 GW of offshore wind and 1 GW of ocean energy by 2030, and 300 GW and 40 GW, respectively, by 2050. In October 2023, new measures were set out specifically for the offshore sector under the dedicated Communication on Offshore Renewables. Member States are now aiming to install 111 GW of offshore renewable generation capacity by 2030 - nearly twice as much as the initial objective of at least 60 GW in the strategy of 2020. The Offshore Communication reinforces the policies of the ORES and introduces additional actions and measures to back the new ambition levels[20].

Furthermore, the **electrification of industry** at ports hosting industrial clusters is driven by the revised European Energy Efficiency Directive (EU/2023/1791) that requires industries to reduce their GHG emissions by 55%. Industries found at ports such as refineries and chemicals are among the largest emitters, meaning there is opportunity for industry - port collaboration. The need for industrial electrification can impact the ports due to the decrease in fossil cargo affecting terminal and port business, but also increase other services that are not typically part of port operations, such as flexibility services, utility services, and land use for renewables or hydrogen production.

[20] eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0668

Maritime transport is expected to grow significantly till approximately 2035 and then remain stable towards 2050. Emission reduction goals for maritime transport are set by the International Maritime Organization (IMO) and the EU. For example, the “Fit-for-55” package targets a 90% reduction of transport emissions, whereas the IMO 2020 rule limits sulphur content in fuel oil, and IMO targets are to reduce the carbon intensity of international shipping by 40% by 2030. Fuel switching from conventional fuels to low-carbon fuels is a challenge when fuels like ammonia or electricity are considered. Blending with low-carbon drop-in fuels like biogas is easier and less expensive. This expected increase in low-carbon fuels, the type of which is driven by the shipping lines as they retrofit or purchase new vessels, is an opportunity for ports to provide **clean fuel bunkering** and other associating services.

Overall energy system integration is the increased interconnectivity of different value chains. Ports can play a role in this interconnectivity that is enabled by the energy transition. Besides the traditional port role of connecting various sectors through transportation and logistics, ports have the opportunity to become energy hubs where many parts of the energy systems come together. All the above-mentioned trends offer ports new business opportunities relating to clean energy that can expand (and replace dwindling) traditional revenue streams and increase clean energy deployment.

3.3 Characteristics of the selected ports

The following subchapters present general characteristics, current energy use and projections for the future as gathered during the interviews with the Port Authorities for each of the selected ports.

3.3.1 Port of Gothenburg

The port of Gothenburg is the largest in the Nordic countries and connects the Baltic Sea to the North Sea. The main port areas are the Ro-Ro Terminal, the APM Container Terminal, the Logent Ports and Terminal, the Energy Port, and the Stena Line ferry ports and Cruise terminals.

The port is handling 776,000 twenty-foot equivalent unit (TEU) containers per year and is Scandinavia’s largest container terminal, with an equivalent share in import and exports. The terminal is operated by over 40 container shipping companies. The main exports are steel, vehicles, and forest products, and the main imports are consumer goods.[21] There is a car cluster close to the port with Volvo as a main player.

The Energy Port is managed by the Gothenburg Port Authority and is the largest open-access energy terminal in Sweden. Specialised terminal operators handle the unloading and loading of goods. There are three refineries close to the port.

The ferry passenger of Ro-Pax traffic is currently in the city centre on the Göta River, with regular routes to Denmark, Norway, and Germany. There is also cruise traffic calling in the city centre and from the terminal in Arendal area outside of the city centre.

Table 3-1: Port of Gothenburg characteristics

Gothenburg Port General Characteristics (2020) [22]				
Location	Main type	Freight (Mt)	Containers (TEU)	Passengers (millions)
Scandic Baltic	General	38	776,000	0.6

Port’s energy system

The port of Gothenburg is connected to the DSO grid of the city of Gothenburg and operates the electrical grid within the

[21] www.portofgothenburg.com/about-the-port/the-port-of-gothenburg/

[22] Port of Gothenburg Sustainability report 2020

Port's premises. The electricity is supplied by Energi Sverige and is labelled with Bra Miljöval, an ecolabel of renewable electricity[23]. Electricity use and GHG emissions related characteristics are summarised in Table 3-2.

The port authority's goal is to reduce its carbon dioxide emissions by 70% by 2030 compared to the 2010 level. There are several ongoing projects in development to meet this target such as a collaboration with industry players for carbon capture and storage, incentives for bunkering renewable fuels, hydrogen refuelling station for trucks, and OPS for tankers in hazardous areas.

To meet the increasing electricity demand for the port's electrification, the port will become a partner in the 1GW offshore wind energy project Västvind of Eolus[24].

Table 3-2: Electricity use and GHG emissions of the Port of Gothenburg[23]

Energy and emission characteristics in 2022			
Port Authority electricity consumption (GWh)	Port Authority emissions (tCO_2e)	Total emissions,[25] (tCO_2e)	Self-generated renewable electricity (MWh)
3.2	217	207,336	0

3.3.2 Port of Kristiansand

The Port of Kristiansand is located next to the city of Kristiansand and is managed by the Port Authority which is the public body responsible for the management of three state-owned ports located along 70 km on the south coast of Norway: Kristiansand, Mandal, and Lindesnes.

The port has regular passenger traffic to and from continental Europe and Great Britain. This includes passenger ferries, cruises, and Ro-Ro traffic. 44% of the income of the port comes from ferry services and 11% from cruises.

Kristiansand port handles traffic of different types of goods, by container and bulk traffic. Goods traffic represents 22% of the ports income and the main types include timber, fuel products (diesel fuel, petrol, coal, etc.), construction products (cement and rock/stones). The port also handles offshore supply to fields in the North Sea, as well as fishery.

Kristiansand port is a pioneer in Norway on OPS with the first installation commissioned in 2014 and a yearly energy flow to OPS of 5 GWh (2022).

The port has projects for electrification of cars and machinery in the terminal, such as electric cranes, trailer trucks, and truck loaders. The vehicle fleet of the port is planned to be fully electric by 2024. Also, the port has installed solar panels on rooftops producing 85-90 MWh/year, with a planned expansion to 500 MWh by 2025. New business models include taking part in the CCS logistics chain development for Kristiansand by facilitating technical solutions for handling and transporting CO_2 to ship loading.

Table 3-3: Port of Kristiansand characteristics

Kristiansand Port General Characteristics (2022)				
Location	Main type	Freight (Mt) [26]	Containers (TEU) [26]	Passengers (millions) [26]
North Sea	General	3.35	49,500	1.6

[23] Port of Gothenburg Sustainability report 2022

[24] https://www.maritimeprofessional.com/news/swedish-port-into-offshore-wind-384585

[25] Includes emissions from road and train traffic to the port within Gothenburg County and ship traffic to the port from 20 km outside the port. The other actors include APM Terminals Gothenburg, Gothenburg Ro/Ro Terminal, and Logent Ports & Terminals AB.

[26] portofkristiansand.no

Port's energy system

The Port of Kristiansand is connected to the DSO Å Energi grid. The port is investing in new solar PV generation contributing to a total of 500 kWh by 2025. The long-term goal is to be self-sufficient on power generation for the port's own operation.

Table 3-4: Electricity use and GHG emissions of the Port of Kristiansand

Energy and emission characteristics			
Electrical energy consumption to OPS in 2020 (GWh) [27]	Emission reduction from OPS (tonnes CO_2e) [28]	Remaining emissions at quay (tCO_2e)[28]	Self-generated renewable electricity (MWh)[28]
18.2 (22.7 incl. Color Line ferries)	17,200	14,400	85-90 (solar)

Assumptions on future electricity demand

Despite large availability of renewable energy, electricity demand in Norway has a clear seasonal pattern. In wintertime the demand is twice the demand in summer. The electricity distribution system needs to be designed to supply the peak demand, leading to high investment costs for the Port.

3.3.3 Port of Marseille

The Port of Marseille is the largest port in France and includes the ports in Marseille and in Fos-sur-Mer, 50 km west of Marseille. The port is managed by the Port Authority of Marseille Fos. The main characteristics of the port are described in Table 3-5.

The main activity of the port is energy handling, which is mainly located in the Fos port. The port handles crude and refined oils, LPG and LNG and has its own pipelines directly connected to the European network. The Berre, Fos-sur-Mer, Martigues triangle comprises a petrochemical complex with close to 2,000 small and intermediary companies and represents one of the largest energy hubs in South Europe.[29]

Another main activity is container shipping, which has grown to 1.5 million TEU per year in 2021. The general cargo segment is also including Ro-Ro and transport of vehicles.

The port has regular passenger traffic, including ferries to Corsica, Sardinia, Algeria, Tunisia, and Morocco, and cruises in the Mediterranean Sea. These are calling in the Marseille port with proximity to the city centre.

Table 3-5: Port of Marseille characteristics

Marseille Port General Characteristics (2021)				
Location	Main type	Freight (Mt) [30]	Containers (TEU) [2]	Passengers (millions)
Mediterranean	Energy	75	1,500,000	3.1 (Ferries: 1.2 Mpax & Cruises: 1.9 Mpax)

Port's energy system

The overall electricity consumption of the Port of Marseille is about 35-40 GWh per year. The port authority procures electricity for own consumption and resale, with the main consumption groups being: High Voltage OPS connections for Ro-Pax service ferry lines to Corsica (6 GWh); Low-voltage OPS connections (3 GWh); private ship use (15-20 GWh) and the consumption of the port authority for its buildings and lighting (10 GWh). The consumption figures mentioned in

[27] Budget 2022 Kristiansand port

[28] Environmental Plan 2022, Port of Kristiansand

[29] Marseille General Brochure 2022

[30] Marseille Fos Annual Report 2021

this section do not include the electricity used in other terminals such as the Container Terminal or other industrial or energy activities that have electricity supply on their own.

The port authority operates its own electricity grid with one connection to the DSO network of ENEDIS in the north-west side of the Port. The electricity is 100% renewable and is supplied via the grid operated by ENEDIS (PPA contract).

Table 3-6: Electricity use and GHG emissions of the Port of Marseille Fos
Source: Interview with the Port of Marseille (5/2023)

Energy and emission characteristics (2022)			
Electricity consumption (GWh)	Port Authority – administrative use (GWh)	Total CO_2 emissions[31]	Self-generated renewable electricity (GWh)
35-40	10	N/A	0

Assumptions on future electricity demand

The Port Authority has a portfolio of decarbonisation projects such as new OPS connections at the North Africa Terminal and the Cruise Terminal. Further development of OPS supplying electrical power to vessels will have a substantial effect on the electricity grid, in terms of power demand and energy consumption. For example, according to IEC/IEEE/ISO standard 80005-1, the demand of a single large cruise ship can be 16 MW. It is estimated that these projects, once developed, will more than double the current electricity consumption to around 60 GWh/year.

According to the port authorities, the port will need to upgrade and reinforce its grid and increase its connection capacity with the regional DSO network. It also plans on expanding its renewable electricity production with 9 MWp installed capacity of solar PVs on roofs in the port.[32]

3.3.4 Port of Rotterdam

The Port of Rotterdam is the largest port in Europe and is managed and operated by the Port of Rotterdam Authority. The main characteristics of the port are described in the table below.

The largest segment of the port activity is energy handling. The port handles crude and refined oils, LPG and LNG and has its own system of pipelines directly connected to the European network. The port area includes five oil refineries, and supplies another five refineries in the Netherlands, Belgium, and Germany via pipelines.

Another main activity of the port of Rotterdam is container shipping with 14.5 million TEU per year in 2021, and thus the largest container port in Europe.

Table 3-7: Port of Rotterdam characteristics

Rotterdam Port General Characteristics (2022)				
Location	Main type	Freight (Mt)[33]	Containers (TEU)[33]	Passengers (millions)
North Sea	Energy	467	14.5 million	-

Port's energy system

The overall electricity consumption of the Port Authority of Rotterdam is 8.94 GWh per year, in addition to this, the cruise terminal is using 45 MWh[33]. The port authority is supplied with electricity with renewable Guarantee of origin (GoO). The port has at present an installed capacity of 89 MWp solar PV, and has calculated that potentially 150 MWp of solar PV

[31] It was not possible to gather accurate data on CO_2 emissions as the Port Authority currently does not report those.

[32] For a more detailed description of these developments, see Section 5.1, Business model 1 (Marseille).

[33] Annual Report 2022 – Port of Rotterdam Authority

capacity can be installed on its premises[34]. The total installed capacity of wind energy in 2020 in the port of Rotterdam was 195 MW.[35]

The Rotterdam port and industry complex has a target to reduce CO_2 emissions by 55% in 2030 compared to 1990, with their policy being more ambitious, targeting a 60% reduction[33]. The port's emissions are generated by the industry (refineries and chemical companies), gas and coal fired power plants, terminals, waste, utilities and other industry.

The port of Rotterdam has a portfolio of decarbonisation projects such as CO_2 capture and storage, electrification, renewable hydrogen production plants, and the production of clean fuels, representing a total reduction of 13,700 ktonnes of CO_2. This represents 20% of the total Dutch target for 2030[33].

Table 3-8: Electricity use and GHG emissions of the Port of Rotterdam in 2022

Energy and emission characteristics (2022)			
Electricity consumption of port Authority (GWh)[33]	Installed capacity self-generated renewable electricity (MWp)[34]	Total CO_2 emissions of port and industry complex[33] (ktonnes)	Direct CO_2 emissions from Port Authority [33] (ktonnes)
8.94	284	23,500	2.53

Evolution of future electricity demand

Rotterdam´s electricity demand is expected to grow almost four times, from about 600 GWh in 2022 to about 2,700 GWh in 2030. It is estimated that about 28% of the electricity demand in 2030 will come from OPS, 21% from electrification of port operations and 51% from other electricity demand.

Currently, the port has only implemented two OPS pilots (Heerema Crane vessels, DFSS seaways). Their target is to have 8-10 shore power projects running in 2025. The 2030 ambition of Port Authority Rotterdam (PoR) is 90% of the vessels visiting the public quays in the urban area and 90% of the Roll-on-roll of offshore, ferries, container and cruise vessels will use shore power. The shore power in urban areas covers amongst others break bulk terminal of Waalhaven, Eemshaven and M4H areas and coasters. For the period after 2050, PoR plans to focus on encouraging innovation in the more complex shipping segment as liquid bulk and dry transhipment[36].

Onshore power supply (OPS) supplying electrical power to vessels will have substantial effect on the electricity grid, in terms of power demand and energy consumption. For example, the demand of a single cruise ship can be up to 20 MW. In addition, the Port of Rotterdam has large ambition in becoming hydrogen hub. For this multiple electrolyser projects are planned (for details see business model on hydrogen economy in section 5.8).

3.3.5 Port of Valencia

The Port of Valencia is located next to the city of Valencia and is managed by the Port Authority of Valencia (PAV), under the commercial name of Valencia port, which is the public body responsible for the management of three state-owned ports located along 80 kilometres on the eastern edge of the Spanish Mediterranean Sea: Valencia, Sagunto and Gandía.

Container cargo is the most important type of traffic in the Port of Valencia, making the Valencia port the main port in Spain for this type of traffic. It also has a large Ro-Ro Terminal that accounts for about 10% of the Port's traffic and has connections to 13 countries and 22 ports. For this cargo, the Port works as a hub for the entire Western Mediterranean region. It distributes goods over a radius of 2,000 km, both in southern Europe and in North Africa (Morocco, Algeria, Tunisia and Libya).

[34] https://www.porttechnology.org/news/port-of-rotterdam-increases-use-of-solar-power/

[35] https://www.portofrotterdam.com/sites/default/files/2022-08/voortgangsrapportage-herijkte-havenvisie-rotterdam-augustus-2022.pdf

[36] POR - Shore Power Program (2023)

The main terminals in the port of Valencia are the MSC Container Terminal, CSP Container Terminal, APM Container Terminal, Grimaldi Ro-Ro Terminal, Trasmediterranea Passenger Terminal.

Valencia handles traffic of all types of goods. The main users of the Port of Valencia include furniture and timber industries, textiles, footwear, agriculture and foodstuffs (grain and fodder, wine and beverages, tinned food, fruit, etc.), fuel products (diesel fuel, petrol, coal, etc.), chemicals and motor vehicles, construction products (cement and clinker, ceramic tiles, marble.), and machinery. The Port of Valencia also has regular passenger traffic to and from the Balearic Islands and Italy.

Table 3-9: Port of Valencia characteristics

Valencia Port General Characteristics				
Location	Main type	Freight (Mt) [37]	Containers (TEU) [37]	Passengers [37]
Mediterranean	Container	79.37	5,052,272	1,373,552

Port's energy system

The Port of Valencia consumes annually between 80-90 GWh of electrical energy in its three ports (Valencia, Sagunto, Gandia). The port authority uses less than 10% of the electricity, around 7-8 GWh per year for its administration, mainly buildings and personnel, the rest is consumed by the various terminals and their equipment.

The Port of Valencia manages its own electricity grid and is connected to the regional DSO network of Iberdrola. It procures electricity via a 2-year electricity supply contract by public tendering with an energy supply company. For the past years this contract included guarantees of origin for 100 % renewable electricity. The majority of the purchased electricity is resold to terminal operators under a 2-year contract at a flat-rate with a mark-up on the price to cover the costs for its own Port's electricity grid. The prices are set for a period of 2 years which gives terminal operators certainty on the costs, which can be considered in their business forecasts.

Table 3-10: Electricity use and GHG emissions of the Port of Valencia[38]

Electricity and emission characteristics (2020)			
Total electricity consumption (GWh)	Port Authority – administrative building use (GWh)	Total CO_2 emissions (tonnes)	Self-generated renewable electricity (GWh)
80	7.3	163,000	0

Evolution of future electricity demand

In the future, the Port's energy system will be affected by the construction of a New Container Terminal that is expected to double the containerized cargo, from around 5 million to 10 million TEU, with a timeline up to 2030. The new infrastructure will be electrified to a large extent (terminal machinery) and will be equipped with a number of OPS connections to supply shore power to ships at berth. The installation of OPS systems is also being considered for the other Terminals such as the passenger service to the Balearic Islands and possibly, in the future, for the Ro-Ro Terminal. The electricity consumption after implementation of these projects is estimated to reach 300 GWh once the Terminal is fully operational[39], while the arrangements on supply, together with grid limitations, can guarantee only 90 GWh. To meet its future energy needs the port authority will reinforce its internal electricity grid with 2 substations (90 MVA each), one on each side of the port and make investments in renewable electricity production with the aim of becoming more self-sufficient.

37 **Statistical Report Port Authority of Valencia December 2022**

38 Environmental Report of Port of Valencia 2020, 2021

39 The indications is that the terminal should be operating on its fuel potential by 2030.

3.4 Evolution of electricity demand and OPS potential to scale-up

Through interviews conducted with Ports as summarised in the previous chapter, it is evident that significant rise in electricity demand at ports will stem from the adoption of OPS systems. Therefore, the initial step is to evaluate the potential of OPS for specific ports. To compute this, we rely on the actual count of ship calls across various vessel types, sizes, and clusters for each port. This information is gathered from DNV's analysis of AIS data, which has been cleaned to remove excessive port stay durations specifically for the Cruise segment. Refer to the paragraphs and figures below for an illustration of the data collected for the Port of Gothenburg, while data for other ports can be found in Appendix E. Timeline of the analysis:

- Between April 2022 and March 2023, five ports—Gothenburg, Kristiansand, Marseille, Rotterdam, and Valencia—experienced a diverse range of vessel types making port calls. Vessel types like Ro-Ro, Passenger Ferries, Cruise, Chemical Tankers, and Containerships spent varying times in the ports.
- Based on the observed traffic, planned Onshore Power Supply (OPS) utilisation rates are projected to 2050.

The projected growth in fleet size indicates as main results of the analyses:

1) an estimated increase in energy demand at berth; and

2) the corresponding rise in OPS electricity demand for larger vessels

3) an anticipated reduction in CO2 emissions, assuming the usage of 100% green electricity for OPS, illustrating a positive environmental impact.

All ports studied here exhibit varied vessel types and OPS utilization forecasts based either on EU mandatory requirements or Ports' own ambition to go beyond these (expressed by Ports), which is summarized in Table 3-11. It displays the diverse OPS adoption rates among vessel categories, projecting corresponding changes in energy demand, OPS electricity usage, and potential CO2 emission reductions by 2050.

Table 3-11: OPS utilization rates

PORT OF GOTHENBURG

Vessel type	2023	2030	2040	2050
Container ship	0%	100%	100%	100%
Cruise	0%	90%	90%	90%
Passenger ferry	100%	100%	100%	100%
Ro-Ro	50%	90%	90%	90%

PORT OF MARSEILLE

Vessel type	2023	2030	2040	2050
Container ship	0%	90%	90%	90%
Cruise[1]	0%	70%	70%	70%
Passenger ferry	50%	90%	90%	90%
Ro-Ro[2]	0%	50%	50%	50%

PORT OF KRISTIANSAND

Vessel type	2023	2030	2040	2050
Bulk carrier	0%	90%	95%	100%
Container ship	2%	90%	100%	100%
Cruise	35%	100%	100%	100%
Offshore	70%	90%	90%	90%
Other cargo	0%	90%	95%	100%

PORT OF ROTTERDAM

Vessel type	2023	2030	2040	2050
Container ship	0%	90%	90%	90%
Cruise	0%	90%	90%	90%
Passenger ferry	0%	90%	90%	90%

PORT OF VALENCIA

Vessel type	2023	2030	2040	2050
Container ship	0%	90%	90%	90%
Cruise	0%	90%	90%	90%
Passenger ferry	0%	90%	90%	90%

[1] The future shares are in line with AFIR requirements if the remaining cruise vessels use alternative zero-emission technology in ports or some cruises are smaller then 5000 GT.

[2] Included the entire Ro-Ro segments, not distinguishing between passenger and other cargo ships.

LEGEND

EU requirements	Local assumptions beyond
EU requirements	Local assumptions beyond

Figure 3-1, Figure 3-2 and Figure 3-3 show the complete results on all three categories for the Port of Gothenburg, selected as the example, portraying a future trajectory where OPS becomes increasingly integrated into port operations. The projections suggest a substantial growth in OPS usage, leading to a significant reduction in CO2 emissions by 2050 for vessels utilizing this technology, underscoring a promising trend toward sustainable maritime practices. Figure 3-4 and Figure 3-5 consolidate the findings regarding electricity supplied to OPS in all five ports, presenting a comprehensive overview of the demand trajectory we sought to investigate and the rationale behind our analysis. The assessment reveals a consistent pattern of demand growth observed across these ports. The results for other ports as well as assumptions used for the calculations are shown in Appendix E.

Port of Gothenburg

The average time in the port varies between 10 and 15 hours, depending on the ship's type.

The results present the evolution of **energy demand for all vessels, energy supplied for shore power and CO_2 reduction** due to the use of OPS. Below are shown the results for Port of Gothenburg, for results of other Ports, see Appendix E.

Bulk Carrier Chemical tanker Container ship Cruise Gas Tanker Oil Tanker Passenger Ferry Service Vessel Ro-Ro Vehicle Carrier

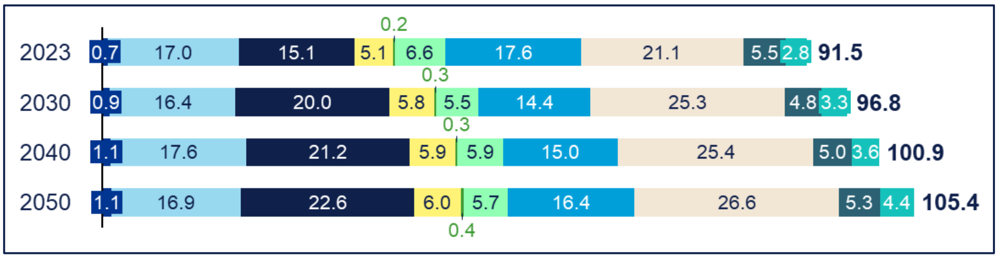


Figure 3-1: Evolution of total energy demand of all vessels at berth for Gothenburg, in GWh

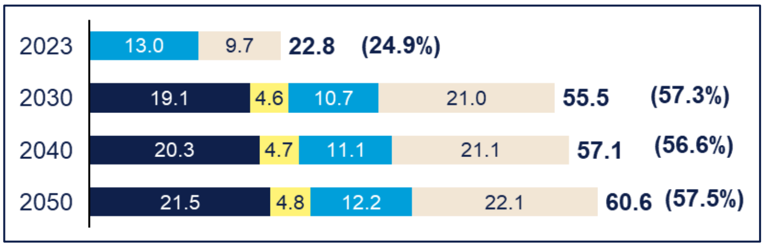


Figure 3-2: Evolution of energy supplied for shore power to vessels > 400 GT in Gothenburg in GWh

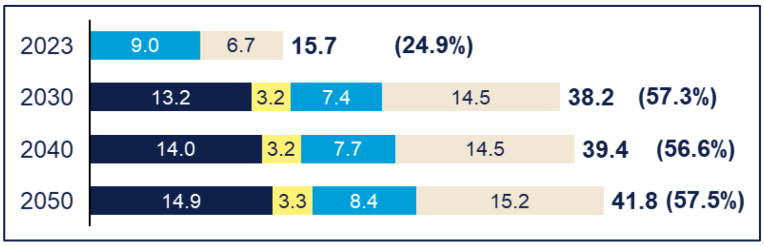


Figure 3-3: Evolution of CO_2 reduction due to use of OPS to vessels >400 GT in Gothenburg, in ktonne

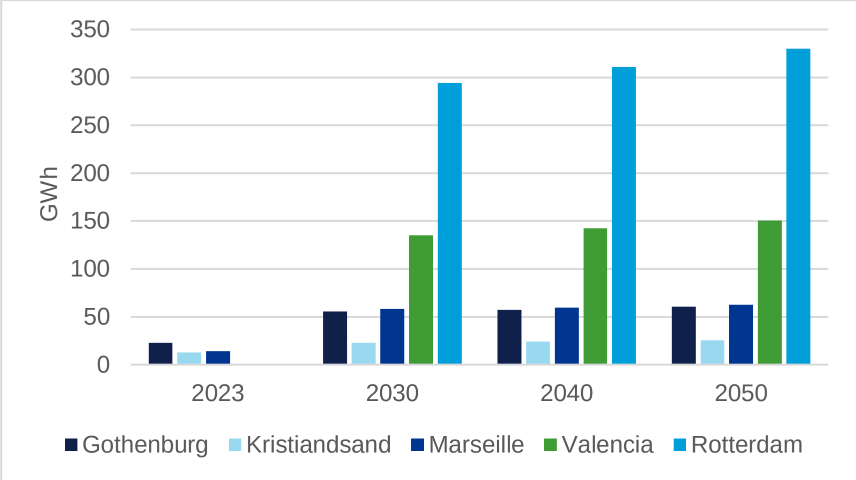


Figure 3-4: Combined results on evolution of energy supplied for shore power to vessels > 400 GT in all five ports

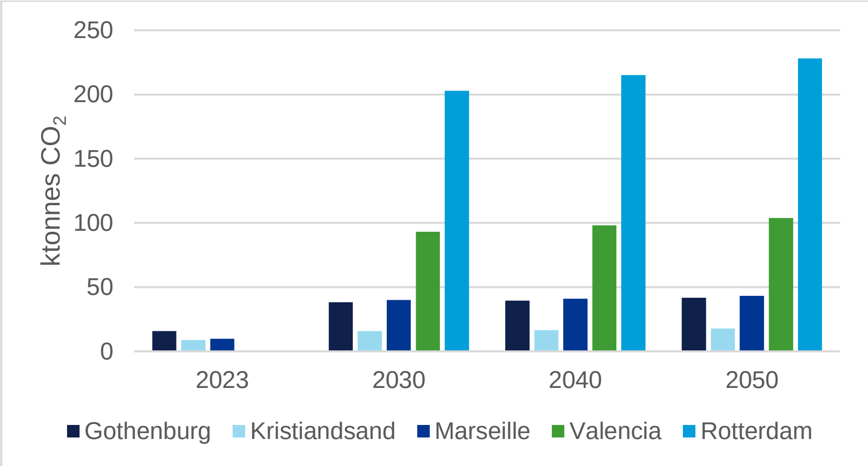


Figure 3-5: Combined results on evolution of CO_2 savings from OPS

3.5 Impact of electrification on electricity infrastructure

To reach net-zero emissions by 2050 the share of electricity in total energy demand would have to increase by 4% annually[40]. In general, peak electricity demand due to electrification can triple[41]. As shown in the previous section 3.4 and confirmed during interviews with the PAs, a significant surge in electricity demand is expected already by 2030 in all ports, driven primarily by Onshore Power Supply (OPS) and overall port electrification. Cruise ships and container vessels contribute substantially, with varying power demands.

Accessing power from medium voltage networks and nearby substations serves as a critical supply point for future electrification and growth. This might be less challenging for ports like Rotterdam and Valencia (but also Antwerp, Barcelona, Bremerhaven and others) who operate their grids, supplying terminals with stable electricity via fixed-rate models, whereas other ports like Gothenburg or Kristiansand rely increasingly more on local DSOs.

Two main challenges reflecting the surge in electricity demand for ports can be observed:

1. **Congested Grid /Power Peaks**: Although there is significant electrical infrastructure present in all ports, the grids are also used at capacity. Strategies to manage power peaks involve deploying spare batteries for

[40] IEA Electrification, https://www.iea.org/energy-system/electricity/electrification

[41] Electrification with flexibility towards local energy decarbonization, https://doi.org/10.1016/j.adapen.2022.100088

machinery, employing smart planning methods to reduce voltage disturbances, and exploring alternative power sources like ship auxiliary engines or optimizing energy usage in non-critical areas. Digital tools for forecasting electricity supply and demand play a crucial role in optimizing charging times for electric vehicles and maximizing the consumption of locally produced electricity.

(Electricity demand in Norway has a clear seasonal pattern. In wintertime the demand is twice the demand in summer. The electricity distribution system needs to be designed to supply the peak demand, leading to high investment costs.)

2. **Renewable Energy Integration**: Efforts to integrate renewable energy sources, such as photovoltaic (PV) installations, wind turbines, and potential wave energy systems, aim to reduce dependency on the grid. However, the surplus of renewable power at certain times poses challenges, necessitating agreements with grid operators for surplus energy distribution.

The assessment of energy infrastructures across multiple ports reveals nuanced strategies and challenges in adopting clean energy practices and managing electricity demand, space constraints and the integration of renewable energy sources.

In **Rotterdam**, the Port Authority has multiple roles, serving as both energy supplier and grid operator. Ensuring terminals receive electricity and managing the grid are top priorities. The port relies on a nearby 132kV substation, with plans for two new substations to accommodate future growth. Focusing on bolstering renewable energy capacity through PV and wind installations aligns with their expansion strategy.

The port's electricity infrastructure in **Kristiansand** revolves around a substation and HVDC terminals, aligning with Norway's seasonal demand patterns. It is investing in shore power facilities and electrification while leveraging hydroelectric power. Flexibility in power supply, such as adaptable OPS systems, is a focus. There's a cautious approach towards investing in direct current networks due to associated costs.

Valencia's Port Authority, operating as an energy supplier and grid operator, ensures stable electricity supply to terminals with fixed-rate charging. Anticipating significant demand growth, the port is planning two new substations. To address this surge, the DSO is committed to providing a 90 MW grid connection. The port's forward-looking approach involves expanding renewable capacity through PV and wind installations, supported by various flexibility sources such as batteries, smart planning, and interrupting non-critical power consumers like air conditioning or cold storage.

Gothenburg stands out among the group as the only port expressing confidence in its grid's capacity to meet future demands. The Port heavily relies on the Hisingen substation for power, where electricity undergoes conversion from 400kV to 132kV before distribution to the city and port. Additionally, within the port area sits the Rya Göteborg power station, a significant 250MW gas-fired plant that supplies heat to the district heating grid, managed and distributed by municipally-owned Göteborg Energi. However, recent plans to construct a battery factory near the port area raise concerns about potential limitations in grid capacity for the Port's operations.

In addition, almost each port also grapples with space limitations, particularly concerning substation expansion and Onshore Power Supply (OPS) facilities.

Marseille faces space constraints in its urban areas, limiting substation expansion possibilities. Upgrading existing equipment to enhance power capacity is under consideration. However, concerns about noise pollution from transformers near water bodies, like the Arenc substation, require thoughtful mitigation strategies.

Space limitations pose challenges also for **Valencia's** substations and Onshore Power Supply (OPS) facilities at quaysides, necessitating meticulous planning to meet growing demand while preserving port operations. Integrating OPS without disrupting berthing procedures remains a concern due to limited available space for electrical connections alongside the quay.

Flexibility Solutions:

Exploring strategies to manage peak demands and enhance operational flexibility within ports is crucial for sustainable energy management. Diverse approaches and technologies are being tested at the selected ports as potential solutions:

- Managing Machinery Start Times: The simultaneous start of high-power machinery like STS cranes influences grid voltage. Implementing slight time delays in their starts could alleviate this issue, especially when multiple machines are involved.
- Optimizing Charging and Operations: Flexibility in electric vehicle charging or Onshore Power Supply (OPS) can be leveraged without disrupting the core function of ports—efficient cargo and passenger movement.
- Utilizing Ship Auxiliary Engines: Preferring cleaner ships and using their auxiliary engines instead of OPS during specific periods can significantly reduce the need for peak power capacity, resulting in more efficient energy utilization.
- Strategic Control of Cold Storage Warehouses: Managing power demand from cold storage facilities and reefers offers the potential to align consumption with renewable energy sources or reduce peaks in power demand.
- Temporarily Modulating Air-Conditioning: Pausing air-conditioning in offices for short durations, contingent upon external conditions, provides flexibility to the power system, aiding in averting sudden demand spikes.
- Innovative Charging Approaches for Trucks: Smartly timing truck charging during waiting periods and surplus capacity windows supports flexibility. Overnight depot charging presents a flexible planning option, while extended waiting times may adversely affect user experience.
- Technological Explorations: Investigating hydrogen or ammonia production as flexible energy sources, heat (steam) flexibility, and electro-boilers for energy storage demonstrates potential avenues for bolstering flexibility in energy usage.
- Industry-Driven Flexibility Initiatives: Industries are embracing more flexible operating models, influencing energy needs and related infrastructure. For instance, simulations in the Rotterdam/Moerdijk cluster illustrate substantial flexibility gains through hybrid boilers and electrolysis capacity.
- Adaptive Industry Strategies: Industries are adopting adaptive strategies, such as designing plants with surplus capacity, allowing for fluctuation in production based on renewable energy availability.
- Innovative Grid Solutions: Smaller industries resorting to battery installations due to local grid constraints showcase nimble, yet expensive solutions compared to grid expansions. However, such solutions enable swift energy storage and release, mitigating grid congestion effectively.

4 DEFINITION OF CLEAN ENERGY BUSINESS MODELS FOR PORTS

4.1 Introduction

A clean energy business model describes how a selected port creates, delivers, and captures value[42] within the port's energy landscape, its customers and the clean energy transition in economic, environmental (GHG and land use) and regulatory contexts. The clean energy business models are viewed and described from a port authority perspective and, where needed, from the perspective of terminal owners and operators. Several clean energy business models can only be well described, understood and evaluated when they are approached beyond the port authority boundaries and its operational reach. For example, OPS where the energy business model description includes energy infrastructure / grid

[42] Business Model Generation, Alexander Osterwalder, Yves Pigneur, Alan Smith, and 470 practitioners from 45 countries, self-published, 2010

operators, energy and services providers, as well as vessel operators and technologies. A good understanding of the business models also requires insights in the main (EU) legislation and guidance.

4.2 Five categories of clean energy business models

Our approach focusses on a clear segmentation of different business models deemed crucial to better understand the different practices related to electrification and decarbonisation of ports. High-level research of the EU and non-EU ports has also been conducted, in order to pre-select the most experienced or ambitious front-runner ports.

The synthesis of the reviewed ports and literature provides a practical, high-level foundation for further analysis. Linking the practices to the policy objectives that have to be considered in this project, the review has been divided into five categories of business models as presented in the chapters below. As such, the review does not extensively discuss literature in relation to technical, economic or regulatory aspects related to those categories, but provides the relevant elements to clearly define categories of the different clean energy business models.

4.2.1 Onshore Power Supply (OPS)

Onshore Power Supply (OPS) is in the literature also identified as Shore Power, Shoreside Electricity (SSE), Alternative Maritime Power (AMP), High-Voltage Shore Connection (HSCV), or Cold Ironing.[43] It provides a technical and commercial solution that enables ships to shut down their internal combustion engines while berthed and plug into an onshore power source. The ship's power load is transferred to the onshore power supply without disruption to onboard services. Emissions to the local surroundings are eliminated.[44]

An OPS installation typically requires a building or a shelter, containing the necessary equipment that includes a switchgear, transformers and frequency converters, needed to adapt the shore electrical characteristics to the ship's ones (such as voltage, frequency).

The project team has selected two operational and one planned OPS case (based itself on operational case) for further analysis of this study. Given the current state of use of OPS in Europe, and the aim of this study to focus on cases with operational experience, this has led to a limited sample of cases, dominated by OPS cases for ferries and cruises. The OPS systems in Marseille and Gothenburg are owned and operated by the ferry company. The OPS system in Kristiansand is owned and operated by the Port Authority. In all identified case the Port Authority was involved in the development and implementation of the OPS.

From 2030 on, offering OPS for ferries, cruises and containers is a mandatory port service in TEN-T ports for vessels above 5000GT in line with the requirements of Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR), unless these vessels use alternative zero-emission technology. This is complemented by Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, which requires the above-mentioned vessel types to use OPS when available in a port. Through literature research, interviews, and workshops, the project team has identified several potential models, including ports collaborating in a subsidiary organization (such as a joint venture between the Port Authority and an electricity supplier) responsible for owning and operating the OPS. Additionally, there are models where OPS investments are integrated into terminal concession agreements, as well as cases where Port Authorities could take the lead in investing in, owning, and operating the OPS infrastructure. It must be noted that OPS is considered as a port service under Regulation (EU) 2017/352 establishing a framework for the provision of port services and common rules on the financial transparency of ports (Port Services Regulation). The Port Services Regulation introduced requirements for the access to the market for port service providers, but does not prescribe any specific models for the provision of such services.

[43] For more detailed description of OPS, see the guidance by European Maritime Safety Agency (2022), available at Ship Safety Standards - Shore-Side Electricity (SSE) - EMSA - European Maritime Safety Agency (europa.eu)

[44] European alternative fuels observatory

It could be anticipated that in future scenarios, Port Authorities will take the initiative in investing in OPS infrastructure, although this may vary depending on funding opportunities. Larger ports, with greater financial leverage, are expected to lead in direct investments. In contrast, smaller ports, facing budget constraints, may prefer models where shipping companies are more integrated into the ownership and operation of OPS, as outlined in the previously described models. Likewise other Port Authorities may opt for other solutions and models as mentioned above, including different models for the provision of OPS to different ship segments. The issue is being discussed among stakeholders in various fora including the Sustainable Ports Subgroup under the European Ports Forum[45], and different ports and EU Member States may opt for different models based on their individual situation.

4.2.2 Electrification and decarbonisation of the port`s operations

This business model category focuses on the decarbonisation efforts of the port's main operations (excluding OPS), such as bunkering, cargo-handling, passenger services, collection of ship-generated waste and cargo residues, pilotage, and towage. It mainly includes all aspects related to the decarbonisation of processes, infrastructure and equipment for passenger and freight handling equipment.

4.2.3 Energy hub and renewable energy production

Seaborne ports are in general characterised by the geographical concentration of high energy demand and supply activities, because of their proximity to energy-intensive industry and metropolitan regions, and their functions as central hubs in the transport of raw materials and energy. Wider aspects of the role of ports in renewable energy production, either for their own use (in one or more of the above models for example) or as an energy hub (production and procurement of several energy vectors and carriers including import and export) will also need to be considered. These clean energy business models are often labelled as energy parks that produce energy e.g. via solar PV or concentrated solar power (CSP) or wind turbines and/or cover further import, storage, transformation and export of energy and are typically found in large or very large ports.

4.2.4 New business models

Various new business models are considered that do not focus on the port's (terminal) core operations but rather on other clean, sustainable, and innovative solutions, such as energy storage (e.g. batteries and hydrogen), transformation (Power-to-X), construction and assembly of (parts of) wind turbines, equipment for tidal operations, and flexibility services such as demand response. These new business models show a high diversity of new activities. Furthermore, the selected business models should have clearly "new" characteristics such as the fuel that is used or other innovative solutions. These models could use existing (or emerging) technologies in new ways, for example port-linked off-shore wind turbines with integrated hydrogen production, carbon capture and technical solutions for CO_2 transportation for re-use in industrial processes or injection in underground storage caverns, or value chain setup for liquified biogas (LBG) with pipe to jetty connections. Due to their innovative nature, these business models do not have operations experience yet and are tested under pilot projects.

4.2.5 Smart grids

This business model category comprises energy transport networks that use digital communications technology to manage the local energy system and to enable its users to react to local changes in electricity demand, supply and market price signals and incentives/signals from grid operators to activate flexibility (grid congestion management, balancing, other ancillary services).

This category focuses specifically on projects that establish within the port area a smart energy system that integrates energy distributed by the network, energy produced in the port area and its vicinity, energy storage, and energy consumption by the port itself and its local users (mainly industry and transport). For large network integration models,

45 Register of Commission expert groups and other similar entities (europa.eu)

we assume the port being itself the energy system operator or having a well-integrated system with a regional energy system operator. For a small grid model, we assume a self-sufficient port energy management without a regional dimension.

4.3 Overview of selected business models

To compile the long list of potential ports and business models for further analysis, a number of industry and policy reports, EU-funded programmes such as Horizon 2020[46], Connecting Europe Facility[47] 1st & 2nd Generation, and European Alternative Fuels Observatory[48] databases were reviewed from which several ports and business models were identified. Desktop research further screened several industry related news channels, collected relevant information on ports' practices and activities and cross-checked these by analysing websites of Port Authorities, annual reports, decarbonisation strategies and plans. Relevant sources are summarized in Appendix A.

While each category as described in 4.2 might include many models as found in screening of European Ports at the beginning of the Project, a final selection was made according to a number of criteria. These were determined in two steps:1) operational experience and 2) diversity of ports.

A port's operational experience with a clean energy business model, listing the ports and business models by number of years of their practice. See Table 4-1.

Table 4-1: Operational experience criteria

Stage of development/experience
> 3 years operational, full coverage
Partly or recently implemented
Pilot project operational
Feasibility phase/design/well defined targets
Ambitions/strategy plans

General segmentation of seaborne ports with the focus on diversity in the port selection, starting from a list of 10 commonly used 'segmentation categories'. The chosen segmentation of the criteria is included in Table 4-2. The 'industrial activities' category identifies the dominant industrial activities. ''Industrial' is used for ports with a substantial number of hard to abate energy intensive industries like steel, ceramics, glass and parts of the chemical industry. 'Energy' is used for activities related to import, storage and processing of energy carriers (coal, oil, natural gas and others) and the production of electricity. 'Mixed business' refers to mixed business zones containing a variety of small and medium sized companies from manufacturing and service sectors.

46 Horizon 2020, https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en

47 Connecting Europe Facility, https://cinea.ec.europa.eu/programmes/connecting-europe-facility_en

48 European Alternative Fuels Observatory, https://alternative-fuels-observatory.ec.europa.eu/

Table 4-2: General segmentation of seaborne ports for the 4 selected criteria

Type of port	Size	Location	Industrial activities
General purpose	Very large	Scandic/Baltic	Industrial
Container	Large	North Sea	Energy
Tanker	Medium	Atlantic	Mixed businesses
Passenger	Small	Adriatic	None
Fishery	Very small	Mediterranean	
Island			

The long list for the pre-selection of relevant business models and ports included 26 European Ports and 3 Non-European ports. On the basis of a first evaluation, ten clean energy business models within five European front runner ports have been selected for further analysis. See Table 4-3.

Project (7) Smart Grid Energy Management Model is now included as a generic desktop study on requirements of Ports with regard to future energy management systems. It comprises examples on smart grids from three ports without operational data as the concerned port representatives were not willing to share the data for publication in a study report.

Project (8) Hydrogen Conversion Park in Rotterdam is included in the study with a qualitative description without cost benefit analysis.

Table 4-3: Overview of selected business models

	Category	Business Model	Description	Status	Port	Size	Location	Type
1.	OPS	OPS 1	OPS high voltage connections at the regular passenger ferry line from Marseille to Corsica.	Operational	Marseille	Medium	Mediterranean	General purpose
2.	OPS	OPS 2	OPS low voltage connections to dry bulk cargo	Operational	Kristiansand	Small	North Sea	General purpose
3.	OPS	OPS 3	OPS high voltage connections at a new passenger terminal	In development	Gothenburg	Medium	Baltic Sea	General purpose
4.	Decarbonisation of Port`s operations	Electrification of RTG	Electrification of RTG cranes in the Container Terminal	Operational	Valencia	Large	Mediterranean	Container
5.	New Business	H_2 Production and use with RES	Production and use of H_2 for terminal equipment with electricity produced with RES self-generation (solar and wind)	Pilot project	Valencia	Large	Mediterranean	Container
6.	Energy hubs	RES generation – solar panels	Installations of solar panels on terminal passenger roofs for self-consumption	In development	Valencia	Large	Mediterranean	Container
7.	Smart Grid	Energy management solution	Smart grid electricity solution	In development	Singapore, Portsmouth, Rotterdam			
8.	Energy hubs	H_2 Conversion Park	H_2 electrolyser, Ammonia import terminal	Early stage	Rotterdam	Very large	North Sea	Energy

5 DESCRIPTION AND ANALYSIS OF SELECTED CLEAN ENERGY BUSINESS MODELS

This chapter provides detailed information on eight selected business models via use cases in several ports (see overview in Table 4-3). The information provided includes a description of the business model accompanied by drivers and enablers, a description of the deployed technology and project implementation details, an impact analysis of the business model a cost benefit analysis with exception of two qualitative models (H_2 Economy in Rotterdam and Smart Grid Energy Management) and finally, the replicability potential.

The intent is to provide sufficient information to the reader to understand the nuances of each model's implementation at the specific port without repeating the methodology of the assessment, which remains similar for all business models. The methodology including for the CBA is explained in section 2.4.3.

5.1 OPS for Ferries (Marseille port)

5.1.1 Definition and Scope

Business model description	Onshore Power Supply System in High Voltage to the regular public service on the route Marseille – Corsica – Marseille
Scope	4 High Voltage 50 Hz OPS connections to Ro-Pax ships
Location	Harbour 3 (at Quai du Maroc and Quai d'Arenc)
Date of Commissioning	2017 and 2019
Lifetime of project	>15 years
Partners	The Port of Marseille Fos, La Méridionale, Corsica Linea, Schneider Electric

5.1.2 Port context: The Port of Marseille

Currently, the OPS systems for the Corsica ferry lines (business model 1) and low voltage for private yachts and dry docks are the only OPS connections in the Port. The low voltage connection of 400 V in 50 Hz frequency has been in place in the Port of Marseille on various berths since around the 1940s.

Location	Vessel type	Voltage	Frequency	Operational
Quay Arenc/Maroc	Ro-Pax	1100 V	50 Hz	2017
Port for private boats	Yacht	400 V	50 Hz	N/A
Dry docks	various	400 V	50 Hz	N/A

Future development plans

The Port has plans on extending the OPS connections to other types of vessels. A number of developing projects are worth mentioning for two reasons: 1) to reflect on the Port in the context of its electrification and decarbonisation efforts and 2) to be able to evaluate the present case for its replicability potential in 5.1.8.

- 4 new OPS connection of 5 MW each for regular Ro-Ro and Ro-Pax lines at the North Africa. The plans include reinforcing its own grid, building transformers, and laying cables.
- Up to five OPS connections of 7.5 MW each plus converter for the cruise terminal.

- Photovoltaic energy installations for own electricity generation on the roofs of the passengers' terminal and three warehouses around the Cruise and the North African Terminals. Altogether, about 50,000 m^2 of solar PVs are planned to be installed in 2024-2025, with the objective of producing up to 9 MW of electricity and later increasing to15 MW.
- Smart grid system for optimal energy management between the supply of self-generated electricity, grid fed electricity and OPS connections.

5.1.3 Drivers and enablers

The main rationale behind the OPS development was to help the city combat pollution. Ships that stop in the Marseille basin contribute (depending on the pollutant) 5% - 10% of the city's overall atmospheric emissions footprint[49]. Future OPS projects will however principally be driven by requirements of EU legislation.

As the proximity of the port to the urban centre has a significant impact on the concentration of pollutants in these highly populated and therefore very sensitive areas, the port is particularly vigilant of its environmental footprint.

5.1.4 Operative model of the business case

Technical solution

Four OPS connections are installed to provide onshore power in high voltage (11,000 volt) and 50 Hz frequency. At the berths the placement of all the connections is identical, they are located 90 meters from the end of the berth, which means only ships of certain dimensions can be connected. The figure below shows exact locations of the facilities around harbour 3.

The OPS connection consists of one-box solutions (OPS crane), similar to those used in the Port of Gothenburg (business case 3) and elsewhere. Although the capacities are between 2-2.5 MW, to anticipate future needs and peak hours, the ships currently use only about 1 MW on average.

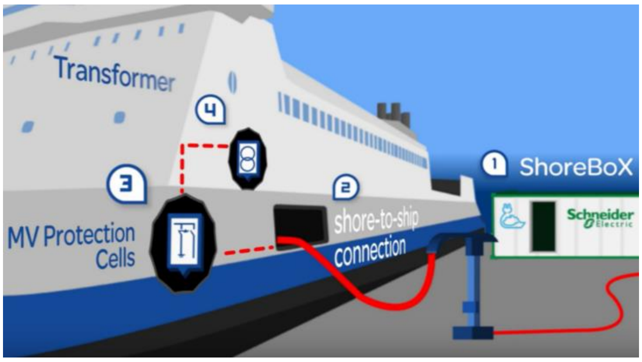


Figure 5-1: Visualisation of OPS System solution implemented in the Port of Marseille
Source: Port of Marseille Fos / Schneider Electric

Since the Marseille – Corsica – Marseille traffic is a regular service, the connections are used regularly on a daily basis. The number of ships varies by the day between two ships on odd days and 5 ships on even days. The ships arrive typically in the morning and leave in the evening, staying at berth for 12 hours. 4 ships can be connected at the same time.

The operation of the OPS connection is straight forward, upon arrival the ship's team collects the socket from the crane, plugs it in the ship and starts the automated electricity transfer between the ship and the dock until the evening when the ship leaves. The connection is made in just a few minutes without power interruption inside the vessel.

[49] Interview with Sophie Rouen (The Port of Marseille); 06/03/2023

Contractual characteristics
The entire terminal is owned by the port authority and rented to both companies that are operating the terminal. The investment related to the onshore power cranes has been made by the companies which also operate these systems.

Three OPS connections are owned by *La Méridionale*, although the company operates only two and rents the last one to the *Corsica Lines*. *Corsica Lines* owns the 4th connection, thus operating two connections in total.

The port authority holds since 2014 and 2017 a long-term electricity supply contract with the OPS operators and is reselling electricity with a 3-5% margin on top of the price of its own supply contract.

5.1.5 Implementation

Prior to 2010 the port authority started investigating how to help the city combat its local emissions, as the port area is situated close to the city centre, especially the terminals for its Ro-Pax vessels. The Port Authority together with *La Méridionale* analysed and compared a number of solutions in other European and North American ports, either OPS systems or systems that can be implemented within the ship itself. The port authority prepared the port's electric grid by converting its substation and laying cables, and the ship company built the OPS cranes and retrofitted its ships.

In 2014, the port authority signed a long-term contract with La Méridionale for supplying electricity as part of its terminal operating contract and in 2017, it was the first shipping company to be connected to the OPS system. In 2017 a similar contract was signed with the second company Corsica Linea and in 2019 the first ship was connected. Since then, the OPS connections have been developed further, both companies converted progressively all their ships' internal electric systems. Since 2020 all ships of the two companies can be connected. Since the connections are located at the terminal reserved exclusively for the regular Corsica lines, no other ships use them.

5.1.6 Impact Analysis

Impact on operation and port`s area
The project did not have any major impact on the port operations during its implementation; a continued traffic of passengers was possible. The representatives from the port and shipping companies mentioned benefits from the OPS that relate to comfort. When the engines are switched off the conditions are quiet, no noise or vibrations, for working personnel as well as for people working or living in the vicinity of the terminal.

Impact on sustainability
The main impact of the OPS installations is a reduction of GHG and other emissions directly at the source by switching off the auxiliary engines.

Between **80% to 90% reduction in CO_2 emissions** has been claimed by the port authority for the Corsica lines when disregarding the time of connection at berth. Similarly, the OPS reduces pollutant emissions such as NOx, SOx, and Particular Matter (PM)[50] and so the port contributes to a better air quality for the neighbouring urban area.

As neither the Port of Marseille nor the ferry companies report on GHG emissions savings and other pollutants yet, the impact of the OPS system on sustainability has been calculated as part of the cost-benefit analyses using data from the interviews where possible, the AIS study and DNV's own assumptions.[51]

However, it is important to note that these numbers are based on average data for the utilisation of auxiliary engines that are same for all ports as explained in Chapter 2 – Approach of the project. During the interview with the Port of Marseille the only data available was the overall electricity consumption via the OPS system, which is around 5 GWh per year. Using average data on aux engine utilisation (33%), best estimates on the number of ship calls of both companies and hours at berth, we estimate the electricity consumption at 16 GWh. This inconsistency has a large

[50] Particulate matter consists of a mixture of solids and liquid droplets. Particulate matter comes in different sizes, with that smaller than 10 micrometers able to enter lungs and cause serious health problems, for detailed definition see European Environment Agency.

[51] For detailed explanations on the CBA please see section 5.1.7

impact on the results, i.e. our estimates result in higher GHG and other emissions savings, which in reality might not be the case. The reason is likely different aux engine utilization, especially given the ships in Marseille berth empty of passengers over night with a minimum of services as compared to e.g. Gothenburg where ships berth a couple of hours and need to keep majority of facilities running.

Table 5-1: CO_2 emission savings from OPS in the regular Ro-Pax service in Marseille port
Source: DNV calculations

#Number of Port calls per year	Hours per stay	Avg aux power [kW]	Energy demand at berth from OPS [MWh/year]	Average fuel consumed at berth [tonnes/year]	CO_2 reduction [tonnes/year]
1,090	11	4,101	16,226	3,245	10,404

Based on a yearly energy demand of 16 GWh electricity per year the OPS (substitution of fossil fuel by renewable electricity) prevents annual emissions of 10,000 tonnes of CO_2 into the atmosphere.

Regarding NOx, SOx, and PM pollutants we applied similar calculations, based on the cost-benefit analyses. The emission reductions are shown in the table below.

Table 5-2: Other emissions from OPS in the regular Ro-Pax service in Marseille port

NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
131	20	3

Impact on electrification and Port`s energy system
Discounting the time needed for connection and disconnection, unusual situations and ships that are not allowed to connect to OPS due to carrying hazardous cargo, we estimate that the degree of electrification of the entire Corsica passenger traffic stands around 85%.

The overall electricity demand for the OPS connections is supplied by grid electricity, which increased the overall port electricity demand.[52]

The OPS system is well integrated into the port's electricity grid through a substation and no major grid upgrades were needed. The energy management did also not require an update. The system can be considered as an additional consumption point, it does not have any flexibility features for the port's grid, nor for the DSO network of the city of Marseille.

5.1.7 Costs and benefits analysis - results

In this case the shipping company has invested in the OPS system. As already stated in section 4.2.1 in future cases the investments are expected from either Port Authority, subsidiary organisations, terminal owner/operator, a third party previse provider or a combination.

The OPS based business case has a total investment cost of 19 MEUR, which consists of 16.5 MEUR for the vessels and 2 MEUR for the OPS infrastructure in the port.

The operational costs are 2.1 MEUR per year, which include the electricity offtake from the grid (2.0 MEUR/year in the medium scenario) and maintenance (0.1 MEUR/year). The pollution costs related to the electricity consumption are zero since the port makes use of 100% green electricity.

[52] The inconsistency between the estimated electricity demand and the real figures is explained in the previous section, under Impact on sustainability.

The fossil fuel-based business case is the BaU, therefore it has no new investment costs, assuming that the engines are already available on board the vessels. For the BaU case bunker fuel, very low sulphur fuel oil (VLSFO) is assumed. The operational costs include maintenance and fuel consumption. The pollution costs include emission costs for CO_2 (well-to-wake), NO_x, PM and SO_2. Table 5-3 provides the initial investment costs and the annual operating costs for the OPS case and the BaU case.

Table 5-3: Total annual costs for OPS case and BaU

	OPS case in MEUR	OPS case including ship investments in MEUR	BaU in MEUR
Initial investment	2.5	19	-
Annual operating cost	2.1	2.1	1.8
Annual pollution costs	0.0	0.0	3.5
Total annual costs including investment cost over depreciation period	2.4	3.8	5.3

In the medium scenario, the business case based on onshore power supply requires an initial investment in the OPS infrastructure but has lower annual costs. Therefore, it is a financially viable alternative to the BaU case. Onboard ship investments for the OPS connection are significant, but are not incurred by the ports themselves and do not affect the ports as emissions do, nevertheless a cost breakdown including these investments is also provided for informational reasons. In this case the annual costs of the OPS business case increase by 60%, which can be explained by the large contribution of investment costs made by ships. Figure 5-2 shows the annual cost breakdown for the OPS cases and the BaU case.

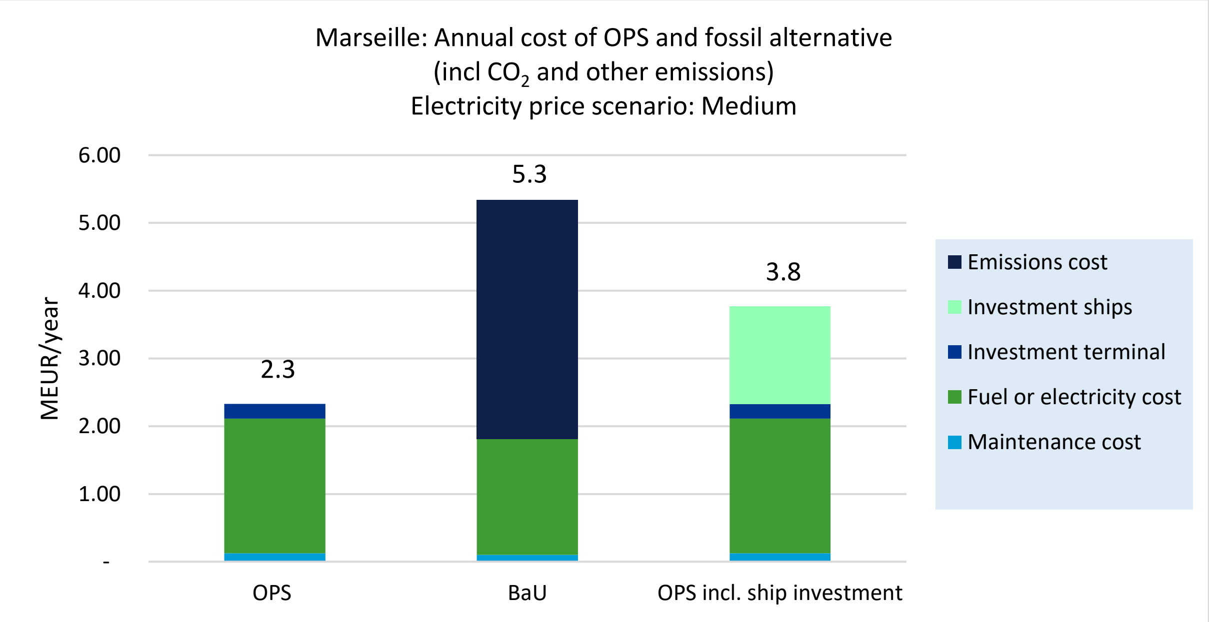


Figure 5-2: Marseille port: Annual cost of OPS and fossil fuel BaU.

Sensitivity analysis

In the OPS business case, changes in the variable CAPEX have the lowest sensitivity and lead to the narrowest spread in the annual costs, for example, a 20% increase or decrease leads to a 2.9% increase or decrease in annual costs. In the BaU business case, changes in CAPEX have no impact because ships are assumed to already have these investments. Changes in the electricity price show significant sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 13.5%. In the specific OPS case, the CO_2 price has no influence because the port of Marseille uses 100% green electricity.

The CO_2 price does have a small negative impact on the annual costs in the BaU case as the bunker fuel used results in CO_2 emissions. An increase or decrease of 20% in the CO_2 price leads to a 4% impact on annual costs. Furthermore, for the BaU case the bunker fuel price has the highest sensitivity, with the widest spread in annual costs (6.4% impact on annual costs).

Even in the case of high CAPEX and high electricity price the OPS business case leads to lower annual costs than the most favourable BaU case (low bunker fuel price, low CO2 price). An overview of the sensitivities is provided in **Error! Reference source not found.**. Furthermore, the tornado charts in **Error! Reference source not found.** visualize the results of the sensitivity analysis.

Table 5-4: Overview sensitivities with min-max value and impact on annual cost.

Parameter	Min - max Value	Impact on annualised cost
CAPEX OPS business case	2.0 – 3.0 (MEUR)	Low sensitivity: 2.9%
CAPEX BaU	-	No sensitivity
CO_2 price	66.9 – 100.4 (EUR/ton)	No sensitivity CEBM, moderate BaU: 4%
Electricity price (OPS)	77.5 – 116.2 (EUR/MWh)	Significant sensitivity: 13.5%
Bunker fuel price (BaU)	421.7 – 632.5 (EUR/ton)	Moderate sensitivity: 6.4%

5.1.8 Replicability

The OPS project for the regular lines to and from Marseille to Corsica was positively affected by a number of important factors:

1) **No large investment into the infrastructure within the port** – the inter-port electricity substation was already in place and the port invested only in the corresponding HV cabling connecting all four OPS cranes. The rest of the system was built by the ferry line companies, including electric equipment within the ships and training of personnel to operate the system.

2) **Long-term electricity contracts and regular traffic** – the regularity of ferry lines made it possible for the port to plan for the procurement and resale of electricity under long term commitments, hence having guarantees on the return on investment. The current OPS system was designed with this in mind, it does not put major requirements on the electricity supply.

3) **Low cost of electricity** – at the time of development of the first OPS connections, the price of electricity in France was 31.80 EUR/MWh (January 2016), a similar range as in the modelling exercise above (39.4 EUR/MWh). The prices have meanwhile increased substantially to around 178 EUR/MWh (January 2023).

The first two conditions can be met in a number of other ports in the EU which makes this case highly replicable, although the economics of the business case (i.e. the competitiveness of electricity versus fossil fuel) vary, which can make the model less favourable than at the time of the investment. It still needs to be considered that when the requirements of Regulation (EU) 2023/1805 start to apply, non-use of OPS by a vessel may lead to a serious penalty for the shipping company.

Scalability within the Port of Marseille

For the Port of Marseille, apart from the 'know-how' gained from working with the system, the replication potential to scale up remains limited. Without major investments in new infrastructure, it cannot be replicated as such elsewhere in the port since the current grid capacity is not sufficient for additional OPS.

In order to fulfil the AFIR requirements for passenger traffic, the port authority is developing plans to equip the North African Terminal and Cruise Terminal with onshore power (for more details, see section 5.1.2). For these projects large investments and planning of the grid infrastructure are needed (internal grid, cable layouts, substation with frequency conversion, reinforcement of entry points to the transmission grid and capacity increase). As an example, the Cruise Terminal alone requires 7.5 MW of OPS capacity for one connection, but having very irregular traffic puts pressure on the grid during peak hours (five cruises connected at the same time, but perhaps only once a week, the other days are connected only one or two). Irregular peaks of this sort leads to low utilization and a negative business case. Better organized planning and smart grid systems are required to improve the financial performance. For a detailed discussion refer to Chapter 6 barriers. As gathered during the interview with the port the overall consumption of the new OPS installations can be expected to be between 28 – 34 GWh per year, which would more than double the amount of electricity that the port authority consumes, excluding terminals such as containers and other industrial activities.

5.2 OPS for Cargo Vessels (Kristiansand port)

5.2.1 Definition and Scope

Business model description	Low voltage OPS connection to dry bulk cargo vessels
Scope	2 low voltage OPS connections at Strømsvika for berth and loading of timber ships, stone ships and other general cargo and bulk carrier
Location	Mandal port (Strømsvika). Quai 220 (timber), quai 221 (stones)
Date of Commissioning	2024
Lifetime of project	20 years
Partners	Three regular shipping companies

Two planned low voltage OPS connections to dry bulk cargo vessels at the Strømsvika port are based on regular traffic from three cargo ships but will also be able to connect other vessels of compatible OPS solutions. The Port of Kristiansand, that provided information requested for this study, built this case on operational data from the port's previously implemented OPS projects.

5.2.2 Port Context: The Port of Kristiansand

Kristiansand Port is a pioneer in Norway on OPS with the first installation implemented in 2014 and a yearly electricity flow to OPS of 5 GWh (2022). In 2018, the port opened Europe's largest shore power plant and Norway's first shore power plant for cruise ships. At the Kristiansand Port, the profits from the OPS business operations are reinvested in new OPS systems and related infrastructure. The port of Kristiansand participates in a collaboration with other ports in the Oslo fjord to offer joint technical solutions for containers and bulk carriers.

5.2.3 Drivers and enablers

The main drivers behind installing an OPS system in Strømsvika Port:

- Environmental considerations: An important contribution of OPS is reducing various atmospheric emissions and providing a better working environment with improved air quality and noise reduction. The port has set a goal to electrify all its berths, including for ships with bulk cargo.

Enablers of the project:

- Technology knowledge: the Port of Kristiansand has a dedicated OPS strategy with well-established technology solutions.
- Regular ship traffic. The port has signed intention deals with three cargo companies, which will create a base load usage and guarantee first users of the OPS.
- The project is only profitable if the port receives grants from ENOVA[53], the governmental institution responsible for allocating grants and other measures to support the energy transition. In the CBA of this business model, it is assumed that the grant is received.

5.2.4 Operative model of the business case

The business model includes two connections for dry bulk cargo vessels at Strømsvika Port in Mandal for berth and loading of cargo ships. Most ships are regularly at two quays in Strømsvika Port, and shipping companies have signed letters of intention to use the OPS for three ships. The project is planned to be commissioned in 2024.

The OPS system is compatible with retrofitted conventional ships and new ships. New builds with battery packs on board for hybrid battery-electric propulsion and electric self-loaders/unloaders can be supplied via the ship's shore power connection. The connection to shore is operated from the ship via a permanent cable reel (crane) where the desired cable length can be extracted.

The business model includes investments in the port infrastructure including cable reels, cabling and grid infrastructure, that represent the major costs. The project requires increasing the grid supply capacity to the port facilities with two new transformers: a 1,600 kVA 22/0.68 kV transformer and a 500 kVA 22/0.4 kV transformer.

Contractual arrangements
The port facility is run by the port authority and is visited mainly by regular ship traffic.

The OPS connections will be owned by the Port of Kristiansand. The port authority purchases electricity and resells it to the shipping companies. It currently pays a fixed price for electricity supplied via the low voltage connection (225 EUR/MWh), which is expected also to be the case in the future.

5.2.5 Implementation

As the main investor in the OPS system, the port is applying for a grant of 50% of the calculated investment costs of 930,000 EUR[54], i.e., approx. 465,000 EUR from ENOVA. Upon its investment decision, the port will finalise the design of the technical solution and search for a technology provider. At the same time, the port needs to prepare the site to enable the grid connection.

The 2,100 kVA grid capacity increase will require a grid connection agreement with the local DSO. Currently, there is a high demand for grid connections in Norway. The application of grid connection is handled by the DSO which analyses the available grid capacity and the related needed upgrades. This process may take from 6 months and up to a year, due to the many requests and is necessary for the project to progress.

[53] Enova is the institution that provides grants on behalf of the Norwegian government to projects that reduce greenhouse gas emissions, develop energy and climate technology and strengthen security of supply. Each year, Enova invests more than 250 MEUR of public resources in sustainable solutions.

[54] 11 million NOK

The implementation phase will not have significant impacts on the normal port operations. The civil work will include installing transformers, laying cables, and installing cable reels and connection points.

The shipping companies that intend to use the OPS system will either need to retrofit their existing ships or invest in new ships that are compatible with the OPS system of the port. In this case, the shipping companies have already built or are rebuilding their ships[55]. In general, installation costs vary greatly depending on the type of vessel, the investment type (new built or retrofitted vessel), the number of connection points on board, and the type of cable handling equipment, batteries, and equipment for electric self-loading/unloading. In this study, an investment cost of 1.75 MEUR is assumed for each of the three ships.

5.2.6 Impact analysis

Impact on operations and port area

When operating, the OPS system will contribute to a better working environment on the ship and at the port due to decreased noise and vibrations caused by combustion engines. Also, the pollution to the surrounding area will be reduced.

Impact on sustainability

As the business model of Kristiansand cargo OPS system is still in an early-stage development, several assumptions are used in the CBA. The electricity demand is expected to be 658,200 kWh/year in 2025, and the corresponding fuel savings at berth are 147 tonnes/year. The cargo ships are generally at shore for around 10 h, with a yearly berth time of 280 h, 570 h and 760 h for the three ships. They intend to have an electricity offtake agreement.

The port authority expects that by shifting to OPS for the studied quays, the GHG emissions will be reduced by around 500 tonnes of CO_2 equivalents. In the table below, the emission savings are expressed in tonnes per year and are calculated using the assumptions from the cost-benefit analyses. The calculated GHG emission savings of 557 tonnes CO_2/year are in line with the port's calculation of 500 tonnes CO_2/year.

CO_2 [tonnes/year]	NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
557	6	1	0

Impact on electrification

The Strømsvika port facility is currently connected to the regional grid by a 315 kVA connection which supplies smaller loads such as general consumption of the port and public lighting. By implementing this business model, the connection capacity is planned to be upgraded to 2,100 kVA. The port will be able to supply all OPS demand from cargo vessels at these quays. The port authority is expecting that the electrification level of bulk carriers at berth will reach 90 % in 2030 and 100% in 2050. The electricity in the Norwegian power grid has a low CO_2 footprint of 30 g/kWh and this is the basis for the expected reduction of the CO_2 footprint of cargo ships that switch at berth from fossil fuel use to OPS.

Impact on energy management

The OPS system will be integrated into the port's electricity grid as an additional demand through the new transformers and does not offer any flexibility features.

5.2.7 Costs and benefits analysis - results

The OPS based business case has a total investment cost of 6.1 MEUR, which consists of 5.3 MEUR for the vessels and 0.8 MEUR for the OPS infrastructure in the port. The operational costs include the electricity offtake from the grid (0.06

[55] The related costs have not been disclosed because they are commercial sensitive information

MEUR/year in medium scenario) and maintenance (0.04 MEUR/year). Pollution costs from electricity grid offtake include the emission cost for CO_2 (well-to-wake), NO_x, PM and SO_2.

The counterfactual case based on fossil fuel BaU has no investment cost, assuming that the engines are already available on board the ships. The operational costs include maintenance and fuel consumption. The pollution costs are 0.15 MEUR/year. Table 5-5 provides the initial investment costs and the annual operating costs for the OPS case and the BaU case.

Table 5-5: Total annual costs for OPS case and BaU.

	OPS case in MEUR	OPS case including ship investments in MEUR	BaU in MEUR
Initial investment	0.8	6	-
Annual operating cost	0.10	0.10	0.08
Annual pollution costs	0.001	0.001	0.15
Total annual costs including investment cost over depreciation period	0.16	0.62	0.23

In the medium scenario, the business case based on onshore power supply requires a higher investment but has lower annual costs (including pollution). Therefore, it is a financially viable alternative to the BaU case. Onboard ship investments for the OPS connection are significant but are not incurred by the ports themselves and do not affect the ports as emissions do, nevertheless a cost breakdown including these investments is also provided for informational reasons. In this case the annual costs of the OPS business case increase by almost 400%, which can be explained by the large contribution of investment costs made by ships. Figure 5-3 shows the annual cost breakdown for the OPS cases and the BaU case.

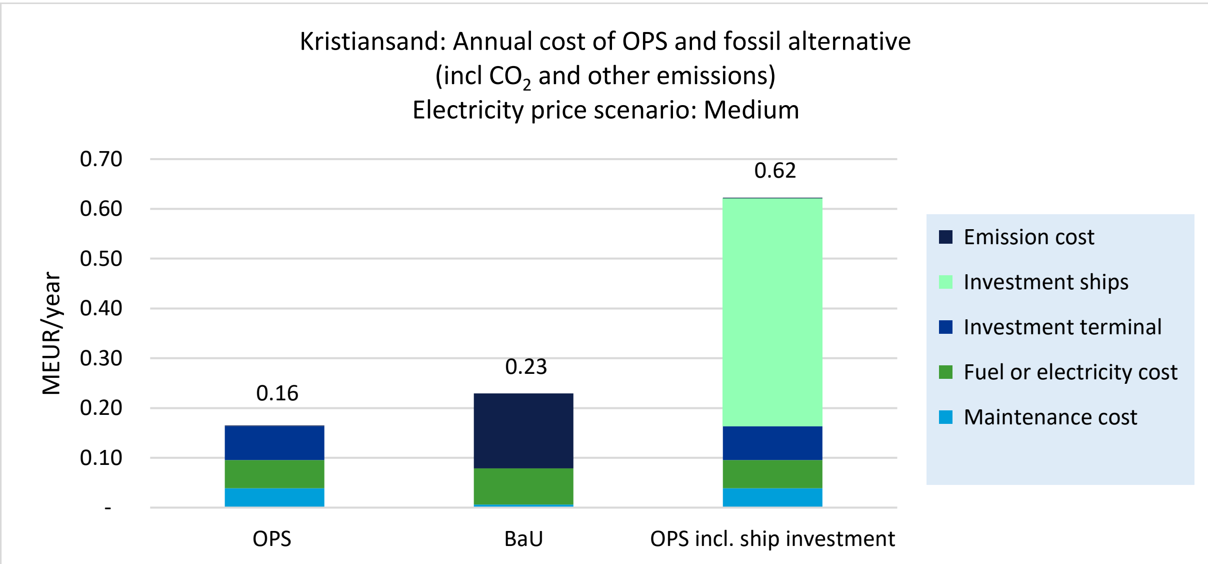


Figure 5-3: Kristiansand: Annual cost of OPS and fossil fuel BaU.

Sensitivity analysis

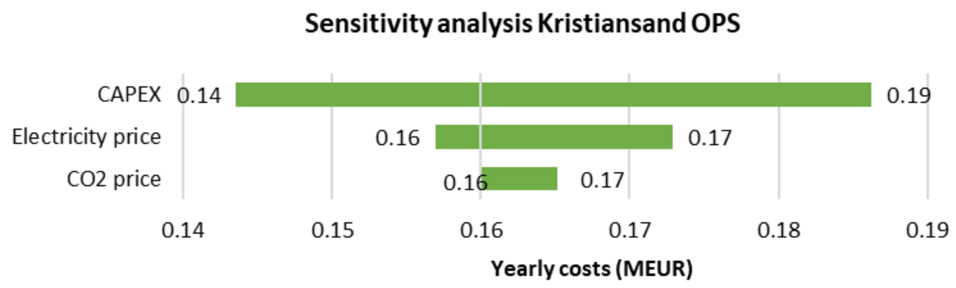
In the OPS business case, changes in the variable CAPEX have the highest sensitivity and lead to the widest spread in the annual costs, a 20% increase or decrease leads to a 12.9% increase or decrease in annual costs. In the BaU business case changes in CAPEX have no impact because investments for ships are considered pre-existing.

Changes in the electricity price show a moderate sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 4.8%. In the specific OPS case, the CO_2 price has negligible influence due to green grid electricity in Norway (very low-carbon intensity).

In the BaU case, the CO_2 price does have an impact on the annual costs, as the bunker fuel used is emitting CO_2 which negatively impacts the BaU case. An increase or decrease of 20% of the CO_2 price leads to a 4% impact on annual costs. Furthermore, for the BaU case the bunker fuel price has the highest sensitivity, with the widest spread in annual costs (6.4% impact on annual costs). The cost benefit results do not change in the sensitivity analysis, under all cases of low and high sensitivities, the OPS business case requires lower annual costs than the BaU case. An overview of the sensitivities is provided in Table 5-6. Furthermore, the tornado charts are provided in Figure 5-4.

Table 5-6: Overview sensitivities with min-max value and impact on annual cost.

Parameter	Min-max Value	Impact on annualised cost
CAPEX CEBM	0.6 – 0.9 (MEUR)	Significant sensitivity: 12.9%
CAPEX BaU	-	No sensitivity
CO_2 price	66.9 – 100.4 (EUR/ton)	Negligible sensitivity CEBM 0.12%, moderate BaU: 4%
Electricity price (CEBM OPS)	48.4 – 72.6 (EUR/MWh)	Moderate sensitivity: 4.8%
Bunker fuel price (BaU)	421.7 – 632.5 (EUR/ton)	Moderate sensitivity: 6.4%



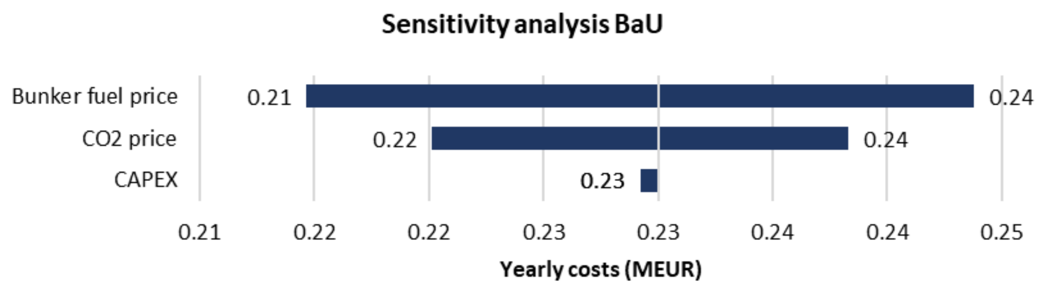


Figure 5-4: Kristiansand Port: Sensitivity analysis OPS and BaU

5.2.8 Replicability

The OPS project in the Port of Kristiansand has shown that the technical solutions are quite mature. The implementation of this business case will show that this technical solution is also suitable for dry bulk cargo vessels and is without any major issue replicable in other ports apart from the need for stable power supply.

Furthermore, the Port of Kristiansand has an organisational structure that incentivises deployment of OPS, by reusing the profits from OPS operations for investments into new OPS systems.

The letter of intent between shipping companies and the port is central in this business case and could be used to secure similar investments in other ports. It provides a guarantee to investors in OPS usage and can in particular be used for ships with regular routes. At the same time, it distinguishes the system as applied for example on passenger routes where shipping companies are usually in charge of investment, operation and maintenance (Marseille and Gothenburg), while cargo companies are only customers of the OPS system, because their vessels have less regular timetables and less regular call patterns in comparison to ferry lines.

The replicability of this business model viewed by the port investments is favourable. When vessel investments are considered, the replicability depends on the shipping company’s access capital, as the business model is based on a large amount of investment costs for shipping companies and is in general not economically feasible without grants.

Scalability within the Port of Kristiansand

The Port of Kristiansand has a large share of calls that are connected to OPS. All ferry lines connect to OPS, as well as many cruises and offshore supply vessels. There are still terminals that have potential for OPS, such as the bulk terminal in Lindesnes or the container terminal Caledonien. The Port of Kristiansand aims on investing revenues from OPS into new OPS projects.

The replication potential to scale up remains limited by the available electricity grid connection capacity and the overall availability of electricity supply. The scalability of OPS to other terminals in Kristiansand will require investments into new grid infrastructure or new onsite electricity generation.

5.3 OPS for Ferries (Gothenburg Port)

5.3.1 Definition and Scope

Business model description	Onshore Power Supply System in High Voltage in a regular Passenger Ferry lines from Gothenburg (SE) to Kiel (DE) and Frederikshavn (DK)
Scope	2 OPS connection in 11 KV (1x 50 Hz, 1x 60 Hz) to Ro-Pax ships
Location	The Port of Gothenburg: Stena Germany Terminal, Stena Denmark Terminal
Date of Commissioning	2010
Lifetime of project	15 years
Partners	The Port of Gothenburg, Stena Line, Processkontroll Elektriska AB, ABB

5.3.2 Port Context: The Port of Gothenburg

The Port of Gothenburg has been one of the Swedish pioneer ports in the OPS domain, having built the first installation in 1989 for low voltage connections. In 2000, a high voltage station was built at the request of and in cooperation with cargo owner Stora Enso for its Ro-Ro vessels. This first high voltage OPS implementation created a growing interest for OPS in the Port and today there are several OPS connections available (see table below).

Table 5-7: Overview of OPS connections in the Port of Gothenburg
Source: Nordic Innovation[56] and the Port of Gothenburg

Location	Vessel type	Voltage	Frequency	Commissioning year
Quay 700 and 712	Ro-Ro	6.6 kV	50 Hz	2000
Stena Germany Terminal	Ro-Pax	11 kV	60 Hz	2010
Stena Denmark Terminal	Ro-Pax	11 kV	50 Hz	2010
Stena Denmark	High Speed	400 V	60 Hz	2015
Stigbergskajen	Yacht	400 V	50 Hz	1989

Future development plans
As part of the city redevelopment, a new Terminal is being built in the outskirts of Gothenburg Arendal. In addition to other port activities[57] it will host Ro-Ro and Ro-Pax ferry lines. In 2022 Stena Line and Gothenburg Port Authority signed a Memorandum of Understanding, in view of moving the ferry operator's terminals (Germany and Denmark lines) to the new location in Arendal. The main rationale behind this initiative is to support the City's plans to develop a dense mixed-use urban area along the riverbanks. Details of these plans are described in the section 5.3.8 Replicability.

In addition, the Port of Gothenburg with its partners are currently developing an innovative solution of the **OPS connection to tanker ships**, called Green Cable, in its Energy Terminal on the island of Donsö. The aim is to set a new global standard for shoreside power for tankers. The project aims to equip all three quays with OPS with investment estimated of around 3.8 MEUR, from which 1.1 MEUR is funded by a Swedish national grant. The aim is to commission the project by 2024.

5.3.3 Drivers and enablers

In the case of the Port of Gothenburg the main driver for the OPS development was environmental regulation. In 2010, the Port of Gothenburg had to agree, in the framework of its new environmental permit, to offer an OPS connection to any ship that requests it and regularly berths at the port. Upon such request, the port authority must provide an onshore power connection within one year, but as in some cases the installation can take up to 18 months to be planned and built, extensions are possible. At the same time, the port needs to investigate every five years the possibility of offering further OPS, through analyses of incoming traffic and specifics such as location of quays and hours the vessels stay at berth.

In 2010 Stena Line was also requested to renew its environmental permit. As operator of a passenger terminal in the city centre of Gothenburg, running regular Ro-Pax service between the Port of Gothenburg and Denmark and Germany, its operations were classified as environmentally hazardous.

5.3.4 Operative model of the business case

Technical solution
Two OPS connections provide onshore power in high voltage (11 kV) and 50 and 60 Hz frequency. At the berth the connections consist of a one-box solution – two OPS cranes. Two ships can be connected to the OPS system at the same time. The power required per vessel is on average 1-3 MW, which differs between summer and winter because of e.g. air conditioning used on board.

[56] On Shore Power Supply in the Nordic Region Report, Nordic Innovation, 2021; available at: https://pub.nordicinnovation.org/On-Shore-Power-Supply-in-the-Nordic-Region/Appendix-v-short-summary-of-on-shore-power-ops-in-sweden.html

[57] By port activities, we refer to the related port (terminal) activities of loading & unloading ships or cargo handling (and or passenger handling) and the required machinery like reach stackers, cranes, forklifts, yard tractors, trucks, and other machinery.

For the route Gothenburg – Frederikshavn (Denmark) a connection with 50 Hz frequency is used. It serves several vessels per day (usually 6 in the summer at high season and 4 in low season). The ships stay at berth between 2 – 4 hours.

For the route Gothenburg – Kiel (Germany) a connection with 60 Hz frequency convertor was developed as the ship used for this route, Stena Germanica, operates on 60 Hz. There is one ship per day that stays 12 hours connected at berth.

Contractual characteristics
The investment, as well as the operation and maintenance, of the OPS connections are carried out by the Stena Line, that also owns the installation. At its terminals only ships of Stena Line berth. The concession contract is usually tendered for 10 years. Hence, in this case, the Port of Gothenburg is not involved in the OPS operations, the contracts or in selling electricity (in Sweden it is by law prohibited for end-users to resell electricity taken off from the grid). The port acts as a landlord and rents the terminal to the company on a long-term basis. Stena Line has a direct supply contract with the electricity provider. Regarding the low voltage connections, the port has a contract with the electricity provider and sells the electricity to the ships without a profit margin. According to the Swedish law electricity used for OPS is subject to minimal taxation rates.

5.3.5 Implementation

As gathered in the interviews, the port authority assesses each possibility for an OPS connection individually and so far only in close cooperation with Stena Line, the terminal's tenant. Although it seems the very first connections were made more to provide for those who might request it (to anticipate the requirement in the port's environmental permit and test the technology) and without necessarily having long-term demand form shippers.

In 2010, in order to renew its permit, Stena Line had to choose between producing its own electricity using alternative high-grade fuels or using shoreside electricity. After discussion with the port authority, Stena Line decided to take over one OPS connection from the port and cooperated with it to install further OPS connections for its regular ferry lines. Once the technical studies had been completed, during a procurement process two technical subcontractors were selected. Planning and design efforts commenced in June 2010 and the special frequency converters, which were required in order to not put electricity grids under pressure, were ordered from a factory in New Zealand.[58] The first ships were connected to the OPS in the beginning of 2011.

5.3.6 Impact analysis

Impact on port's/terminal's operation and integration
The project implementation had no major impact on the port operations; a continuous traffic of passengers was possible. The representatives of the port and shipping companies mentioned benefits from the OPS that relate to comfort (no noise or vibrations) for working personnel and for people living in vicinity to the berth (the terminal is located in the city centre).

Impact on sustainability
The main impact of the OPS installations was a reduction of CO_2 emissions directly at the source. The auxiliary engines are switched off while the ship is supplied with onshore power from the grid. With this switch a 90% reduction in CO_2 emissions has been claimed by the port authority when disregarding the time of connection at berth. Similarly, the OPS allowed to reduce pollutants such as NOx, SOx, PM, and hence improved the integration of the port in the urban area.

As neither the Port of Gothenburg nor Stena Line report yet on the GHG and other emissions savings on these particular routes, the impact of the OPS system on sustainability has been calculated as part of the cost-benefit analyses using data from the interviews where possible, AIS study and DNV's own assumptions[59] We estimate a total

[58] Environmental Gains at port of Gothenburg, a case study, ABB, 2011

[59] For detailed explanations on the CBA please see 5.3.7

annual consumption of nearly 4,000 tonnes of diesel fuel at berth when not connected to OPS with significant local environmental consequences. The OPS prevents the emission of almost 12,000 tonnes of CO_2 per year, the results are presented in the table below.[60]

Table 5-8: CO_2 emissions savings from OPS in the regular Ro-Pax service in Gothenburg Port
Source: DNV calculations

Route To/From	Number of Port calls per year	Hours per port call	Avg aux power [kW]	Energy demand at berth [MWh/year]	Average fuel consumed at berth [tonnes/year]	CO_2 emitted at berth [tonnes/year]
DE	365	11	7,768	10,292	2,058	6,599
DK	2,000	2	6,117	8,074	1,615	5,177
Total				18,366	3,673	11,776

As regards to NOx, SOx, PM pollutants similar assumptions were applied. These calculations are based on the cost-benefit analyses. The emission savings are shown in the table below.

Table 5-9: Emission savings from OPS in the regular Ro-Pax service in Gothenburg
Source: DNV calculations

NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
155	24	4

Impact on electrification

Since all ships from both companies during their calls in the Port connect to onshore power, the degree of electrification is more than 90%, discounting time needed for connection and disconnection and unusual traffic between the berths when ships sometimes waiting for a spot.

Impact on energy management

The overall electricity demand for the OPS connections in the port is around 18 GWh per year all supplied with grid electricity.

5.3.7 Costs and benefits analysis - results

The OPS based business case has a total investment cost of 12 MEUR, consisting of 10 MEUR for the vessels and 2 MEUR for the OPS infrastructure in the port. The operational costs are 1.5 MEUR per year, including the electricity offtake from the grid (1.4 MEUR/year in the medium scenario) and maintenance (0.1 MEUR/year). The pollution costs related to the electricity grid offtake are 0.1 MEUR/year, including the emission costs for CO_2 (well-to-wake), NOx, PM and SO_2.

The reference case (counterfactual) is based on the use of fossil fuelled auxiliary engines has no investment cost as this is BaU for the port and auxiliary engines are already on the ships. The operational costs of 2 MEUR include maintenance and fuel consumption, while the pollution costs are estimated at 4 MEUR/year. Table 5-10 provides the initial investment

[60] The ships from both the Stena Line ferry routes to Denmark and to Germany make more than 2,555 calls per year, including berth to berth transfers. The number of actual regular calls is estimated at 2,365. These stops can last up to 4 hours for the Denmark route and up to 12 hours for the Germany route, from which it is necessary to subtract the time necessary for (dis)connections and berth to berth traffic.

costs and the annual operating costs for the OPS case and the BaU case. In Figure 5-5 the annual cost breakdown is shown.

Table 5-10: Total annual costs for OPS case and BaU.

	OPS case in MEUR	OPS case including ship investments	BaU case in MEUR
Initial investment	2	12	0
Annual operating cost	1.5	1.5	2.0
Annual pollution costs	0.1	0.1	4.0
Total annual costs including depreciation costs	1.7	2.6	6.0

In the medium scenario, the OPS business case requires a higher investment but has lower annual costs (including pollution). The OPS business case has overall lower annual costs than the BaU case. Onboard ship investments for the OPS connection are significant but are not incurred by the ports themselves and do not affect the ports as emissions do, nevertheless a cost breakdown including these investments is also provided for informational reasons. In this case the annual costs of the OPS business case increase by approximately 55%. Figure 5-5 shows the annual cost breakdown for the OPS cases and the BaU case.

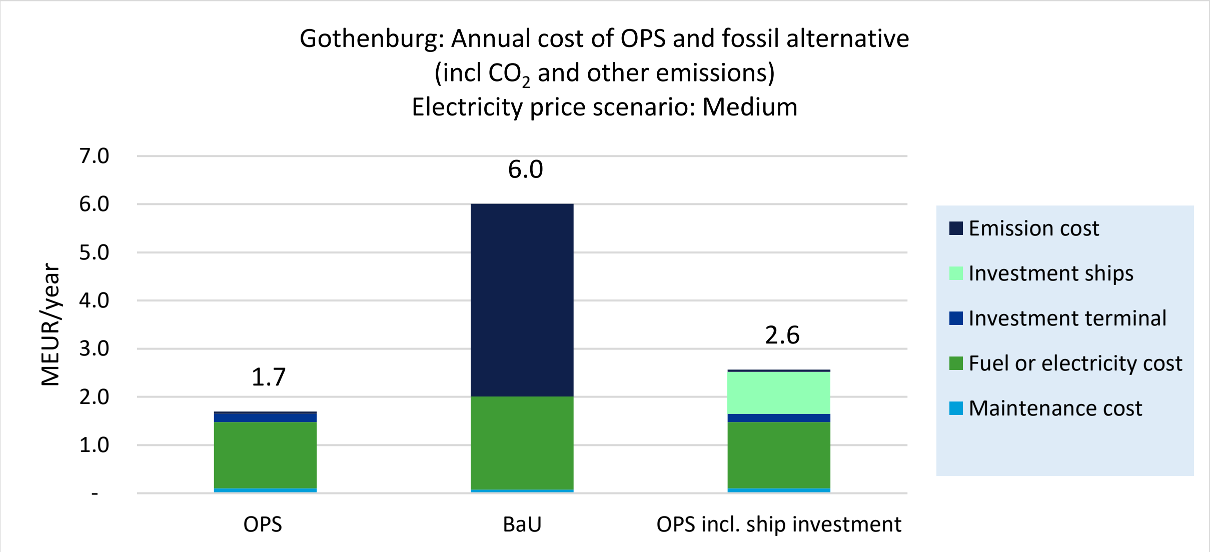


Figure 5-5: Gothenburg Port: Annual cost of OPS and fossil fuel alternative.

Sensitivity analysis

In the OPS business case, changes in the variable CAPEX have a moderate sensitivity and lead to a narrow spread in the annual costs, a 20% increase or decrease leads to a 3.2% increase or decrease in annual costs. In the BaU business case changes in CAPEX have no impact because investments for ships are considered pre-existing. Changes in the electricity price show the highest sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 10.7%. In the specific OPS case, the CO_2 price has low influence as green grid electricity with low-carbon intensity is used.

In the BaU case, the CO_2 price does have an impact on the annual costs, as the bunker fuel used is emitting CO_2 which negatively impacts the BaU case. An increase or decrease of 20% of the CO_2 price leads to a 4% impact on annual costs. Furthermore, for the BaU case the bunker fuel price has the highest sensitivity, with the widest spread in annual costs (6.4% impact on annual costs). Even in the case of high CAPEX and high electricity price the OPS business case leads to lower annual costs than the most favourable BaU case (low bunker fuel price, low CO_2 price). An overview of the sensitivities is provided in Table 5-11. Furthermore, the tornado charts are provided in Figure 5-6.

Table 5-11: Overview sensitivities with min-max value and impact on annual cost.

Parameter	Min-max Value	Impact on annualised cost
CAPEX CEBM	1.6 – 2.4 (MEUR)	Moderate sensitivity: 3.2%
CAPEX BaU	-	No sensitivity
CO2 price	66.9 – 100.4 (EUR/ton)	Low sensitivity CEBM 0.3%, moderate BaU: 4%
Electricity price (CEBM OPS)	30.8 – 46.2 (EUR/MWh)	High sensitivity: 10.7.0%
Bunker fuel price (BaU)	421.7 – 632.5 (EUR/ton)	Moderate sensitivity: 6.4%

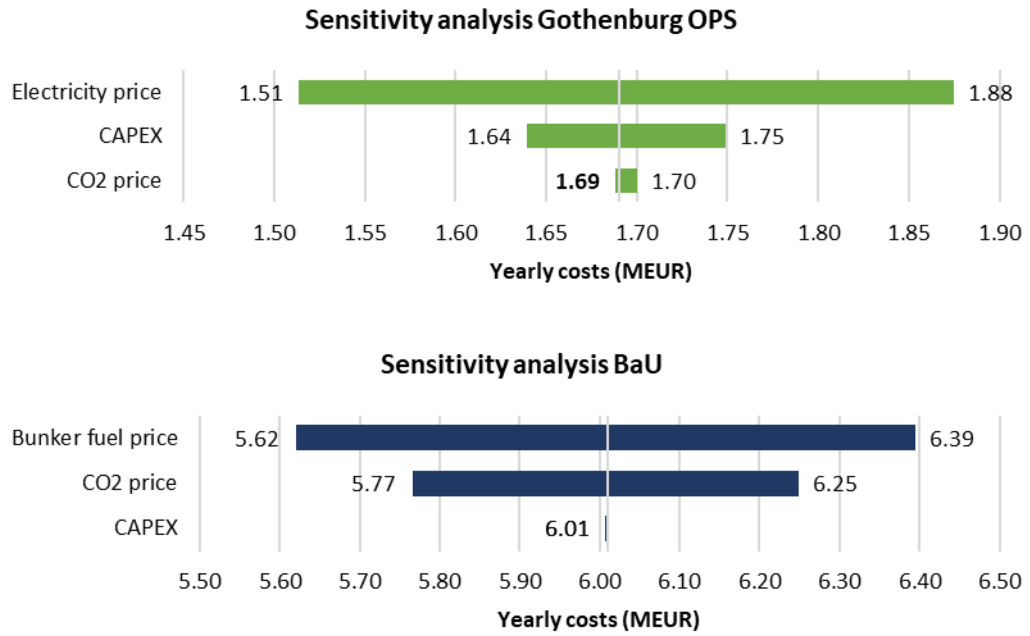


Figure 5-6: Gothenburg: Sensitivity analysis tornado charts OPS.

5.3.8 Replicability

The OPS concept as implemented in the Port of Gothenburg is replicable mainly in ports that have regular ferry lines and where the shipping company acts as terminal operator. In the Port of Gothenburg, the port authority is not responsible for designing, building, maintaining and operating the systems, but only agrees to the use of the land. As the port does also not act as electricity supplier; this approach can be replicated in ports where strict regulations on electricity resale apply.

Scalability potential in the Port of Gothenburg

Currently Stena Line and the Port of Gothenburg are cooperating on the development of a new terminal. Even though the lease agreements for the terminals used for the Denmark and Germany lines by Stena Line have been extended until 2035, the parties have agreed on an earlier termination because of the City's decision to redevelop the area.

A **new Terminal** is being built in the outskirts of Gothenburg Arendal. Besides other port activities and Stena Line's Ro-Pax lines, it will also host a Ro-Ro terminal. Stena Line will have two berth spots with the possibility to connect two ships at the same time, one for each route. The terminal will have several connection points because of the different lengths of ships and connection systems. The capacity of the OPS will be 6 – 6.5 MW per vessel to be able to act as charging station for all electric vessels) or the current 2 - 2.5 MW (as an alternative for auxiliary engines). It is a completely new terminal. None of the current infrastructure components can be reused (they are more than 20 years old) or scaled up (being more than 10 km away, on the other side of the seaway). The Port of Gothenburg is as landowner responsible for all land preparations such as berth building, grid connections and general civil works, while Stena Line is responsible as investor and operator of the terminal for developing OPS connections, including substations, frequency converter, cabling from the grid and to the OPS cranes (connection shore to ship).

The main challenges in the development are funding and the short timeline, as the operations should move to the new location by 2027. Regarding costs, each connection is estimated to require a total capital investment of up to 3 MEUR on the port side. The frequency converter is in particular expensive. The availability of a suitable electricity grid connection in the area and the overall electricity system adequacy are also becoming a major challenge, because of other developments in the area (e.g., Volvo battery factory).

5.4 RTG Electrification (Valencia Port)

5.4.1 Description and Scope

Business model description	Electrification of RTG (Rubber Tyred Gantry) cranes at the Container Terminal
Scope	Switching from diesel fuelled to electric RTG cranes - both retrofitted from diesel cranes (15) and new (18) electric cranes.
Location	MSC Terminal Valencia (MSCTV) Container Terminal
Vessel type	Container ships
Date of Commissioning	2016
Partners	MSCTV, the Port of Valencia

Since 2016, the MSC Terminal Valencia (MSCTV) has converted the fleet of RTG (Rubber Tyred Gantry) cranes from diesel to electric driven as well as acquired new e-RTGs.

The electrification of RTG cranes included the installation of a busbar system that consists of 6 km of electric rails. The terminal is composed of 22 blocks, of which 18 are electrified.

The business model is well established in the Port of Valencia and the MSCTV and has shown good results in terms of CO_2 emissions reduction and operational costs with the main advantages coming from a more efficient system.

5.4.2 Port Context: The Port of Valencia

As mentioned in Chapter 3 Clean Energy ports, the port of Valencia is a major container port in Europe. MSC is operating the Container Terminal MSCTV, which has a surface area of 337,000 m^2 including warehouse and administration buildings. The terminal is equipped with 8 STS (Ship to Shore) cranes, 25 RTG (Rubber Tyred Gantry) cranes, 53 terminal tractors, 7 reach stackers, and 600 electricity connection points for refrigerated containers (Reefers).

MSCTV handles yearly over 1.6 million TEU and has a capacity to handle up to 2 million TEU. The terminal has yearly over 2,500 calls, and a capability to handle ships up to 20,000 TEU.

The terminal operator has electrified its RTGs and is running a pilot project to convert its reach stackers to hydrogen driven. MSCTV also plans to install solar panels. To further electrify the terminal, the terminal operator is looking into offering OPS connection to the ships at berth, which will require a large investment in the grid connection and additional power supply.

MSC will move the terminal to an area north of the current Port of Valencia that is four times as large as the current terminal. This move is scheduled by 2029.

5.4.3 Operative model of the business case

The terminal consists of 22 sections with a capacity of 11,000 TEU each (called blocks). 18 of these blocks are equipped for electric RTGs (e-RTGs). The infrastructure includes 6 km busbar system in the terminal divided into 10 crossed lane sections between the blocks. The busbar system provides electricity to the e-RTGs which are always connected to the power source while moving in the lanes of the blocks. One busbar can provide electricity to two blocks. Each of the10 busbar systems is connected to one substation of 1.25 MW capacity each. These 10 substations are all connected to the original 10 MW connection to the grid outside the terminal.

The e-RTGs are connected to the busbar through a connection in L-shape, called L-arm, from where it gets its propulsion lifting power. In normal lifting operation, the e-RTG is always connected to the busbar. It can disconnect and move between blocks by using a battery to drive between busbars.

Conventional RTGs use diesel motors to power the electric machinery of the crane. When retrofitting, this motor is exchanged with a connection to the busbar and makes the conversion to an e-RTG possible without major changes to the crane.

Another capability of e-RTGs is regeneration. As shown in Figure 5-7, the energy from letting down a container with a e-RTG can be regenerated and used in lifting with another e-RTG connected to the busbar. To absorb the excess energy produced during the lowering of containers, an energy storage system can be attached to the system, which is not the case in Valencia yet.

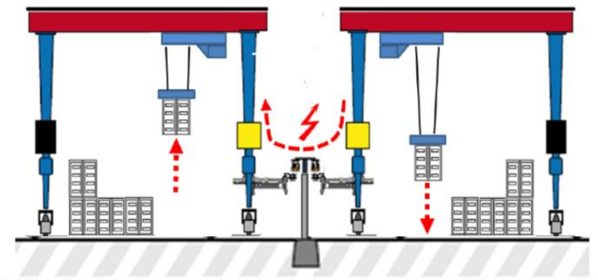


Figure 5-7: Regeneration of power in e-RTGs.

5.4.4 Drivers and enablers

The electrification of RTGs is included in the main Port's Strategy regarding shipping, port handling machinery, ports' works and buildings decarbonisation.

The main drivers behind the transition to electrical RTGs in the MSCTV terminal are:

- improved efficiency through reduced maintenance and energy cost savings,

- environmental considerations by contributing to reducing CO_2 emissions and better working environment.

The main enablers of the project are the close cooperation between the operational, maintenance, and infrastructure teams within the MSCTV terminal, and their position as a long-term tenant of the terminal. This provides an efficient and predictable project development. Additionally, all major electricity infrastructure was in place and there was no need for a major grid reinforcement.

5.4.5 Impact analysis

Impact on port's operations and integration

The electrification allowed an increased efficiency by having more running hours of the RTGs resulting in lower maintenance cost per running hour. Electric RTGs require less hydraulics repairs compared to diesel RTGs and have a leaner machinery, which leads to savings in replacement costs. Additionally, e-RTGs have a higher energy efficiency compared to diesel where fuel is partly converted to heat while e-RTGs have an energy recovery potential.

The construction of the busbar system requires a lot of civil work and the operation of the affected blocks (11,000 TEU capacity) to be paused for 3 months. The electrification significantly reduces the noise levels and the pollution to the environment around the port. This leads to better working conditions for the port personnel and improves the ambient environment in Valencia.

Economic benefits

As learned from the interview with MSCTV the electrification has reduced the maintenance costs by 50% and fuel costs by 60%. Overall, it has been a very successful project for the MSCTV terminal. It has also helped extend the validity of the terminal licence and acquire knowledge for a planned new large container terminal north of the Port of Valencia.

Sustainability

The electrification of 18 RTGs in the container terminal has allowed 2,000 tonnes savings of CO_2 (20% of the total CO_2 emissions of the terminal) per year (2018). The implementation of the RTG systems led to a reduction of 65% of CO_2 emissions from 2017 to 2022. By switching to e-RTGs, particulate matter from exhaust gases, local greenhouse gases and pollution emissions were eliminated.

In the table below the emission savings are expressed in tonnes per year with the calculations based on the cost-benefit analyses (see 5.4.7) for 17 retrofitted RTGs and 11 new e-RTGs.

CO_2 [tonnes/year]	NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
4,939	10	2	0

Degree of electrification

The electricity consumption of the system was around 2,300 MWh in 2022; it varies every year depending on the container traffic. The total electricity consumption of the terminal increased gradually with more RTGs being retrofitted or by acquiring electric ones. After the implementation, a 12% increase of the terminal electricity consumption has been observed. The increase in the terminal total electricity consumption as shown in the table below, is even larger (6,000 MWh) as it includes other electrification projects of the terminal and because the traffic grew substantially since 2015.

About 80% of the RTGs have been electrified. The remaining diesel engines are only used to transfer the RTG from one container lane to another or from the container lane to the maintenance area and during normal operation they remain switched off.

The electrification of the RTGs required the installation of 10 new substations within the terminal, but it did not require an increase of the available 10 MW capacity from the regional grid.

Currently, there are constraints on the electricity grid and there is no spare capacity left for further large-scale electrification of the terminal, or for increasing the Reefer (Refrigerated containers) capacity in the port, without increasing the grid capacity connection or installing local electricity production.

Table 5-12: Electricity consumption

	Before implementation (2015)	After implementation (2022)
Terminal's Total Electricity consumption	13,500 MWh	19,500 MWh
Electric RTGs' electricity consumption	0 MWh	2,300 MWh

Energy efficiency

RTGs represent more than 50% of the total fuel consumption at a typical container terminal. The implementation led to the replacement of diesel fuel, by electricity supplied from the grid. In addition, the busbar enables the recovery of electricity in lifting operations, as described in 5.4.3.

The electrical RTGs have a relatively low share in the total electricity use of the terminal (12%). The electricity use varies depending on the workload and it is, to a small degree, possible to shift the load during the day without affecting the port operations. The power demand is to some extent smoothed out by the non-simultaneous use of the different cranes and the recovery of energy from putting down containers.

With more efficient and performant battery technology, it is possible to use battery e-RTG rather than a busbar system as combination of electric and battery could be useful to reduce peak electricity demand. The installation of a busbar required a lot of civil work and affects the port operations. The implementation of battery driven e-RTGs is dependent on the investment cost of the technology and the battery performance.

5.4.6 Implementation

Before deciding on electrifying the RTG fleet, Valencia Port has visited several ports that were developing similar projects, in particular in England, Turkey and Togo. The main advantage of a busbar system compared to cable reels is the flexibility, and at the time, the battery capacity was not sufficient for the ports operation.

The terminal operator has undertaken a comparison of different e-RTGs suppliers. The supplier of the busbar solution is Conductix Whamplfler, and the cranes are supplied by Konecranes. The cranes have been commissioned over a period of six years in different phases to spread the investments and to test the solutions on how to best integrate them in the overall day to day operations of the terminal.

The first investment was 3 new e-RTG cranes and by the end of 2022 the terminal had 28 operational e-RTG including retrofitted RTG's.

The stages of development included two times 3 months of civil work to install the busbar system in two rounds during 2017 and 2018. The affected terminal area had to be closed for this period and the terminal lost stacking capacity. By June 2018, 80% of the stacking area was electrified. The remaining 2 blocks that are not electrified will most probably continue to use diesel RTG because it would require too much civil work to electrify these, and they act as a flexibility tool to diversify the fuel type of the RTGs. The close cooperation between the operational, maintenance, and infrastructure teams within the MSCTV terminal has enabled a smooth integration of the new system in the terminal, with a minimal interruption of the normal operations.

To properly take into account the EU Green Deal and Fit for 55, the port authority has reviewed its investment strategy to avoid wrong investment decisions. The investment strategy for electrification of e-RTGs was considered to be in line with the policy objectives.

The payback period of the investment was calculated to be 12 years and has shown to be 7 years after the implementation. MSC has a long-term contract with the port authority in Valencia to operate the MSCTV. This enables the operator to take long term investment decisions. The electrification of the terminal has helped extend MSC's operation contract in the port.

5.4.7 Costs and benefits analysis - results

In this Section the costs and benefits of e-RTG in the Valencia Port are analysed. Table 5-13 presents the financial inputs used in the CBA.

Table 5-13: Financial inputs CBA - RTG Electrification Valencia Port

Decarbonisation of ports' operation – RTG Electrification Port of Valencia		
Financial input	**e-RTG**	**Diesel RTG**
Investment cost new e-RTG (MEUR per unit)	1.79	1.70
Investment cost retrofitted e-RTG (MEUR per unit)	0.13	
Investment cost e-infrastructure MEUR	3.3	
Maintenance costs e-RTG (EUR/ operational hour)	19.4	40.9
Diesel price (EUR/L)	0.91	

The CBA analysis is based on the current fuel type and fuel prices. For the electricity price, the reference year 2023 is used. In 2023 the average wholesale day-ahead market price in Spain was 87.1 EUR/MWh. This average day-ahead wholesale market price is taken as the medium scenario. For other general assumptions on prices and electricity mixes used please refer to Appendix D.

The decarbonisation business case (e-RTG) has a total investment cost of 54.1 MEUR, consisting of 50.8 MEUR for the equipment and 3.3 MEUR for the electricity infrastructure. The operational costs include the electricity cost from the grid (0.4 MEUR/year in medium scenario) and maintenance (2.2 MEUR/year). The external costs for the electricity grid offtake include costs for CO_2 emissions (well-to-wake), NO_x, PM and SO_2.

The fossil fuel-based BaU has a total investment cost of 47.6 MEUR (solely bases on diesel RTG replacement). The operational costs include the maintenance costs and fuel consumption. The external costs are estimated at 0.7 MEUR per year. Table 5-14 provides the initial investment costs and the annual operating costs for the e-RTG case and the BaU case. In Figure 5-8 the annual cost breakdown is shown below.

Table 5-14: Total annual costs for e-RTG case and BaU

	e-RTG case in MEUR	BaU in MEUR
Initial investment	**54.1**	**47.6**
Annual operating costs	2.6	6.2
Annual external costs	0.1	0.7
Total annual costs including depreciation costs	7.4	11.1

In the medium scenario, the electrification business case requires a slightly higher investment but has lower annual operating costs (including emissions costs). Therefore, it is a financially viable alternative.

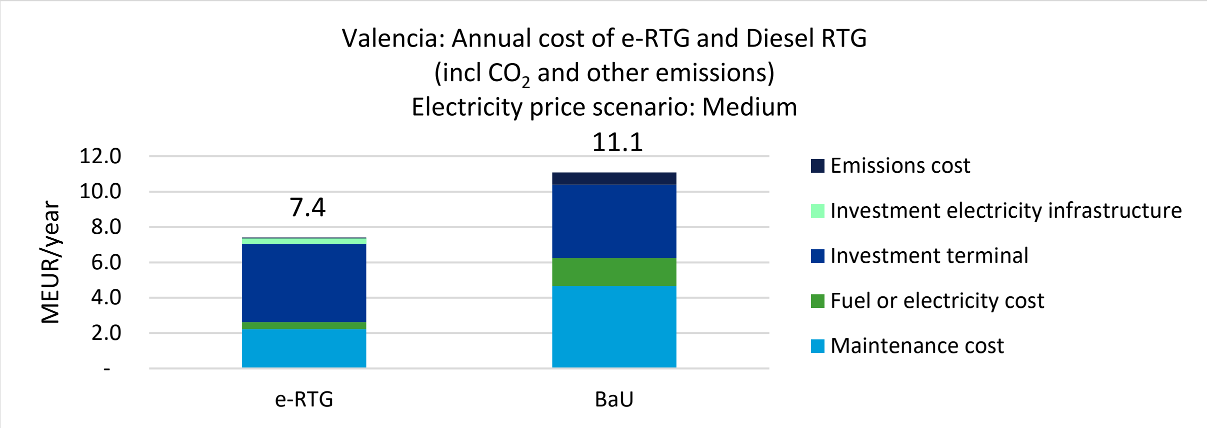


Figure 5-8: Valencia: Annual cost of e-RTG and diesel RTG

Sensitivity analysis

In the e-RTG business case, changes in the variable CAPEX have the highest sensitivity and lead to the widest spread in the annual costs, a 20% increase or decrease leads to an 8.1% increase or decrease in annual costs.

Changes in the electricity price show a low sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 0.8%.

In the specific e-RTG case, the CO_2 price has low influence due to the low share of emission costs in the total annual costs, due to relatively low-carbon intensity factor of the Spanish electricity grid.

In the BaU case, variation in CAPEX have the highest impact, a 20% increase or decrease leads to a 7.5% increase or decrease in annual costs. The CO_2 price has a low impact on the annual costs, an increase or decrease of 20% of the CO_2 price leads to a 0.9% impact on annual costs. Furthermore, for the BaU case the fuel price has a moderate impact on the annual cost, showing an increase or decrease of 2.8% on annual costs.

Even in the case of high CAPEX and high electricity price the e-RTG business case leads to lower annual costs than the most favourable BaU case (low CAPEX, low fuel price). An overview of the sensitivities is provided in Table 5-15. Furthermore, the tornado charts are provided in Figure 5-9.

Table 5-15: Overview sensitivities with min-max value and impact on annual cost.

Parameter	Min-max Value	Impact on annualised cost
CAPEX CEBM	43.3 – 65.0 (MEUR)	Significant sensitivity: 8.1%
CAPEX BaU	38.1 – 57.1 (MEUR)	Significant sensitivity: 7.5%
CO_2 price	66.9 – 100.4 (EUR/ton)	Low sensitivity CEBM 0.1%, and BaU: 0.9%
Electricity price (CEBM e-RTG)	69.7 – 104.5 (EUR/MWh)	Low sensitivity: 0.8%
Fuel price (BaU)	0.7 – 1.1 (EUR/l)	Moderate sensitivity: 2.8%

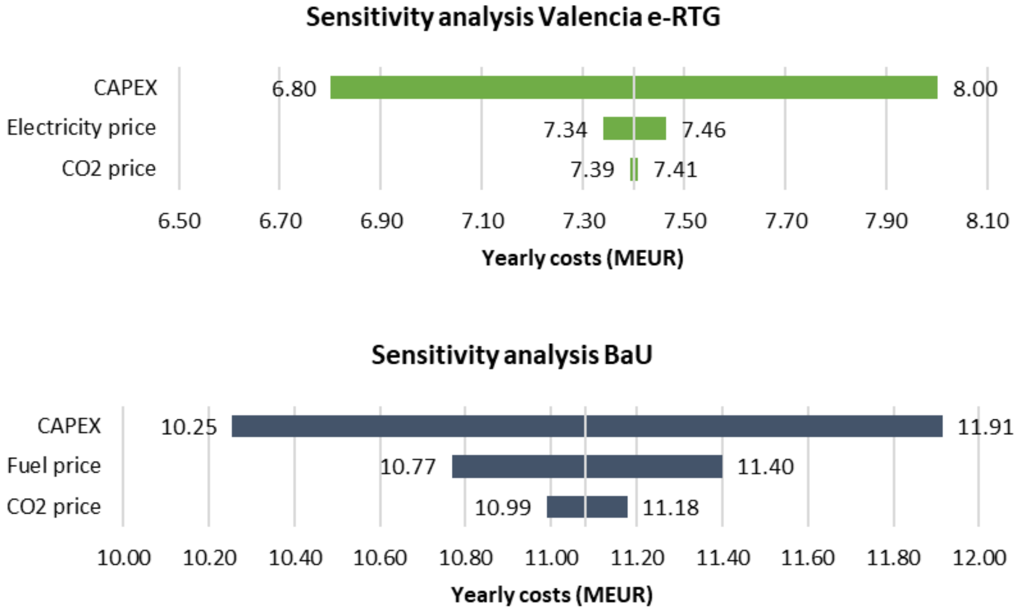


Figure 5-9: Valencia: Sensitivity analysis tornado charts e-RTG.

5.4.8 Replicability

The e-RTG technology is easily replicable to other ports in Europe. The business case did not prove to have specific issues that would hamper its replicability, provided that an adequate and reliable electricity supply can be ensured. If not, capacity upgrades which can be time consuming and costly would be required. The alternative technology of battery driven e-RTG would today represent a more mature solution than in 2016 when MSCTV took the investment decision. Battery e-RTGs as explained above would offer more flexible operation and require less civil work for the implementation than e-RTGs connected to a busbar system. This would therefore also reduce the time the terminal cannot operate at full capacity.

Scalability within the port

MSCTV currently has plans to build a new terminal north of the existing one, approximately four times larger than the existing one. For this new terminal, the port will continue using e-RTGs. The higher degree of electrification, and the increased terminal size will require a larger electricity supply. The lack of sufficient electricity grid capacity for the new terminal will necessitate a reinforcement of the electricity grid. Potentially a new PPA for electricity supply will also be required.

5.5 Production and use of H_2 for terminal equipment with onsite produced RES electricity

5.5.1 Description and Scope

Business model description	Replacement of horizontal and yard transport equipment – from diesel-powered to H2 reach stackers with H2 production onsite and RES self-generation (solar and wind)
Scope	Hydrogen production facility / Terminal machinery
Location	The MSCTC Terminal Valencia: container ships up more than 20,000 TEU capacity
Date of Commissioning	2023 pilot project of one reach stacker and mobile H_2 refuelling station
Lifetime of project:	12 years
Partners	MSCTV, the Port of Valencia, Fundación Valencia port, Hyster

The Port of Valencia is testing a prototype of one reach stacker powered with hydrogen and a mobile refuelling station at their MSCTV Container Terminal. The hydrogen is imported. It is located at the MSCTV Container Terminal operated by MSC. The objectives of the project are to test and validate hydrogen-powered solutions in the terminal operations for the port and for the maritime industry in general, with the aim of having applicable and real emission free solutions without affecting port operations.

The presented business model takes the situation further by analysing the complete replacement of the entire fleet of machinery and the construction of a hydrogen production facility with generation of renewable electricity onsite. It builds on the previous similar work done by the Port of Valencia known as H_2Ports[61] and to those authors we are grateful for cooperation, here with DNV's own assumptions and assessment. Because of the model being in testing phase, the implementation is not covered.

5.5.2 Port Context: The Port of Valencia

The port/terminal context is described in section 5.4.2.

5.5.3 Operative model of the business case

Reach stackers are an important component of the operative model of the port terminal as described in section 5.4.3 and in 5.4.4. Together with yard tractors they are part of the main equipment that moves containers within the terminal, especially within the yard subsystem to the loading/unloading subsystem.

In the traditional terminal operative model, the equipment including RTGs, terminal yard tractors, reach stackers and most of the rest of cranes and vehicles runs on diesel fuel. It usually involves the storage and dispenser at the terminal from which the fuel supply is taken when needed. To switch the machinery to hydrogen-fuelled, a more complex solution is needed, either for using imported or locally produced hydrogen.

The use case considers a Container Terminal with a stable energy demand during the lifetime of the project, managing a total of 1,400,000 TEUs, being 350,000 as import, 350,000 as export and 700,000 as transhipment. While yard

[61] This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (Euorope's Horizon 2020, Hydrogen Europe and Hydrogen Europe Research). The project consortium was composed by: Fundacion de la Comunidad Valenciana para la Investigación, Promoción y Estudios Comerciales de Valenciaport, Ballard Power Systems Europe AS, Autoridad Portuaria de Valencia, Centro Nacional de Experimentación de Tecnologías de Hidrógeno y Pilas de Combustible, MSC Terminal Valencia, Hyster-Yale Nederland BV, Grimaldi Euromed SPA, ATENA SCARL – Distretto Alta Tecnologia Energia Ambiente, Enagás SA

tractors carry most of the containers, reach stackers are used mainly to support operations. Hence, we follow the H_2Ports assumption that 10% of the containers are managed by reach stackers.

As the equipment that will use hydrogen as a fuel is mobile, it can reach a predefined area for the refuelling operations. For that reason, a fixed Hydrogen Refuelling Station (HRS) has been considered as the most adequate alternative for the refuelling. Apart of a possibility of importing hydrogen, which is a costly alternative, the business case focus on H_2 production using electrolyser Proton exchange membrane (PEM) technology is assumed, due to its more compact design, flexibility to adapt to changes of loads and simplicity of operation. Figure 5-10 shows all the elements that will be necessary at the terminal, including a containerised electrolyser, hydrogen buffer storage, containerized compressor, high pressure hydrogen storage, dispenser, and hydrogen terminal machinery.

Regarding the electricity supply for the hydrogen production facility, renewable electricity production onsite is assumed. Considering climate conditions similar to those in Valencia, the number of yearly equivalent hours of production are estimated at 1,500 hours for wind energy. Since the required supply from wind energy is equal to 2.28 GWh/year, the total wind power capacity to be installed is 1.53 MWp. Regarding the solar PV system, the number of yearly equivalent hours is estimated at 1,800 h, thus leading to a total capacity requirement of 1.27 MWp. The costs of such installation are highly dependent on the type of system selected, even though a conservative ratio of 1,200 EUR/kWp for wind energy and 2,000 EUR/kWp for solar PV can be considered as reasonable, leading to a total investment amount of approximately 4.4 MEUR.

The reach stackers themselves are vehicles in testing phase running on fuel cell system. Fuel cell cars are powered by compressed hydrogen that feeds into an onboard fuel cell stack that doesn't burn the gas, but instead transforms the fuel's chemical energy into electrical energy. This electricity then powers the vehicle`s electric motors.

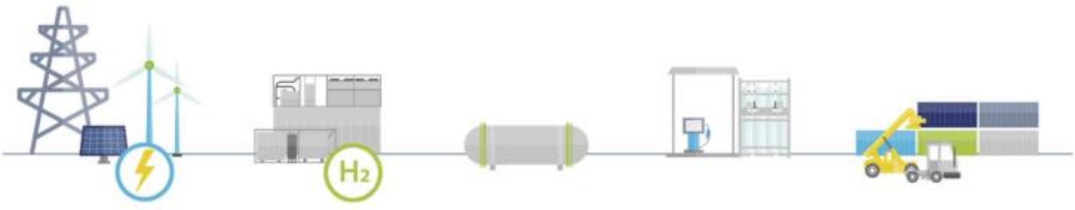


Figure 5-10: Hydrogen supply model
Source: H_2Ports

5.5.4 Drivers and enablers

The Port Authority of Valencia has set its goal of evolving to a zero net emissions port by 2030.The strategy is driven by the Spanish Government's commitment to achieve 100% electrification of the ports by 2030 (National Energy and Climate Plan for 2021 – 2030)[62] as well to align its approach with the European Green Deal which states that *"transport must be infinitely cleaner"*, highlighting the urgent need to reduce GHG emissions from the maritime transport sector.

The main objectives of the Strategy include[63]:

- Promoting the decarbonisation of the Spanish port system, including the incorporation of the circular economy in port construction projects and port operations.
- Fostering the digital transformation of the Spanish port system.

The Strategy is articulated around six blocks (renewable energy generation; H_2 production; intelligent energy and traffic systems; decarbonisation of handling machinery and buildings; hydrogen-based technologies for road transport) of

[62] Spain's integrated National Energy and Climate Plan for 2021-2030. The National Energy and Climate (NECP) Plan is a ten-year integrated document mandated by the European Union to each of its member states in order for the EU to meet its overall greenhouse gases emissions targets.

[63] Strategy towards Zero Emissions by 2030, Port Authority of Valencia, 2021

interventions on the value chain of the port sector. The necessary initiatives are framed as enablers to zero emissions (furthermore also to reduce PM and other pollutants harmful to health).

5.5.5 Impact analysis

Impact on port's/terminal's operation and integration

The impact on the terminal's operation is likely an increase in productivity resulting from less maintenance costs, time and lower energy costs as well as an increased comfort by reducing the noise, vibrations and local emissions to the working staff. By generating its own renewable electricity, the port would also become less dependent on electricity supply and fluctuating electricity market prices.

Impact on sustainability

This case results in a 100% local reduction in CO_2 emissions. As (80% of the electricity needs is covered by locally produced renewable electricity and 20% by electricity supplied via the grid with RES guarantee of origin certificates. Similarly, the H_2 reach stackers would avoid pollutant emissions such as NOx, SOx, PM. In the table below the emission savings are expressed in tonnes per year with the calculations based on the cost-benefit analysis (see 5.5.6).

CO_2 [tonnes/year]	NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
1.8	3.6	1.0	0.1

Impact on electrification

Before the project implementation the overall electricity consumption of the terminal is around 19.5 GWh; after the commissioning of the H_2 production installation with an operating fleet of 10 reach stackers the consumption will grow to 25 GWh per year, about 1 GWh would be taken off from the grid.

To evaluate the impact of this business case on electrification, we assess how much of the road-like driving equipment of the terminal, that is reach stackers and yard tractors, is electrified by the business case and what would still be running on diesel fuel. For the transport equipment of the terminal, the implementation would electrify 30% of the operations and decrease the diesel consumption by 560,000 litres, as only yard tractors would run on diesel.

Area	Before implementation	After implementation
MSCTV Total electricity consumption per year	19.5 GWh	25.2 GWh
Electrification of reach stackers and tractors	0 % electrification	30 % electrification
Diesel consumption	1,773,000 litres	1,2130,000 litres

Impact on energy management

The increased electrification of the terminal's operation would mainly (80%) be supplied by renewable electricity generated onsite, mainly offshore wind energy and solar PV.

5.5.6 Costs and benefits analysis - results

The decarbonisation business case (H_2 reach stackers) requires investments of 5 MEUR for the equipment, 1.4 MEUR for the H_2 production facility and 4.4 MEUR for the wind energy and solar PV plants. The operational costs are 1.9 MEUR/year, including the electricity offtake from the grid (1.3 MEUR/year in medium scenario) and maintenance costs of 0.6 MEUR/year. The external costs for the electricity taken off from the grid include the emission costs for CO_2 (well-to-wake), NO_x, PM and SO_2.

The fossil fuel-based BaU case has a total investment cost of 3.5 MEUR, which only includes the equipment (diesel reach stackers). The operational costs include maintenance and fuel consumption. The external costs are 0.2 MEUR per year. Table 5-16 provides the initial investment costs and the annual operating costs for the H_2 reach stackers and the BaU case. In the figure below the annual cost breakdown is shown. Based on the cost and price assumptions used in this study, this hydrogen-based option would not provide overall net societal benefits, contrary to most considered electrification options.

Table 5-16: Total annual costs for H_2 reach stackers case and BaU.

	H2 reach stackers case in MEUR	BaU in MEUR
Initial investment	**10.8**	**3.5**
Annual operating costs	1.9	0.9
Annual emission costs	0.02	0.2
Total annual costs including depreciation costs	2.88	1.46

In the medium scenario, the decarbonisation business case requires a higher investment and does not lead to lower annual costs (including pollution). Therefore, this decarbonisation business case is more costly than BaU.

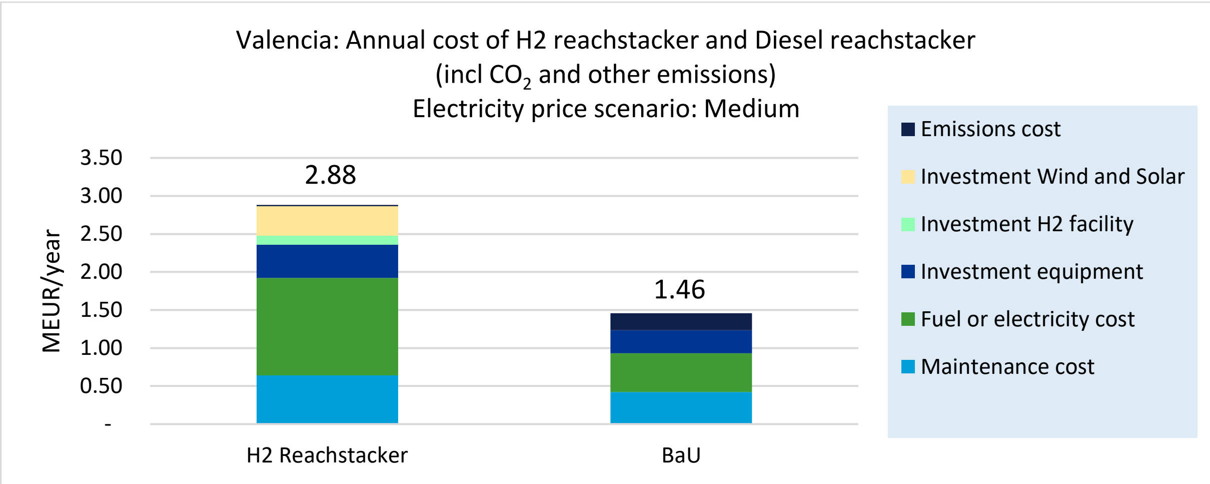


Figure 5-11: Valencia: Annual cost of H2 reach stacker and diesel reach stacker

Sensitivity analysis

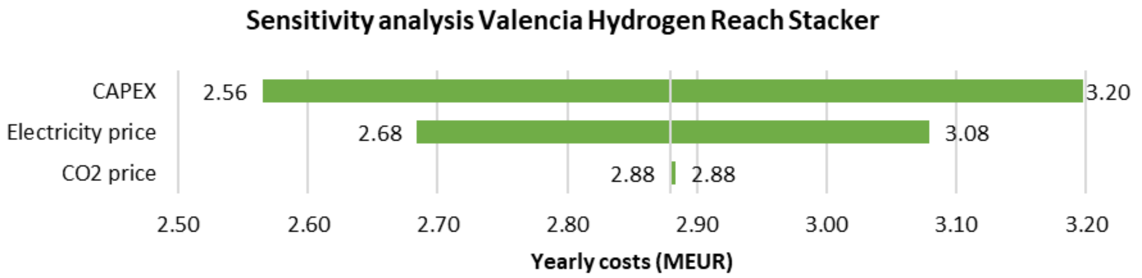
In the H_2 reach stacker business case, changes in the variable CAPEX have the highest sensitivity and lead to the widest spread in the annual costs, a 20% increase or decrease leads to a 11.0% increase or decrease in annual costs. Changes in the electricity price show a moderate sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 6.9%. In the specific H_2 reach stacker case, the CO_2 price has low influence due electricity supply coming mostly from renewable sources onsite.

In the BaU case, variation in CAPEX have the highest impact, a 20% increase or decrease leads to a 10% increase or decrease in annual costs. The CO_2 price has a moderate impact on the annual costs, an increase or decrease of 20% of the CO_2 price leads to a 2.1% impact on annual costs. Furthermore, for the BaU case the fuel price has a moderate impact on the annual cost, showing an increase or decrease of 7% on annual costs.

The cost benefit results do not change in the sensitivity analysis, under all cases of low and high sensitivities, the H_2 reach stacker business case requires higher annual costs than the BaU case. An overview of the sensitivities is provided in Table 5-17**Error! Reference source not found.**. Furthermore, the tornado charts are provided in Figure 5-12.

Table 5-17: Overview sensitivities with min-max value and impact on annual cost

Parameter	Min-max Value	Impact on annualised cost
CAPEX CEBM	8.6 – 12.9 (MEUR)	Significant sensitivity: 11.0%
CAPEX BaU	2.8 – 4.2 (MEUR)	Significant sensitivity: 10.0%
CO_2 price	66.9 – 100.4 (EUR/ton)	Low sensitivity CEBM 0.1%, moderate BaU: 2.1%
Electricity price (CEBM H_2 reach stackers)	69.7 – 104.5 (EUR/MWh)	Moderate sensitivity: 6.9%
Fuel price (BaU)	0.7 – 1.1 (EUR/l)	Moderate sensitivity: 7%



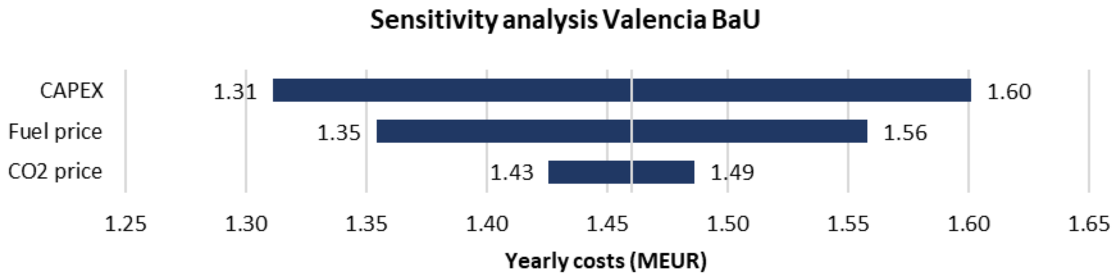


Figure 5-12: Valencia Hydrogen Reach Stacker: Sensitivity analysis.

5.5.7 Replicability

Reach stackers are a type of stacking equipment widely used in all container terminals, although they are also present in large ports` installations developing a wide variety of operations (empty container stacking, loading/unloading of containers in trains, etc.) which leaves potential upon technological maturity to be replicable in different ports.

Scalability within the port

Within the terminal the rest of the transport equipment could also be replaced by hydrogen fuel-cell systems or electricity power, one can think of yard tractors for instance, once the technology matures. Currently there are around 60 terminal yard tractors at MSCTV in Valencia used for regular operations. The replication would be less difficult if the main layout and design of the hydrogen production system already in place would have enough space for future expansion. To scale up the production of the hydrogen fuel necessary for the tractors' fleet we assume an additional capacity of around 60% throughout the entire chain would be necessary. For instance, in terms of onsite RES production additional wind turbines or solar panels would need to be installed as well as additional electrolyser capacity, storage and refuelling station(s). As an alternative, hydrogen imports could be considered once the H_2 import market develops.

Additionally, this type of equipment is also used in the Ro-Ro terminal to transport rolled cargo into vessels. In the Port of Valencia case, 10 yard tractors perform all the Roll On and Roll Off operations in the Grimaldi's Terminal Europa and have the potential to switch to hydrogen fuelled machinery. In that case the entire hydrogen operative model could be further scaled up by building additional capacity.

5.6 Renewable Electricity Production (Valencia Port)

5.6.1 Description and Scope

Business model description:	Renewable electricity production
Scope:	2 Solar PV installations, onshore wind turbines and wave energy device
Location:	Club Nautico - Principe Felipe Dock; Valencia Europa Terminal vehicle warehouse; Norther extension of the port
Date of Commissioning:	2014 - 2030
Partners:	The Port of Valencia; Pavasal - Pavener; Lantania S.A.U and Tecmo Instalaciones

Since 2016, the Port Authority of Valencia has been planning solar PV energy installations onsite for use within the port. The first PV solar power plant is located at the Principe Felipe dock and is planned to be fully operational by the end of 2023. The second plant is also currently under construction on the roof of the Valencia Terminal Europa vehicle warehouse with a foreseen installed capacity of 5.5 MW and operational date in 2024. The business case also includes onshore wind, and wave energy, both currently being assessed by the PA without having a FID yet.

5.6.2 Drivers and enablers

The main driver behind the installations of solar PV is the decarbonisation plan of the PA which envisages an emission neutral port by 2030 and possibly turning the Port of Valencia into a 100% green enclosure.

Enablers of the project are the favourable geography of the port, with a high load factor for PV throughout the year leading to a competitive electricity cost, and the available space for installations.

5.6.3 Port Context: The Port of Valencia

For the port context of Valencia, please see the previous chapters 5.4.1 and 5.4.2

5.6.4 Operative model of the business case

Solar Photovoltaic Plants

The two solar plants will generate around 11,350 MWh per year and cover 14% of the Port's current electricity consumption. Both projects are financed by the European Union's Next Generation funds and the Spanish Government's Recovery, Transformation and Resilience Plan

Club Nautico breakwater and Príncipe Felipe dock

The first solar plant is being installed on the Club Náutico breakwater and on the Príncipe Felipe dock, and uses an area of 6,420 m^2. It will have a 30% slope for optimum generation and an installed power of 1,461.6 kWp that allows to generate around 2,3 GWh/year. The project had a base tender budget of approximately 3 MEUR, including the financing cost during the construction period for the solar plant of 10 months with finalization in late 2023 and the maintenance cost for 50 months.

Europa Terminal

At Europa Terminal, operated by the Grimaldi company, rooftop installations will cover a surface area of 27,700 m^2. The infrastructure will have 10,773 photovoltaic modules installed on a metallic structure inclined at four degrees and facing south with overall installed power capacity of 5,500 kWp. The project also includes four transformers that will be installed in two transformer centres with two units of 1,250 kVA and another two of 1,600 kVA. This installation will generate around 9 GWh/year. The budget is approximately 16 MEUR, with a period for the execution of the work of 19 months and 36 months for maintenance.

Onshore Wind Turbines

Three onshore wind turbines installations will be installed in the northern part of the port with an overall installed capacity of 18 MW. Although this project is still in planning phase, the port has been working on wind energy for some time and had collected information on the available wind resource from previous measurement campaigns. The speed and direction of the wind at different heights was determined with a Light Detection and Ranging (LIDAR) by using light pulses, and the resulting recorded data was used to analyse and evaluate the viability of wind energy turbines at the Port of Valencia. The installation would generate around 38 GWh per year.

Wave Energy

The port considers the installation of a wave energy converter (WEC) designed to generate renewable electricity is another project under consideration in Valencia and last one included in this business model. The device will be located in the hammerhead of the Marina where waves flow freely. The WEC will occupy a surface area of 105 m^2 and is expected to be operational in 2023/2024. It will not affect navigation. The WEC will have a capacity of 270 kWe and would generate around 1 GWh per year.

5.6.5 Implementation

The Port Authority first developed two separate design projects of solar plants with detailed system requirements which were submitted both for financing by the European Union's Next Generation funds and the Spanish Government's Recovery, Transformation and Resilience Plan. Upon the approval of the projects, regular tender processes for construction and maintenance have been launched and were awarded to different consortium of companies (Project Club Nautico in 2022 a joint venture of PAVASAL-PAVENER and Europa Terminal to the joint venture made up of Lantania S.A.U and Tecmo Instalaciones, Obras y Servicios S.A. in 2023).

5.6.6 Impact Analysis

Impact on port's/terminal's operation and integration

The impact on the Port's operation is negligible. The construction and installation of renewable electricity production facilities does not hinder cargo and passenger handling in any substantial way. General discomfort in terms of noise and temporary site closures due to construction works are the only negative impacts. By generating renewable electricity onsite, the port will become more independent on electricity supply via the grid and the related grid fees and fluctuating market prices.

Impact on sustainability

Onsite generation of green electricity substitutes electricity that the port takes off from the grid. We calculate the impacts of this project, using Spain's electricity mix as a reference for the electricity grid. The results in terms of emission savings, are presented in the table below. The emission reductions are indicative because the calculation is based on the national Spanish emission reduction factor. The factors differ per country and location and will also change over time. Since Valencia Port currently sources 100% electricity via Certificates on guarantees of origin the market-based emissions for Valencia are already 0. This project will also serve as an enabler to facilitate new electrification projects in the port such as OPS or terminal equipment that normally would run on polluting fuels such as diesel.

CO_2 [tonnes/year]	NOx [tonnes/year]	SOx [tonnes/year]	PM [tonnes/year]
316,3	0.4	0.0	0.2

Impact on electrification

To evaluate the impact of this business case on electrification, we assess how much of the electricity use will be generated onsite compared to the base case. As seen in the table above, RES project installations could together cover more than 65 % of Port of Valencia's electricity needs if the consumption stays on the current level. In the case of 2030 consumption, if the majority of electrification projects are implemented according to the PA, including the new container terminal as described in Chapter 3, the Port will need around 300 GWh, the RES installations would cover around 17% of the estimated electricity demand.

Area	Before implementation	After implementation	
		Current	Scenario 2030
Electricity consumption port	80 GWh	80 GWh	300 GWh
Self-generated renewable electricity	0	52 GWh (65 %)	52 GWh (17%)

Impact on energy management

To optimally integrate the self-generated electricity into its system, the PA would need to install an advanced Smart Energy Management System. Solar Battery would be at the centre of such design. With a capability of monitoring the Port`s usage of electricity, the internal battery management would automatically divert the excess energy to the battery, rather than to inject it into the grid.

5.6.7 Costs and benefits analysis - results

The renewable energy business case total investment cost consists of 21.6 MEUR for wind energy, 4.9 MEUR for solar PV, 1.1 MEUR for wave energy and 0.8 MEUR for floating PV. The operational costs include offtake of grid electricity since the renewable electricity production does not cover all electricity demand in the port (external costs). The total renewable electricity capacity generates about 52 GWh per year, requiring additional grid offtake of 248 GWh/year, to cover the total electricity demand of 300 GWh per year. The external costs for the electricity taken off from the grid are 28 MEUR/year.

The BaU business case (100% grid offtake) has no investment costs and consists of offtake from the grid and external costs. Table 5-18 provides the initial investment costs and the annual operating costs for the renewable electricity production case and the BaU case. The figure below provides Figure 5-13 the annual cost breakdown.

Table 5-18: Total annual costs for renewable energy and BaU case.

	Renewable energy case in MEUR	BaU case in MEUR
Initial investment	**28.3**	-
Annual operating costs	28.1	33.8
Annual external costs	4.0	4.8
Total annual costs including depreciation costs	34.6	38.7

The renewable energy business case is financially viable compared to BaU. In the medium scenario, the difference is about 4 MEUR/year over a 20-year depreciation period.

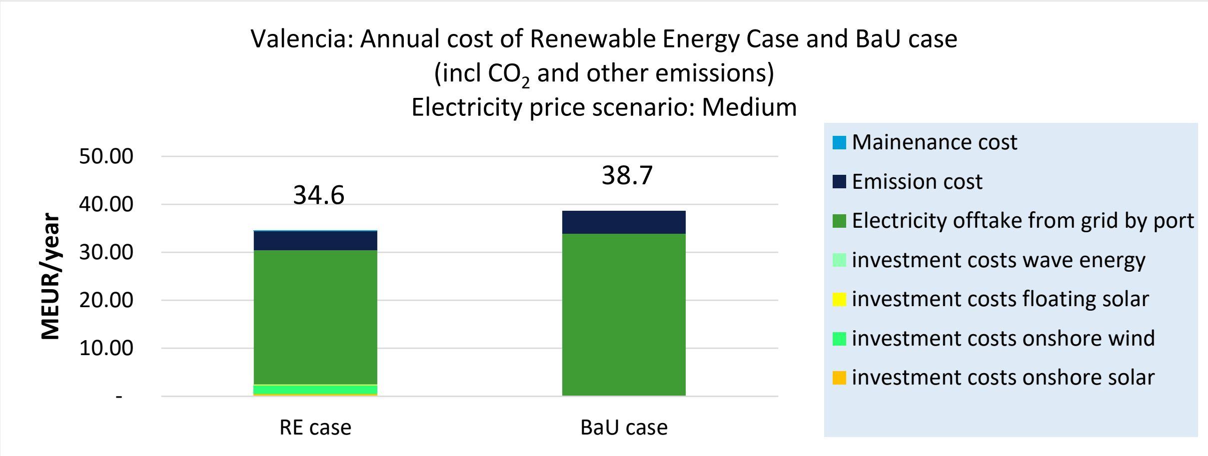


Figure 5-13: Annual cost of Renewable Energy case and BaU in Valencia.

Sensitivity analysis

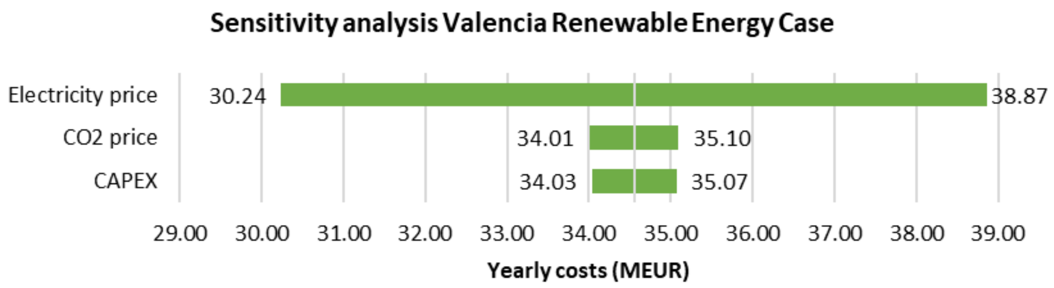
In the renewable energy business case, changes in the variable CAPEX have low impact, a 20% increase or decrease leads to a 1.5% increase or decrease in annual costs. In the BaU business case, changes in CAPEX have no impact, because investments for renewables are not taken into account, as all the electricity is consumed from the grid. Changes in the electricity price show a significant sensitivity, a 20% increase or decrease in electricity price has an equal upwards as downwards impact on the annual costs of 12.5%. This is due to the required electricity offtake from the grid, in order to supply the port electricity demand, which cannot be totally covered by its own renewable energy production. In the specific renewable energy business case, the CO_2 price has a low impact, with a 1.6% increase or decrease on annual costs, due to the carbon intensity of the Spanish electricity grid, and the combination of electricity supply from RES onsite.

In the BaU case, the CO_2 price has a moderate impact on the annual costs, as all the electricity demand from the port has to be purchased from the electricity grid. An increase or decrease of 20% of the CO_2 price leads to a 1.7% impact on annual costs. Furthermore, for the BaU case the electricity price has the highest sensitivity, with the widest spread in annual costs (13.5% impact on annual costs).

The most favourable BaU case (low electricity price), achieves lower annual costs than the max value in the sensitivity of the renewable energy business case. An overview of the sensitivities is provided in Table 5-19. Furthermore, the tornado charts are provided in Figure 5-14.

Table 5-19: Overview sensitivities with min-max value and impact on annual cost.

Parameter	Min-max Value	Impact on annualised cost
CAPEX CEBM	22.6 – 34.0 (MEUR)	Low sensitivity: 1.5%
CAPEX BaU	-	No sensitivity
CO_2 price	66.9 – 100.4 (EUR/ton)	Low sensitivity CEBM 1.6%, and BaU: 1.7%
Electricity price	69.7 – 104.5 (EUR/MWh)	Significant sensitivity CEBM 12.5% and BaU: 13.5%



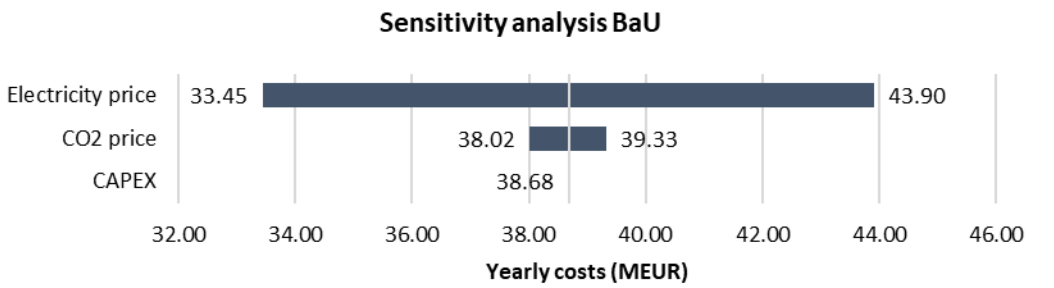


Figure 5-14: Valencia Port Renewable Electricity Generation Case: Sensitivity analysis

5.6.8 Replicability

The business model for renewable electricity installations, including solar, onshore wind, or wave energy, within a port setting is inherently influenced by a myriad of location-specific factors. While solar and onshore wind energy are matured technologies and widely applied across all regions, wave energy is relatively new and not yet implemented at large scale. The success of such installation hinges on the geographical context, prevailing weather conditions, energy infrastructure availability, and local energy consumption patterns. The symbiotic relationship between these variables underscores the different parts to consider in this model. The proximity of a port to abundant sunlight, consistent wind patterns, or reliable wave energy sources, coupled with adequate energy storage and distribution infrastructure, can create a conducive environment for cost-effective and sustainable electricity generation as shown in the analyses. The replicability of this business model in other ports is, however, conditional upon the careful assessment of these unique local dynamics.

5.7 Smart Grids

As seen in the previous business cases, ports start to install fully electrified equipment and use electricity as the main source of energy. The importance of energy efficiency and demand response management while integrating renewable energy draws more attention from many ports in our analyses. At the same time, as large-scale energy end-users, ports express interest in adopting EMS since energy prices have increased over years and sustainable operations are a key target for the industry. An improved EMS in combination with Smart Grid or Microgrid and additional tools such as battery storage are of growing interest and a number of ports in the EU are currently developing pilot projects to improve their EMS. Although most of these projects are still at early stages, which prevents us from presenting data that could be meaningfully assessed, we describe hereafter some front-runner projects in ports such as Port of Portsmouth, Port of Antwerp, Rotterdam and Port of Singapore to illustrate these developments and evaluate their replicability potential.

5.7.1 Energy Management Systems (EMS)

Energy Management Systems (EMS) in ports aim to control and optimize energy demand, energy supply, energy flows and storage at the end-user level with modern hardware and software tools such as battery storage or data-driven platforms. In these cases, the EMS becomes a Smart Energy Management System comprised of Smart Grid or Microgrids, and as such it becomes more independent from the electricity grids. Hence, its main function remains similar: to adjust the energy demand to match available energy supply considering energy prices, grid tariffs and technical constraints. Energy demand comes mainly from the equipment (e.g. cranes, yard handling equipment) during container and cargo handling, OPS for providing shoreside electrical power to ships during berthing, reefer containers for keeping them cool in the yard and other facilities. Energy can be supplied from the utility grid and onsite renewable energy sources generation (RES) such as wind energy or solar power plants. A basic illustration of a port Smart Energy Management System is shown in the figure below.

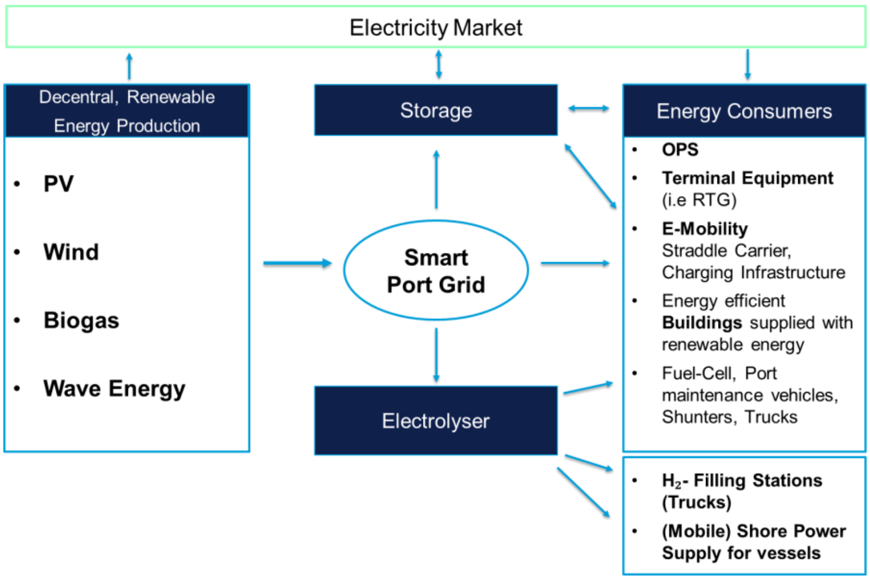


Figure 5-15: Basic illustration of energy flows in Port's Smart Energy Management System

Source: DNV, partly based on SHARC II of the Bremerhaven Port[64]

In such systems, each component has its own field device with a sensor that become nodes on communication networks and act as intelligent remote agents to operations, control and asset management centres. These devices are enabled to make localized decisions, coordinate with peers, self-monitor their own needs, monitor changing local system conditions, communicate warnings to the control centres, request operations changes and maintenance actions, and take action to protect and reconfigure the delivery grid to minimize problems and optimize reliability. Control centres also become closely integrated with the field devices. All the above requires increased operational complexity, two-way communication capability, distributed computing/intelligence, large communication infrastructure and finally large initial capital investments.

[64] **Bremerhaven; Smart Harbor-Application Renewable Integration Concept, available online at: https://sharc-project.de/en/projekt/; accessed 25.08.2023**

5.7.2 Ports of Portsmouth, Singapore and Rotterdam

Not every port is able to invest in or use all the tools from such a full-fledged system yet. That is why initially pilot projects focus on a small fraction of a port or a single terminal.

In the case of **the Port of Portsmouth** (UK)[65], the PESO pilot system, standing for "Port's Energy System Optimisation", being deployed at the International Port Terminal integrates local electricity generation, novel energy storage, and smart energy management. It aims to demonstrate how ports can meet emerging onshore power demand and the requirements of ships as they increasingly use more shore power and adopt electric propulsion while minimizing the need for expensive electricity grid upgrades and optimizing the use of variable grid tariffs and electricity commodity prices. The port has already installed a solar PV and battery system, which is now fully operational, comprising 2,660 solar panels and providing 35% of the site's electricity needs.

The project involves the implementation of a dual chemistry battery and an AI-based multi-level control system in the port's energy network, developed by Swanbarton, a specialist in energy storage and control technologies. The control system, that also includes an AI-based capability, learns from historic energy consumption profiles to ensure that the battery can deliver as much energy as possible when demand is high. The technology has been extended further by creating a predictive 'digital twin' model that can ensure the battery has storage capacity to fully utilise energy generated by onsite renewable generation or procured from the grid at times of low price.[66]

This combined capability to minimise the cost of energy needed to supply vessels with energy and to drive the port's own assets is a critical aspect of the PESO value proposition and as such it is funded by Innovate UK, the UK's innovation agency.

Energy Storage is also the main component of the Smart Grid Management System (SGMS) at the Pasir Panjang Terminal at **the Port of Singapore**, one of the largest and busiest container terminals in the world. Operated by PSA Corporation (formerly the Port of Singapore Authority), the terminal is capable of serving the world's largest container vessels.[67]

The SGMS has been in operation as a pilot project since late 2022. It aims to improve the energy efficiency of port operations by 2.5% and reduce the port's carbon footprint by 1,000 tonnes of CO_2 eq. per year.

The Energy Storage has a 2 MW installed capacity and is designed to manage peak consumption at the terminal. When a surge in energy consumption is expected, the battery supplies energy to cater to the demand, minimizing spikes in the terminal's energy off-take from the grid. During periods when the storage is not used to manage demand, it participates in the National Electricity Market of Singapore to provide ancillary services to the power grid and thus generates revenue.[68]

The project is part of a smart grid development partnership between the Energy Market Authority (EMA) of Singapore and the Port's Authority with a budget of 8 MUSD in the form of grants, that aims to transform the Port's energy usage through the use of smart grid technologies and energy management systems. As such, the partnership is part of the Acceleration Energy Storage for Singapore Program, which aims to promote the adoption of storage systems in Singapore through use cases of various business models. The program also supports EMA's target of deploying 200 MW of energy storage systems beyond 2025.[69]

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[65] Portsmouth International Port is a multipurpose port located in the United Kingdom. The port handles various types of cargo, including containers, energy cargo, and passengers.

[66] PESO Project; Portsmouth-port.co.uk; available online at: https://portsmouth-port.co.uk/news/peso-project-successfully-demonstrates-how-to-cost-effectively-decarbonise-and-improve-air-quality/; accessed 25.08.2023

[67] PSA Singapore, available online at: https://www.singaporepsa.com/our-business/port/; Accessed on 25.08.2023

[68] PSA Singapore, available online at: https://www.singaporepsa.com/2022/07/14/singapores-first-energy-storage-system-at-psas-pasir-panjang-terminal/; Accessed: 28.08.2023

[69] Ibid.

While the two previous cases build up the smart energy management systems by directly investing in infrastructure such as their internal grid and energy storage, the Distro project of **the Port of Rotterdam** departs from the existing infrastructure and builds a large marketplace in which more efficient use of energy can take place. The Distro's main objective is to avoid grid congestions and additional infrastructure buildout. As shown in Chapter 3, the PoR expects its electricity consumption to grow 3-6 times by 2050. In addition, the electricity generated by the offshore wind energy parks alone that enters the national grid at the PoR might amount to up to 50% of the total offshore wind energy generation in the Netherlands, while consumption will be mainly situated outside of Rotterdam. In such a scenario there is a need to balance and better integrate the energy system. The Distro project aims to connect renewable energy producers with local consumers via a high frequency trading platform based on blockchain technology.

This marketplace transacts in real time over a forward market, responding to external suppliers and feed-in tariffs. Every market participant in the community can benefit from more competitive prices, by consuming onsite renewable generation, dynamic demand response and optimised use of available energy storage capacity. A potential client does not need to build additional infrastructure in order to participate. It must only give access to its meter (smart meter) with a strong frequent signal. The system is designed to work alongside energy procurement agreements such as PPAs. To improve the overall cost efficiency, it uses the imbalance prices provided by TenneT (Dutch TSO), but operationally it does not interact with the TenneT system.

The project currently undergoes a small pilot phase with 30 energy off-takers within the PoR, one RES generation plant on the rooftop of a PA's administrative building with 42 solar panels and 1 energy battery storage.

Once fully implemented, the Distro project expects the electricity bill of the Port of Rotterdam to decrease from 4 MEUR to 3 MEUR per year only due to more efficient electricity use and trading.

5.7.3 Replicability

Smart EMS (SEMS) technology can offer added value to a wide range of ports where these technologies have the potential to be replicated and adopted, contributing to more sustainable and efficient port operations. The increasing penetration of (mainly variable) renewable energy sources will justify the extensive deployment of these systems in European ports, as they offer substantial advantages such as a better integration of renewable power sources into the system and smoothing of peak power demand. Presumably any port that has at least one RES generation plant (e.g. wind, solar, wave energy) onsite with several power consumption points (OPS, recharging stations, electric cranes) will in principle benefit from installing some sort of smart energy management system.

The 'early adopter' ports are likely to be in locations where vessels are obliged imminently to electrify in order to comply with local policies related to carbon emissions and air quality. Examples include passenger ferries and water taxis operating in cities with strict rules in place prohibiting fossil-fuelled combustion engines. Electrified terminals and electricity recharging facilities will be required, and SEMS will have a critical role to play in minimising costly impacts on the local grid. It will do this by smoothing the power demand (load shifting) in the port, by prioritising electricity offtake at times of excess capacity in the grid (e.g. at night) or the electricity market (high supply of wind and solar energy), and by optimising the use of local storage capacity. The energy stored in the system can then be made available to end-users (e.g. vessels) when needed. A similar opportunity is presented by the growing take-up of electric vehicles. These will need to access charging facilities and it will be important for port's operators to ensure that simultaneous charging of multiple vessels and vehicles does not lead to grid congestion. SEMS can help do this, and also minimise the cost of energy provision to the port.

All of the projects shown above are pilot projects that will help to demonstrate further replicability elsewhere. In the case of Portsmouth, the project is financed by government funds and aims, once successfully completed and fully tested, being applicable to other ports in the UK. Also, the smart grid with battery storage implemented in Singapore is currently being tested at the Euroterminal in the Port of Antwerp-Bruges. In the future we expect more of these types of models to be tested in European ports providing better data to assess and evaluate their impact on ports.

Table 5-20: Main characteristics elements and impacts of SEMS

Main elements	Functionality
Modern hardware and software tools Battery storage Data-driven platforms Smart Grids or Microgrids Intelligent remote agents for operations, control, and asset management to enable two-way communication and distributed computing	Control and optimize energy demand, supply, flows, and storage at the end-user level Adjust energy demand to match available energy supply considering energy prices, grid tariffs, and technical constraints

5.8 Green Hydrogen Economy (Port of Rotterdam)

Business model description:	Qualitative description of Hydrogen Economy in the Port of Rotterdam
Scope:	Green Hydrogen production, import and export activities
Location:	The Port of Rotterdam
Date of Commissioning:	Up to 2030
Partners:	The Port of Rotterdam; Shell; Gasunie; Tennet and others

The Port of Rotterdam's hydrogen portfolio covers the complete hydrogen value chain, including projects related to import/export, production, conversion, transport and storage infrastructure, and usage in industry and mobility. Because of the early stage of development of the value chain and unavailability of data of single or integrated projects, this business model remains qualitative, without CBA analyses. It focuses on listing single projects that build up the hydrogen value chain and describes the role of the Port Authority.

5.8.1 Context

Traditionally, the Port of Rotterdam is one of the busiest ports in the world with a strong focus on its energy cluster, almost half of its cargo consists of energy.[70] It includes movements of coal, oil, biomass, LNG, residual heat and captured CO_2. There are a number of receiving oil and gas terminals, refineries and increasingly also renewable energy projects such as the North Sea's offshore wind energy farms and, last but not least, the Port of Rotterdam has a large industrial base.

With the increasing energy flows in the last two decades, more fossil energy use also means more CO_2 emissions. Clean energy solutions and efficiency measures are being increasingly important for the Port. According to the Port Authority, a robust hydrogen value chain can help the port combat climate change and prepare it for a path of a more sustainable future.

Indeed, the Port of Rotterdam has some of the key elements to be a pioneer for a large-scale energy transition. It has a large but very concentrated energy port at a short distance from industrial parks (around 45 km away), it has terminals already in place that connect the port with most major ports around the globe and has large-scale industrial companies that can use green hydrogen (or derivatives) as a substitute in their industrial processes in large quantities (e.g. refineries or fertiliser producers).

[70] For more detail on Port's characteristics see chapter 3.3.

Offshore Renewable Electricity Generation

- In terms of offshore wind energy, there is around 7.4 GW of installed capacity planned to be connected to the Port of Rotterdam by 2030, which represents about 35 % of all offshore wind projects in the Dutch part of the North Sea. These projects are presented in the table below.
- The PoR expects between 2 to 2.5 GW out of those 7.4 GW of capacity to be used for hydrogen production within the Port.
- Up to 2050, the Netherlands aim to have 70 GW of capacity in offshore wind energy and the PoR expects to connect 25% - 50% of this capacity on its territory.

Table 5-21: North Sea wind energy farms to be connected to the Port of Rotterdam up to 2030

Source: Port of Rotterdam Authority

Wind energy farms	Capacity	Operational
Hollandse Kust Zuid, kavel 1-4	1.4 GW	2023
Ijmuiden Ver, kavel 1-3	2 GW	2029
Ijmuiden Ver Noord, kavel 1-5	2 GW	2029
Nederwiek, kavel 2	2 GW	2030
Total	**7.4 GW**	

5.8.2 Renewable Hydrogen economy development model

Regarding the green hydrogen economy, there are several projects being developed or planned in the Port of Rotterdam from local production via electrolysers, import terminals of hydrogen or its derivates from outside of the Netherlands to hydrogen pipelines to transport hydrogen further. The overall goal is to establish a robust value chain that can supply hydrogen in a cost-effective way to Northwest Europe and sustain the role of the Port of Rotterdam as a major energy port.

Hydrogen production

The production of hydrogen in the Port of Rotterdam is currently being planned through a couple of projects in a dedicated area of Maasvlakte, where the Port Authority reserved 24 hectares of its land that is being redeveloped into a Hydrogen Conversion Park. The Park's main objective is to host hydrogen production facilities and the ambition of the Port Authority is to achieve 2 to 2.5 GW of electrolysis capacity installed by 2030.

The Conversion Park is located next to the open sea, hence enabling the shortest distance to offshore wind energy farms and saving costs on further electricity networks onshore. The park will have a high voltage substation built by TenneT (national electricity TSO) at Amaliahaven that will connect the offshore wind energy parks to the grid. The planned facilities are listed in the table below. Each of the projects is planned to produce hydrogen with electrolysers using Proton exchange membrane technology (PEM), using renewable electricity from an offshore wind energy farm in the North Sea.

Table 5-22: Planned green hydrogen production facilities in the Port of Rotterdam using offshore wind energy farms (Conversion Park 1 - Maasvlakte)

Source: Port of Rotterdam Authority

Developer: facility	Capacity	FID	Operational
BP & HYCC: H2-Fifty	250 MW	2023 (planned)	2026
Shell: Holland Hydrogen 1	200 MW	2022 (confirmed)	2025
Air Liquide: Cuthyl	200 MW	2023 (planned)	2026
Not announced	200 MW	2024	2026-2027
Uniper	100-500 MW	2023 – 2028 (planned)	2026-2030

Important to note is that so far, all the project owners also have full or partial stakes in one of the offshore wind energy farms, which seems to be a main precondition for their final investment decision. For the majority of these projects the produced renewable hydrogen will be transported further inside the port and used in refinery processes – substituting blue or grey hydrogen produced with CO_2 emissions (e.g. by steam gas reforming); these refineries are owned by the same company as the planned electrolyser facility. Even though some companies, such as Shell, also plan to supply hydrogen as a fuel to refuelling stations in the Port's area, for instance for heavy duty transport vehicles, the majority of hydrogen produced in the Rotterdam port will be supplied and consumed within the port area, decarbonising industrial operations.

Hydrogen import

There seems to be a broad consensus that most of the Netherlands' and neighbouring countries' future green hydrogen demand will in the short to medium term not be satisfied by domestic production and that a large share will be imported.[71] This is mainly due to the limitations of renewable electricity production in the region. Hence, besides hydrogen production, that is expected to only partly cover the consumption of the port's energy-intensive industrial companies, the Port Authority is also focusing on attracting large hydrogen (and derivatives) imports.

Shipping hydrogen is however more challenging than shipping oil or coal. One option is to liquify the hydrogen by cryogenic process to minus 253 degrees Celsius, which is quite costly, another is to transform it into a carrier, like ammonia or methanol or lastly, it could be chemically combined in a so-called liquid organic hydrogen carrier (LOHC).

To facilitate future imports of hydrogen or its carriers into the Port of Rotterdam, a number of initiatives are being prepared. The majority of these are import terminals that aim to enable the reception and storage of various hydrogen carriers such as green ammonia and its consequent conversion to hydrogen for customers in Rotterdam and Northwest Europe.

One of the import projects is the development of the **ACE Terminal** by a consortium led by Gasunie. The ACE Terminal is supposed to be built at a former natural gas storage facility operated by Gasunie in the Maasvlakte area, which is planned to be redeveloped into an ammonia import terminal. As such, the 'open access' terminal will enable the reception and storage of ammonia as a hydrogen carrier for customers in north-western Europe. It consists of deep sea quay capacity to receive ships, flexible storage capacity, and possibly a cracking facility for ammonia to be directly converted into hydrogen on site. When the project will be realised, in addition to storage facilities, the Terminal will also provide for the transhipment of ammonia and the onward transit of both hydrogen and ammonia to end users. While the Consortium cannot yet invest due to an inexistent demand for green hydrogen or carriers, it tries to connect the supply with demand. So far there has been some activity on the supply side to transport green ammonia from Spain to the

[71] Forschungsstelle für Energiewirtschaft e.V; Imports of green hydrogen and its derivates in a climate neutral future – meta study; 2022

Terminal in Rotterdam by Cepsa and Iberdrola, but large commitments from the demand side are still missing. As already mentioned, the green hydrogen market remains almost inexistent as end-users continue assessing which options (including CCS, renewable electricity, and other renewable vectors) will be the most efficient for their particular decarbonisation plans. And for hydrogen in particular, there remain uncertainties on which of its carriers will at the end break through as the most economic option. This altogether presents large industrial end-users with a risk of lock-in effect, where investing into an energy source that will not be developed in future markets can be costly if not detrimental for their businesses.

Potential sites for additional Terminals in the PoR are being studied; Koole Terminals is e.g. exploring imports of LOHC and OCI terminal is planning to expand its terminal facility, which is currently the only ammonia import terminal in the port.

Hydrogen pipeline infrastructure in the Port of Rotterdam

To enable hydrogen local production and consumption or import for local use or further export, there is a need for pipeline infrastructure.

In order to connect hydrogen supply (Electrolyser facilities and import terminals) with the end-users in the Port of Rotterdam, a dedicated hydrogen pipeline network called Hynetwork is planned. This network will consist of existing natural gas pipeline to be retrofitted to transport hydrogen and/or newly build additional pipelines. The backbone will connect the area of Maasvlakte, where hydrogen production facilities are planned to Pernis, a site of major refineries. The pipeline will be developed alongside the main port corridor of future import terminals which can easily be connected. For this project Gasunie, as the national gas transportation company is responsible with FID being expected towards the end of 2023.

Figure 5-16: Hynetwork - hydrogen pipeline within the Port of Rotterdam
Source: Port of Rotterdam Authority

Furthermore, the construction of additional pipeline systems to transport hydrogen outside of the port, firstly to the industrial site of Chemelot but also further to the North Rhine Westphalia region in Germany, known as Delta-Rhine Corridor, is being considered. This is a part of a wider plan of European Gas TSOs, known as the Hydrogen Backbone network, connecting major supply points with demand centres.

5.8.3 Role of the Port's Authority

The role of the Port's Authority in developing the hydrogen economy in the Port is more that of a landowner and enabler, rather than a direct investor. The PA attempts to make sure all the elements necessary for a hydrogen economy are in place. First, it collaborates with energy producers/suppliers to get large amounts of renewable electricity close to the Port area. Second, applies to TSOs for developing necessary infrastructure that can then be used by suppliers and consumers of various hydrogen products such as pipelines and grid connections. Finally, it attempts to match suppliers with potential users in the future hydrogen market by trying to be a facilitator or mediator.

Regarding the Hydrogen Conversion Park, the PA initiated the development by preparing land with basic engineering works so the future tenants can build their hydrogen facility there. The area has been put forward in close cooperation between the PA and tenants, which are basically the companies that won the offshore wind energy park tenders, and as such it is not an open access area. In that regard the PA is also responsible for the process of requesting the electricity landing grid connection that is built by TenneT and corresponding High Voltage substation and cabling layouts onshore.

The PA is looking further for additional measures on how to make the development most energy efficient e.g., by exploring the use of heat as a side product from the Electrolyser facilities. Producing hydrogen via electrolysis involves high energy losses amounting to around 25%. Those loses are released in the form of heat. However, if captured and used to feed into a heat network, these energy losses become a source of energy for other applications (e.g. district heating). 12 PJ of heat is expected to come from hydrogen plants in the Conversion Park and around the same amount from the chemical industry. By 2050 the heat supply is expected to reach 45 PJ. This means the port can provide enough heat for the equivalent of about 500,000 households by 2030. By 2050, the supply could be enough to heat around one million households. Replacing natural gas-fired central heating systems with a fully-fledged district heating system in South Holland could reduce CO_2 emissions by two to three million tonnes each year as claimed by the Port Authority.

For the hydrogen import facilities, the PA has an even less active role. In the potential future terminals (either new ones or converted), the PA will be responsible for deep-sea quays which are suitable for large seagoing vessels (e.g. VLGC) and their maintenance, all other infrastructure is to be developed by terminal owners/tenants.

The hydrogen pipeline that is supposed to be the backbone of the hydrogen value chain in the Port of Rotterdam, will be developed and operated by Gasunie.

5.8.4 Summary – main requirements for green hydrogen deployment in ports

The developments in the Port of Rotterdam are still at an early stage, which largely reflects the immaturity of the green hydrogen economy in general. This is made evident by the large number of ambitious projects announced in memoranda or letters of intention but only very few projects have reached the FID stage. Because of this, it is difficult to analyse a replicability potential. Therefore, we summarize hereafter the main requirements for ports that intend to facilitate the development of green hydrogen activities following the example of Rotterdam.

Large RES availability or import facilities

Large quantities of renewable electricity need to be available for green hydrogen production. Mainly ports that are in the vicinity of large offshore wind energy farms are likely to be able to attract producers of green hydrogen.

With regard to the potential role of ports in the import of green hydrogen, ports need to be able to receive hydrogen or its derivates in special terminals. Potential terminal operators are trying to bring together supply and demand side partners in order to realise investments in these facilities. Here the main obstacle is the lack of certainty at the demand side, i.e. potential users are not yet ready to commit especially in long term agreements.

Large Industrial base

Refineries and chemical industries or other industrial plants that are in the vicinity of the Port and can use green hydrogen to decarbonise their operations can have a role of an initial off taker. Ports with a large energy or industrial cluster are well positioned to be the first adopters of green hydrogen.

Possibility to become an export/import hub

Ports that are close to a large natural gas network, and of the planned hydrogen transport infrastructure (e.g. hydrogen backbone, connecting them to a wider region and its neighbouring countries, such as in the case of Rotterdam), have advantages. Ports that are not well connected with gas networks, will not be able to take full advantage of this opportunity to become a hydrogen hub.

6 BARRIERS AND RECOMMENDED MITIGATIONS

6.1 Introduction

This chapter describes in detail the main barriers and challenges for electrification of port activities including Onshore Power Supply (OPS) and the role of ports as energy hubs, handling clean fuels such as hydrogen and derivatives. It also provides an analysis of the mitigations needed to help overcome them.

This task has been informed by a detailed review of relevant literature, which is listed in Appendix A, together with individual interviews and a broader stakeholder workshop.

Though there are significant barriers to the scale-up of port decarbonisation business models, policy measures at the EU level and other mitigations exist to support port authorities and the wider maritime ecosystem in reducing emissions. It is important to note, when considering the barriers and challenges described below, that legislation such as AFIR and FuelEU Maritime are changing the paradigm for some technologies, such as OPS, and will result in increased deployment and demand, and expected cost reduction due to economies of scale.

Definitions

This report makes a distinction between barriers and challenges to better express the level of difficulty faced by the ports in deploying these technologies to achieve decarbonisation.

<u>Barrier</u>: In this report, a barrier is defined as an obstacle that impedes progress and achieving the final goal. It can be internal or external, and temporary, enduring, or permanent.

<u>Challenge</u>: In this report, a challenge is defined as a milestone that needs to be achieved and requires significant effort. It can be internal or external and is subjective.

Impact analysis

The barriers and challenges have been analysed using a framework based on DNV's risk matrix, to show the probability of the barrier occurring and the impact of the barrier. For the mitigations, the same framework has been used to show the probability and impact of the barrier post-mitigation. The risk assessment was completed by the project team and is based on the above-mentioned literature and stakeholder engagements. The framework is provided below.

DNV assesses risks by using risk matrices as shown in the figure on the right. These risk matrices show the probability of the risk occurrence on the horizontal axis and the impact on the vertical axis. Combining the probability and the impact leads to either a green, yellow, orange or red mark, indicating the risk severity.

Risk description: Brief explanation of the risk faced.

Probability: Probability that the risk will occur:

- High: ≥ 75%, it is almost certain that this will happen
- Medium: ≥ 25% and < 75%, it is likely that this will happen
- Low: < 25%, there is reason to assume this can happen

Impact: Impact of the risks:

- High: Material risk with major impacts on costs, time, and/or quality.
- Medium: Impact may be material on costs, time, and/or quality.
- Low: No material impact on costs, time, and/or quality.

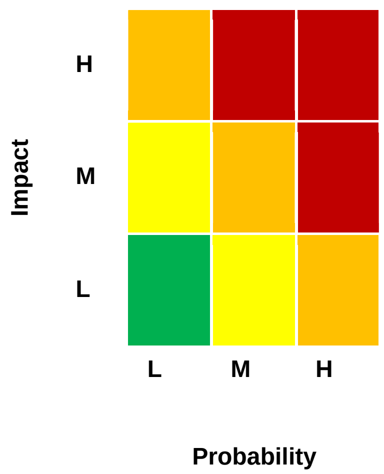

Figure 6-1: Risk Matrix

Risk: Overall rating based on the combination of probability and impact, as depicted in the risk matrix.

- High risk: Red flag, has a potential major impact and requires mitigating actions with high urgency
- Medium risk (orange): Could become a material risk and requires mitigation, urgency lower
- Low risk (yellow): Risk level is low, low urgency for mitigation.
- No risk (green): No need for mitigation or further actions.

Observation and implications: Description of the observations and possible consequences of the identified potential risk**.**

6.2 Onshore power supply (OPS) and electrification

The most significant barriers and challenges to OPS and electrification are presented in Table 6-1. The identified barriers and main challenges are described in detail in the rest of this chapter. The information provided includes the probability of these barriers or challenges occurring and the impact they could have as well as possible methods to mitigate them. The table summarizes the overall magnitude of the barriers and challenges before mitigations are considered.

Table 6-1: Summary of main barriers and challenges to electrification and OPS deployment by severity[72]

Barrier	Probability	Impact	Overall magnitude
Electricity grid capacity limitations and upgrade delays	M	H	MH
Infrastructure investments - high costs and access to capital	H	H	HH
Lack of workforce availability and technical skills	H	H	HH
Challenge			
Implementation of suitable business model for OPS	M	M	MM
High electricity costs and grid tariffs	M	H	MH
Lack of available space	M	H	MH
Electricity supply / provision rule limitations	H	M	HM
Lack of global regulations for OPS and carbon pricing	M	M	MM

6.2.1 Barrier: Electricity Grid Capacity Limitations and Upgrade Delays

Introduction/context

OPS and electrification cannot be implemented if the local grid is unable to support the increased power capacity requirements that are expected to occur in the coming years. Timely upgrades are needed by the TSOs/DSOs to accommodate this increase in demand and support electrification and OPS deployment, which is promoted and required by AFIR. Though the obligation to meet AFIR requirements is placed on Member States and not individual ports, ports can still be significantly affected by delayed upgrades and other technical shortcomings.

[72] Barriers and challenges pre-mitigations may have similar scoring, but mitigations are typically easier for challenges.

Observations

Existing electricity network infrastructure at most ports will need significant upgrades to meet much larger future (peak) power demands as the ports electrify significant portions of their operations and deploy OPS. Additionally, for port electrification, lack of smart technologies (i.e. not time-shifted/non-automated/non-controlled) may lead to much larger power demands in the future compared to smart use (e.g. although not directly port related, smart charging of electric vehicles leads to a 54% peak power reduction)[2]. This growth has been confirmed in the analysis of the ports (see also chapter 3.5 and Appendix E).

- Valencia´s electricity demand is expected to grow more than threefold, from about 80 GWh in 2022 to 300 GWh in 2030. The port's plans for solar and onshore wind energy will increase local generation, but the grid will need to be upgraded to support both the onsite generation and the increased demand.
- Rotterdam´s electricity demand is expected to grow almost four times, from about 600 GWh in 2022 to about 2,700 GWh in 2030[73].
- Kristiansand: The total OPS demand for vessels bigger than 400 Gton is estimated to almost double from 12.9 GWh in 2023 to 22.9 GWh in 2030 and 25.6 GWh in 2050.
- Marseille: The total OPS demand for vessels bigger than 400 Gton is estimated to grow almost fourfold from 14.2 GWh in 2023 to 58.1 GWh in 2030 and 62.7 GWh in 2050.
- Gothenburg: The total OPS demand for vessels bigger than 400 Gton is estimated to grow approximately 2.5 times from 22.8 GWh in 2023 to 55.5 GWh in 2030 and 60.6 GWh in 2050.

The above electricity demand growth numbers for the ports mostly include the effect of the AFIR legislation. For the Port of Rotterdam, the increase was estimated for only 50% of large container vessels meaning that it will most probably have a larger increase in electricity demand[74]. The need for grid extension naturally depends on the utilisation of the current grid capacity and share of OPS related electricity consumption of the port (area).

In most Member States, the transmission system operators (TSOs) are legally obliged to provide timely grid reinforcements and upgrades leading to the equipment that needs to be connected, and the grid users are typically responsible for the direct costs of dedicated substations and connecting lines[75]. A port or the OPS provider therefore would be responsible for dedicated substations and connections, while the TSO is responsible for reinforcing the grid to enable additional grid injection or offtake. This is similar for the DSOs[76,77]. However, discussions with utilities and grid users show that currently there are long lead times for grid upgrades or new/reinforced grid connections, due to grid congestion, permitting issues or lack of available or skilled workforce at the TSOs/DSOs.

[73] Ports: green gateways to Europe, https://www.dnv.com/Publications/ports-green-gateways-to-europe-179372

[74] Strategy for Shore Power in the Port of Rotterdam, https://www.portofrotterdam.com/sites/default/files/2021-05/strategy-for-shore-power-in-the-port-of-rotterdam.pdf

[75] ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2019, https://eepublicdownloads.entsoe.eu/clean-documents/mc-documents/201209_ENTSO-E%20Transmission%20Tariff%20Overview_Synthesis%202019.pdf

[76] ACER Report on Distribution Tariff Methodologies in Europe, https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Report%20on%20D-Tariff%20Methodologies.pdf

[77] Emissions-EUETS.com, Distribution System Operators (DSOs), https://emissions-euets.com/internal-electricity-market-glossary/623-distribution-system-operators-dsos

Analysis based on several national energy and climate plans[78,79,80,81] and IEA policy[82,83,84] reviews shows that multiple Member States (for example: the Netherlands, France, Italy, Portugal, Spain) are upgrading the electricity network infrastructure to enable reaching the 2030 energy and climate goals will be very challenging. In the Netherlands for instance, depending on the location, it can take 3-10 years before a requested capacity upgrade is fully implemented[3]. As discussed in Chapters 3 and 5, this problem does not occur in all of the considered port cases but is country or area dependent.

In addition to these types of grid upgrades, the distribution network at the ports needs to be renovated completely to create new routes and add equipment to support OPS and electrification. These upgrades can include delivery centres (secondary substations), new cabling, specific types of transformers (for OPS), frequency converters, ground switches, etc.

A European Sea Ports Organisation (ESPO) survey states that Ports in smaller cities, or remote locations or islands may be less suited to electrification due to potential lack of adequate electricity generation capacity, which is accounted for in AFIR by providing exceptions to islands, but not remote locations.

Delays in capacity upgrades are also occurring due to the lack of skilled technical workforce, an issue in many EU countries that is exacerbated by the fact that there is significant need for massive transmission and distribution grid upgrades and extensions to support the large-scale deployment of renewable energy sources and the electrification of the heating and transport sectors almost simultaneously.

Probability: Medium

The overall probability of this barrier occurring is medium. As mentioned before, it is likely that many European countries (or port locations) will face this barrier, as grid congestion and long lead times are currently problems in 3 out of 8 ports studied. The other ports indicated that at present, there is no issue in obtaining additional electricity network capacity for their current OPS needs. However, this will no longer be the case for future needs, especially to meet OPS obligations and electrification goals, considering that nearby industry's decarbonisation efforts can severely limit the grid's capacity availability for the ports. Onsite electricity generation projects on the ports' territory will also affect the required capacity of onsite transformers and substations and local distribution grids and may require further upgrades.

This barrier is location, port traffic, and Member State dependent. Based on the information collected from the port interviews showing the number of ports affected, it is assigned an overall medium probability. But it is important for ports to properly understand their location-specific grid upgrades required and to gauge the ability of responsible parties to complete these upgrades in a timely manner.

Impact: High

This barrier has a high impact on the implementation of the decarbonisation options as timing, workforce and costs significantly affect deployment. A delay in the grid connection may mean that for example, in the case of OPS, the port cannot provide all the AFIR OPS requirements on time. Additionally:

- Some delay in the realisation of OPS connections can delay meeting international, national or local emission reduction targets (GHG emissions and/or air quality targets). A number of ports have set emission reduction goals themselves such as Barcelona with a 50% decarbonisation target by 2030, Rotterdam with a 90%

[78] Integrated National Energy and Climate Plan 2021-2030, Spain https://energy.ec.europa.eu/system/files/2020-06/es_final_necp_main_en_0.pdf

[79] Integrated National Energy and Climate Plan 2021-2030, The Netherlands, https://energy.ec.europa.eu/system/files/2020-03/nl_final_necp_main_en_0.pdf

[80] Integrated National Energy and Climate Plan 2021-2030, Italy, https://energy.ec.europa.eu/system/files/2020-02/it_final_necp_main_en_0.pdf

[81] Integrated National Energy and Climate Plan 2021-2030, Sweden, https://energy.ec.europa.eu/system/files/2020-03/se_final_necp_main_en_0.pdf

[82] The Netherlands 2020, Energy Policy Review, https://iea.blob.core.windows.net/assets/93f03b36-64a9-4366-9d5f-0261d73d68b3/The_Netherlands_2020_Energy_Policy_Review.pdf

[83] France 2021, Energy Policy Review, https://iea.blob.core.windows.net/assets/7b3b4b9d-6db3-4dcf-a0a5-a9993d7dd1d6/France2021.pdf

[84] Portugal 2021, Energy Policy Review, https://iea.blob.core.windows.net/assets/a58d6151-f75f-4cd7-891e-6b06540ce01f/Portugal2021EnergyPolicyReview.pdf

reduction in scope 1 and 2 GHG emissions by 2030 from a 2019 baseline, and Hamburg with a CO_2 emissions reduction goal of 50% by 2025 from a 2012 baseline.

- Delay in the realisation of OPS connections might lead to penalties on national or local level. Member States and cities have sustainability and emission reduction goals that can affect the local ports. At the EU level, penalties to ports are not applicable as the requirement for compliance rests with the Member States, not the ports.
- Concessions for terminal operations can also include emission reduction clauses, making timely electrification and OPS deployment important. One of the terminal operators interviewed was convinced that without substantial emission reductions their contract to operate the terminal would not be extended.

Mitigating actions

To address the infrastructure related capacity shortcomings, one mitigating action is to consider a connection to other substations that may have available capacity, though this is a location and grid specific solution. Behind-the-meter optimisation of electricity demand (demand side management) to lower the required capacity offtake from the local DSOs or TSOs is another mitigation. Examples include peak load shifting by looking at the simultaneous use of the equipment and shifting their use to low-peak load hours. However, since not all port operations are highly flexible, there is a limit to how often the use of equipment can be shifted. The deployment of battery storage for peak load shifting is also an option although still quite expensive. Batteries can be used for internal energy management (electricity demand response) and could also be an option to address local grid congestion. In that case, the battery operator would offer flexibility services to the concerned grid operator.

Electricity demand management is also a mitigating measure a port can undertake, for example by providing OPS only to certain ships (AFIR identified). Overall, ports can utilise flexibility assets and services such as energy storage, vehicle-to-grid, demand response, and (flexible) onsite electricity generation to partially alleviate the need for network upgrades.

For hybrid-powered vessels, one possible mitigation for ports is to provide a battery swap service, where batteries are charged onshore and loaded and unloaded onto ships. This can be a solution for short journeys with large numbers of vessels and short times in the port, since it would enable slower battery charging and hence longer battery life, as well as the option to charge batteries during off-peak hours. This high CAPEX solution could be more cost effective over the lifetime for ports where there is a high number of vessels call for short times. This mitigation measure of battery switching will require close collaboration between ports and vessels' operators, since the responsibility of charging batteries (i.e. "fuelling a vessel") lies with the port, but directly affects the vessels. In the case of non-EU routes, such as Calais-Dover, it also requires cooperation with third countries to develop possibly joint funding solutions. This mitigation action could represent a profitable business model for the port or 3rd party provider.

Finally, onsite renewable electricity generation, such as solar and wind, can also alleviate the need for capacity upgrades. Local equipment such as substations may need to be upgraded or installed to support the deployment of renewables. However, local increase of generating capacity can significantly reduce the need for grid upgrades from the DSOs or TSOs.

Probability after mitigation: Medium

The proposed mitigating actions can shift the need for grid capacity upgrades further into the future and in some cases perhaps even alleviate them. However, due to the large OPS power requirements, the need will typically remain, but it will just be pushed out to the future. If utilities are allowed additional time to provide upgrades, through port provided demand response, storage and other suggested mitigation actions, the pressure to upgrade different parts of the grid almost simultaneously can be somewhat relieved, but not eliminated.

Impact after mitigation: Medium

Once mitigating actions have been taken, the impact level is expected to be reduced to medium. This is because some ports will be capable of supporting OPS and electrify their operations without the need for immediate grid upgrades. The impact cannot be completely mitigated though as the effectiveness of the solutions depends on the port size, infrastructure, and current grid status. The mitigation actions may also only allow for partial OPS deployment and electrification without grid upgrades but not the full requirements or goals, meaning that for example a port can deploy half the OPS systems or electrify half of the terminals through the proposed mitigations, but still requires grid capacity upgrades to deploy the remainder.

6.2.2 Barrier: Infrastructure Investments - High Costs and Limited Access to Capital

Introduction/context

There are two main barriers for energy infrastructure deployment: 1) high investment costs and 2) limited access to capital. Infrastructure investments for OPS and port electrification are capital intensive and can lead to long payback periods especially for OPS providers with low traffic volumes. The high investment costs are driven by costly 50/60Hz frequency converters (typically) needed for OPS to ship connections, lack of sufficient electricity network capacity in the ports, need for new substations, cabling management, electrical wiring, civil works, different ship sizes resulting in need for multiple OPS connection points, and irregular ship schedules leading to high peak power but low infrastructure utilisation. Electrical equipment such as Rubber-Tired Gantry Cranes (RTGs) or electric Reach stackers are also substantial investments.

Funding and access to capital varies significantly between ports and Member States and can depend on the type of ownership, the port size, type and traffic levels, each Member State's laws regarding tenders, return on investments, and general procurement and operation of port assets. Ports often make investments which even though have a high societal value for the surrounding communities and national interests, they do not generate adequate return on investments, making it difficult for ports to attract external (private) investors.

Observations

Energy Infrastructure investment costs are (relatively) average to high compared to other port infrastructure investments[85]. They are at the same level as basic port investments, such as berths, quay walls, and jetties. Port interviews, workshop inputs and desktop review provided information regarding prices and the ability to access funding (see also Chapter 5 for more details on pricing).

- Marseille's four OPS connections required a capital investment cost of 2.5 MEUR, which was covered by the companies utilising the systems, not the port authority.
- The Port of Kristiansand installed OPS for cargo ships. The investment costs amounted to 930,000 EUR and the business case would have been negative without the 50% government grant the port received.
- The Port of Gothenburg installed a high voltage station for the OPS to one of the shipping companies, which carried out the OPS development and owns the installations. The investment costs were 2 MEUR.
- Insights from tenders for OPS at the Port of Valencia's cargo terminal show that the investment costs to implement OPS are approximately 11 MEUR of which 80% are for a new substation, cable management and wiring, and control systems.

[85] The Infrastructure Investment Needs and Financing Challenge of European Ports, https://www.espo.be/media/Port%20Investment%20Study%202018_FINAL_1.pdf

- The Port of Los Angeles was the first port to install OPS in the world. As of January 2022, it had 24 berths with OPS systems at a total investment cost of around 230 MUSD.
- The Terminal Valencia (MSCTV) operator converted the fleet of RTGs to electric driven. The total investment cost was 54.1 MEUR and the payback period was 7 years.
- Regarding smart grid, besides the costs of the individual assets, a large part of the investment lies with the controllers and monitoring devices. Costs vary depending on the number of assets controlled and the complexity of the schemes and algorithms. A 2018 study by the U.S. National Renewable Energy Lab (NREL) found that controller costs vary significantly with a mean of 155,000 USD/MW[86].
- The Port of Rijeka has plans to install OPS and electrify port equipment. The OPS investments will be made by the port authority which plans to apply for EU co-financing since Croatia is an EU Cohesion Country. Electrification investments will be made by the terminal operators.
- The Port of Calais also has plans for extensive electrification and OPS. Funding mechanisms are uncertain especially when the OPS case is considered as stand alone. If OPS is combined with other electrification projects, such as truck electrification, there is more flexibility to access capital and have better return on investment.

Though other port investments such as rail and road transport connections are higher than energy investments, there are often provisions regarding return on investment and payback periods, meaning that they do not need to make a return as they are considered social and critical or required investments for port operations. However, regarding OPS, the impact of FuelEU Maritime will be that demand for electricity by vessels is ensured, as vessels will be faced with significant penalties if they fail to comply with the legislation. As such, the situation after 2030 is expected to be different as high levels of OPS utilisation will allow for recovery of the investments. Furthermore, as OPS requirements will apply for several TEN-T ports, the risk of evading traffic will be reduced as ships will be faced with the same requirement to connect to an OPS in the alternate ports too. Complexities also arise with (some) investment decisions at ports requiring approval by a government body, as is the case for example in Spain, the Netherlands (national level) and Sweden (municipal level)[87]. To add to the funding complexities, OPS and electrification are not BaU investments, making it harder to access non-grant funding.

The ESPO study also reveals that ports are targeting EU grant funding for energy-related projects, which is possibly the result of port authorities' lower ability to invest in energy infrastructure.

Probability: High

The overall probability of this barrier occurring is high. All ports that will offer OPS will face high costs for OPS installations and all ports that will electrify their goods' handling and transport equipment will require high CAPEX projects and supporting grid infrastructure. Though the probability of high costs is large, payback periods for different projects and assets will vary, making some projects harder to implement than others. Regarding access to capital, the issues are port dependent as some ports may have easier access to national (public) funding and external investors. Even in those cases, energy infrastructure projects could still compete to acquire funding for core or other port projects. This increases the possibility of facing funding inadequacies or constraints due to the high amount of capital required. Most interviewed ports mentioned they will rely on EU and national grants and funding for these types of projects, as they are having difficulties making the business case. It is important to note that it is the overall responsibility of the Member State to ensure that requirements in AFIR for the installation of OPS in ports are met.

[86] National Renewable Energy Laboratory, Phase I Microgrid Cost Study: Data Collection and Analysis of Microgrid Costs in the United States, https://www.nrel.gov/docs/fy19osti/67821.pdf
[87] Local Governments and Ports, https://www.itf-oecd.org/sites/default/files/docs/local-governments-ports.pdf

Impact: High

The impact on the ports of this barrier is high. The high infrastructure costs can slow down or even reduce the OPS deployment at ports where access to capital for energy infrastructure is difficult and/or expensive. Thus, ports may need to stager OPS deployment if they cannot access the needed funding and may not meet AFIR mandates on time. The high costs and/or lack of funding will impact ports with low utilisation of OPS more since they will face longer payback periods and hence have a more difficult business case.

Mitigating actions

AFIR and FuelEU Maritime are expected to lead to the reduction of some of the investment costs as more systems are installed (larger equipment suppliers' base), asset utilisation increases and economies of scale take place. Port-vessel collaborative efforts on port call optimization and Just-In-Time arrival of vessels[88] achieved by adjusting the cruising speeds of ships based on berth availability, can further reduce costs by requiring less OPS installations to serve larger numbers of ships and can help improve the utilisation level of OPS. Furthermore, step-by-step introduction of OPS in ports can also ensure higher utilisation when AFIR is implemented. Increasing technology maturity, increased collaboration with the IMO and shipping companies, where possible, will also reduce investment costs.

Emissions reduction goals for terminals (through electrification or clean fuels) can be included in new/negotiated tenant contracts, sharing infrastructure costs with the terminal operators. By shifting part of the responsibility to decarbonise to the terminal operators, new funding opportunities and strategies become available.

Assigning energy-related projects as core port infrastructure can open new funding avenues and decrease the expected return on investment or payback periods of such projects. This is already the case for OPS in some Member States, where OPS is allowed a 25-year payback period.

High investment costs relating to smart grids can be offset by energy and economic efficiency gains, system balancing and other revenue opportunities.

Capital support (subsidies or funds) is an important external mitigation measure to support both the greening of port equipment and the rollout of alternative fuels infrastructure/OPS. The US Inflation Reduction Act (IRA) could be an inspiration as it contains support for both. This measure is zero cost for the ports relying on government assistance, but high for the different governments that distribute the grants. Depending on the port, different financing, development, and operation options for these types of assets can be considered, which could put the investment costs (and profits) on 3rd parties rather than on the port authorities and/or the government. Finally, EU funding is available in the form of grants (e.g. CEF fund) and loans (e.g. EIB) that can help early adopters deal with some of the above-mentioned issues. The available funding is not enough to support all needs but can promote early action. As electrification and OPS technologies are increasingly deployed and investments become more favourable, additional funding options will also become available.

Probability after mitigation: Medium

The proposed mitigating actions can reduce some of the investment costs, or at a minimum the impact of the costs by allowing for longer payback periods, less concurrent infrastructure deployment, sharing of expenses (and profits) and reducing initial investment financing needs either through optimization of operations, economies of scale and increased funding options and access to capital. The probability is reduced to medium. In the long term, as more systems get installed and OPS systems become commonplace, the investment costs will reduce further, and tested business models are expected to allow for more funding options.

[88] Just in Time Arrival Guide, Barriers and Potential Solutions, https://greenvoyage2050.imo.org/wp-content/uploads/2021/01/GIA-just-in-time-hires.pdf

Impact after mitigation: Medium

The impact of high infrastructure investment costs for OPS, electrification and smart grids after the identified mitigating actions will also be reduced. The improved access to capital, collaboration between port authority, terminal operators, government, and technology providers and increased technology maturity will allow for quicker infrastructure deployment that ultimately reduces the possibility of delays in meeting mandates and GHG emissions reduction goals.

6.2.3 Barrier: Lack of Workforce Availability and Technical Skills

Introduction/context

Electrification and decarbonisation of the economy require a workforce with new competencies to support the design, deployment, operation, and maintenance of new technologies. This well-trained workforce will play a vital role in assisting different segments of the economy, including ports, meet their clean energy goals. As the need for skilled workers increases, competition amongst industries and organizations to attract and retain this workforce will also intensify.

Observations

In the cases of OPS and electrification, port personnel need to be able to operate and maintain systems based on these new technologies. Existing personnel typically does not have adequate knowledge or competencies relating to OPS, electrification or low-carbon fuels, meaning that they will either need to be retrained, when possible, or additional personnel will need to be hired. This is especially true for maintenance and operation personnel.

- Depending on the “new” tasks, retraining can be simple or complex. For example, retraining workers to use electric vehicles or machinery instead of diesel/heavy oil ones is not complex. Retraining for the maintenance requirements will be more challenging as this often requires people to learn new skills that could differ significantly from their current skillset (e.g. mechanical vs electrical skills). In addition, the workforce (retrained or new) will need to attain new certifications.
- The uncertainty on the exact personnel needs to operate the new equipment is also problematic. The current EC 80005-1 standard requires one person onboard and one onshore (Person in Charge) for the connection. Ports will typically staff at least two employees onshore for safety reasons. It is unclear who will be making the physical connection, the ship or shore operator, and where the responsibility lies. This could be a new role that currently does not exist at ports. An example of competencies needed relate to the OPS connection (available in the EC 80005-1 standard), where the first time a ship connects to OPS a compatibility test needs to be carried out. This is to test the electrical connection between the ship and the OPS. Visual inspections of the switch board and control panel of the ship are also needed each time they connect to OPS.

Scarcity of workforce with the required technical skillset is also expected. Ports will compete with other industries for competent workers, who will choose the most attractive (to them) sectors. This is already an issue, as the overall knowledge about electrification within the shipping industry and ports is lower compared to, for example, the automotive industry. For a large part, this is related to the lower average pay an electrical engineer receives in the shipping industry.

Probability: High

The probability of lack of skilled technical workforce to participate in port operations relating to OPS, electrification and low-carbon fuel technologies is high. Currently the issue may not be critical, but as more of these technologies are implemented by ports and other industries, the lack of adequate workforce will increase. There are already sectors, such as DSOs and TSOs throughout Europe facing significant shortages in technical personnel. These similar skills are required by the future port operations and maintenance workers. Competition for these workers will also increase the probability ports will face a significant lack of skilled personnel.

Impact: High

The lack of skilled workforce has a high impact on port operations and logistics. Without the required knowledge operations can be significantly affected due to the lack of correct and timely maintenance, delays in technology deployment or utilisation, increased expenses, reduced (worker) shifts, etc.

Mitigating actions

Ports can establish programs to facilitate the transfer of knowledge and skills from experienced professionals to new recruits, ensuring the preservation of industry expertise. This mitigation has both an internal aspect as ports will need to invest in internal trainings, and an external aspect, as national education and training programmes would help mitigate the issue. Member States with higher unemployment such as Spain, Greece, Estonia, Sweden, France and Italy have an additional incentive to promote vocational schools and careers in ports and other industries that require similar technical skills. Increasing the attractiveness of these types of skillsets and careers through financial incentives, scholarships, apprenticeships, school collaborations with private and public companies for internships, and strong public campaigns, can increase interest for such positions. Terminal operators have more (financial) flexibility to participate in the above-mentioned programmes and collaborate with schools to promote these required skills and careers.

The Ports of Valencia and Barcelona included operation and maintenance of the OPS for the two first years in their OPS tenders. One reason was to help with continuity and on the job training, but also help understand the staffing needs for OPS in the future.

Discussions regarding vocational training for technicians to gain the required skillset are underway in some Member States, often initiated by the ports. For example, the port of Valencia has initiated discussions with Formación Profesional which oversees vocational schools regarding specific skills and courses the Port will require for operating in this new electrified and decarbonized environment. The Port of Gdynia in Poland, through a worker training company, is also investigating possible collaborations.

Probability after mitigation: Medium

The mitigating actions require public or private schools and the ports themselves to take action. Though these actions require collaboration between these different entities, robust training programmes can significantly reduce the probability of ports facing this barrier. Salary discreteness between different industries is harder to resolve and require structural organizational changes. The probability can be reduced to medium.

Impact after mitigation: Medium

The mitigations also reduce the impact of this barrier to the ports. A better trained and capable workforce will reduce maintenance, operation, and technology deployment issues and thus also reduce costs and other negative impacts associated with inefficient operations.

6.2.4 Challenge: Implementation of Suitable Business Model for OPS

Introduction/context

OPS is not yet a widely deployed technology, and as such there is not much precedence on how to design and implement a successful business model. The lack of demand is the main challenge in creating a sustainable business model, bur AFIR and FuelEU Maritime are expected to address this demand issue. OPS services can be supplied by the port authorities or other entities depending on specific country, local, or port regulations, mostly affecting the sale of electricity through OPS. Multiple barriers and challenges mentioned in this chapter affect the OPS business case, including electricity supply and provision rules, high infrastructure investments (in certain cases) without a favourable return on investment that thus do not attract external investors, and the lack of suitable space at ports.

Observations

Currently, depending on a port's overarching business model, a third-party company may be providing electricity and fixed installations to the ships (while the port authority is the overall managing authority), or a terminal operator that interfaces with the vessels may be managing all aspects of serving the berthed ships. In the case of OPS deployment and operation there are therefore different possible models for who will have ownership and who will be providing the service and managing it. It could be the local electricity provider, a third party, the terminal operator, or the port authority.

Though Member States have their specific local electricity supply and provision rules, there are also common European Union rules that play a role in the OPS business case, such as the mandated unbundling of electricity generation, supply and sales from network activities. So, the OPS business model strongly depends on electricity sector rules and available power distribution models.

- As mentioned in 3.3.5, the port of Valencia, owns and operates the distribution grid at the port operating similarly to a local utility. Currently the port outsources OPS operation and maintenance, mainly to better understand the business case (operations, maintenance and revenue streams). Furthermore, it cannot upcharge for the electricity sold being the local grid owner.
- The Ports of Valencia and Barcelona need to build substations to accommodate the increased electricity demand due to OPS. Ports that do not operate their distribution grids rely on the local DSOs or retailers for needed upgrades or electricity services. For example, the Port of Rotterdam is working with an electricity supplier for the OPS service.
- The Port of Los Angeles invested in OPS. In this case, the City of Los Angeles Department of Water and Power provides electricity. The port is responsible for the installation and maintenance of the (electric) facilities that serve the ship loads. The port is invoiced by the utility and in turn re-invoices the terminal tenants that use OPS. The port does not add a service charge to its invoices. It should be noted that California has mandated OPS usage.

The business model should also account for national legislations or regulations since most ports cannot make their own independent decisions. For example, the Ministry of Transport of Spain requires port investments to have a positive business model (some exceptions apply). In most instances, OPS can be a positive business model today only due to financial aid from the EU and national grants. There exists a funding gap that requires attention, but this could potentially diminish as operations scale up and if the cost of electricity decreases. This issue is even more critical for ports with seasonal traffic, due to the low OPS utilisation which affects the business case and as a result the funding options. As vessels adjust to comply with FuelEU Maritime legislation, OPS utilisation will increase and the business case is expected to become favourable for many ports, which can in turn increase the viability of EIB or other private funding.

Large investments in ports can be made by non-port authority entities. For example, terminal operators own the machinery at their terminals, and are thus responsible for those investments. Depending on the concession contracts which include clauses regarding operation, maintenance, and services provided, OPS services could be part of the concession.

There are a variety of options ports should consider regarding OPS deployment, but the lack of precedence makes it unclear which selections will provide the optimal business case for the ports in the long term.

Probability: Medium

The probability that ports will have to deal with the difficulties and underlying barriers or challenges of implementing an adequate business model for OPS is medium as this challenge will be mostly encountered by the early adopters. It is also dependent on the Member State and port type and size as providing OPS at multiple berths for different types of vessels increases the complexity of the business case. However, this could be an opportunity to better distribute the power demand of the port, for example by creating a charging policy that requires staggering the timetables.

Impact: Medium

The complexity and variation in port options regarding business models for OPS will mostly affect bigger and medium size ports, which are mandated to supply OPS. At the same time, the FuelEU Maritime legislation mandates the use of OPS for large container and passenger vessels in these ports from 2030 and thus creates a captive demand.

Local electricity rules can affect the business model as they may have a negative impact on the ability of the port to have a positive return on their investment. Currently, a port's ability to effectively plan and deploy OPS is still affected by uncertainties regarding national governments' expectations and support regarding OPS, possible ownership models and charging schemes to recover investment costs (and possibly generate a margin). Information sharing between vessels' operators and their status regarding OPS readiness or the actual amount of energy required by different types of vessels during berth are also lacking. Many of these issues though are expected to be addressed by the implementation of the AFIR and FuelEU Maritime legislation.

Mitigating actions

Appropriate market model designs for the offtake of electricity via OPS is necessary. This can be done, for example, by direct payment for the electricity (like a fuelling station) or by an hourly (or other) berthing fee charge for OPS connection. Third party ownership of the OPS or contracts to maintain and operate the OPS, or including an OPS requirement as part of the terminal concessions could also provide a solution to the funding difficulties port authorities may face for OPS deployment. This business model, where the terminal operator owns and operates the OPS, is already being used in some ports.

Better collaboration between vessels and port operators can also help mitigate the issue. There is currently no public, trustworthy list of vessels that are OPS ready. This means that ports need to discuss the OPS possibilities of ships with each ship operator individually, a time-consuming task. Knowledge of the OPS readiness status of vessels will help the ports with long-term planning of OPS deployment.

Collaborating with the local utility, DSO or TSO for special OPS tariffs or a PPA could also help alleviate some of the issues related to electricity costs. Member State electricity sector rules may also need to be revaluated to make the business model work.

Finally, AFIR requires Member States to submit draft National Policy Frameworks by the end of 2024 that address OPS deployment. FuelEU Maritime will increase communication between ship companies and ports including vessel OPS readiness, allowing for better planning of OPS deployment. Other issues such as getting accurate insight in OPS readiness and actual amount of energy required by different types of vessels during berth might be more complex and might take longer to resolve.

Probability after mitigation: Low

These mitigating actions can considerably reduce the issues relating to the implementation of suitable business models for OPS. The challenge is an amalgamation of multiple barriers and challenges, but solutions to mitigate at least some of these will reduce the probability of this challenge occurring to low.

Impact after mitigation: Low

The mitigation actions also reduce the impact of this challenge. With a better grasp of the possible business model(s) for OPS, ports will be able to select options that fit their specific port and facilitate OPS deployment.

6.2.5 Challenge: Electricity Costs and Grid Tariffs

Introduction/context

Since increased electrification and OPS will lead to larger electricity consumption by ports, terminals, and shipping companies, electricity costs will have a major impact on the business cases. A major challenge to OPS and electrification is the grid tariff structure, including distribution fees.

Observations

Electricity commodity prices at the spot (or forward) market can fluctuate significantly. However, the challenge is mainly related to network tariff regulations and how suppliers and network operators structure their tariffs for end-users. Electricity retail prices and network tariffs are connected to the voltage level and the tariffs (most) ports fall under make use of contract demand (which can differ per Member State), which is often set according to the annual peak demand and can also include fixed charges.

- As mentioned before, OPS usage can increase peak demand significantly. Ports that have seasonal traffic are especially affected by high electricity grid costs due to these high peak demands and low OPS utilisation. Ports with regular traffic still face issues as simultaneous OPS usage will significantly increase electricity demand and thus the overall cost of electricity.
- Ports with multiple OPS connections could see a surge in their electricity peak demand if large ships are berthed simultaneously. For example, a cruise port with two large cruise ships connected to OPS at the same time can have a 32 MW peak from OPS alone. This peak can set their annual contract demand and fees that apply throughout the year, even if their average offtake is much lower.
- High electricity costs might also hinder the progress of electrification in port operations (such as e-RTGs) since, unlike OPS, it is not a legal requirement. In addition, there is still some uncertainty whether the potentially lower maintenance cost of equipment will effectively (partially) compensate for the higher energy costs of running electrical equipment.
- Electricity prices and grid tariffs differ per EU country, making it more costly for ships to use OPS in some countries than others. The current legislation mandating the deployment of OPS could diminish the cost impact by increasing OPS utilisation and removing alternative (non-low-carbon) fuelling and berthing options.

Probability: Medium

In 2022, electricity prices reached an exceptionally high level, and it is difficult to forecast future price developments, as they depend on external factors, such as the availability and prices of primary fuels, deployment of renewable energy sources, geopolitical influences and technology maturity.

Electricity grid tariffs, however, can to some extent be forecasted, and will be affected by the large investment programs needed to upgrade the grids. The impact on ports can be substantially affected by the tariff structure (e.g. capacity versus volume related tariff).

The probability that ports will face high electricity procurement costs is medium as long as the electricity retail prices level and network tariff methodology remain unchanged. This probability is based on the fact that different Member States may structure electricity tariffs differently, electricity commodity prices themselves vary to some extent throughout the EU, and some ports, such as cruise ports and ports with seasonal traffic, will be more affected by high electricity procurement charges.

Impact: High

The impact of high electricity procurement costs can be high. Higher electricity costs if cannot be passed on to the end-users will reduce the ability of ports to recover OPS and electrification investments. High electricity procurement costs that are passed on to ship operators can make specific ports less attractive for shipping companies - a difference of a few euro cents per kWh can have a substantial impact due to the high electricity needs of the ships at berth. High electricity procurement costs will also increase port operating expenses once equipment has been electrified.

Mitigating actions

This challenge could be mitigated by electricity tariff restructuring or special tariffs for OPS, similar to arrangements in some countries for electric vehicle charging. The application of the FuelEU Maritime Regulation will also help reduce the risk of a port being less attractive as the obligation to use OPS will also apply to ships calling in alternative TEN-T ports. The addition of battery storage to OPS systems or other parts of the port grid can reduce the peak load and hence the overall electricity cost. Onsite renewable energy generation such as solar and wind energy can also provide some mitigation, especially when combined with storage and smart system/grid optimisation. When considering the lower cost of fossil fuels and how that may affect ship operators' choices, high CO_2 emission costs (ETS) can affect the decision of ship operators to switch to electricity at berth from non-clean fuels, making electricity a more attractive option. Securing favourable Power Purchase Agreements (PPAs) with electricity suppliers, and ensuring stable and predictable electricity prices can be also reduce the impact of this challenge.

Finally, ports can negotiate with shipping companies that create the excessive (seasonal) power demand and adapt the berthing strategies by passing some of the costs directly to the shipping companies or vessels.

Probability after mitigation: Medium

Some of these mitigating actions will be more difficult to implement as they require external intervention, such as electricity network tariff restructuring. The challenge and the mitigating solutions also differ by Member State and some ports may still face high electricity procurement costs even after these mitigations, especially compared to ports in other Member States.

Impact after mitigation: Medium

The mitigations also reduce the impact of this challenge by reducing network tariff charges, although the solutions (e.g. batteries) can be costly.

6.2.6 Challenge: Lack of Available Adequate Space at Ports

Introduction/context

Ports might not have sufficient adequate space for the OPS infrastructure, especially if mitigating solutions mentioned in previous barriers and challenges such as battery storage are to be included. OPS infrastructure whether mobile or stationary requires a significant amount of space once deployed to serve a vessel. Depending on the type of terminal the availability of space for OPS infrastructure, including cabling, can be limited.

Observations

Mobile OPS needs approximately 3 meters between the vessel and the OPS system for charging. The cables are large and (preferably) require trenches to underground them. Some OPS systems will also require transformers which can also be large. Figure 6-2 shows examples of mobile OPS and cable management options. At existing cable tunnels and service galleries space may be already limited.

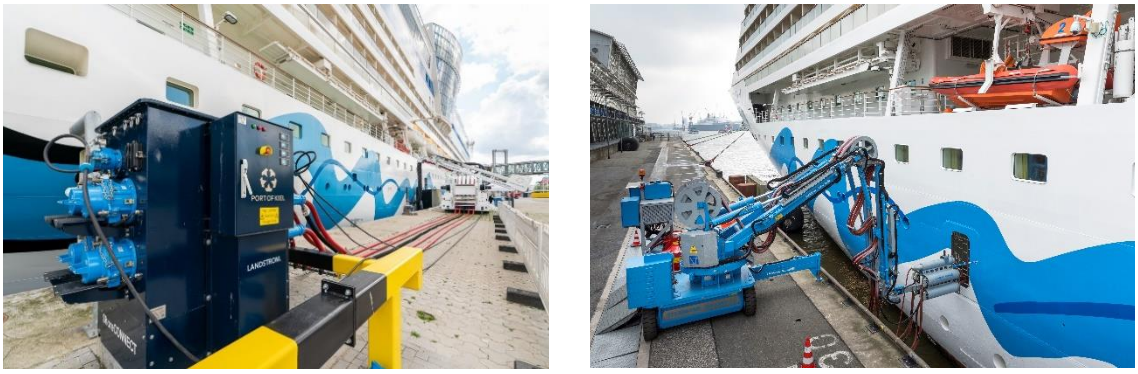

Figure 6-2: Mobile OPS deployment – required space and cable management

Source: Siemens press release, Cruiseandferry.net newsletter

This space needed to deploy OPS is generally available at most quays, but it could reduce available space for other port operations. From Figure 6-3 (right) it is obvious that if OPS were deployed to serve a ship berthed one of the traffic lanes would be closed off restricting port traffic.

Another issue can be at container terminals that have narrow quays (Figure 6-3 - left) and many obstacles such as bollards, ropes, ladders, etc. In this case there is almost no space to deploy OPS.

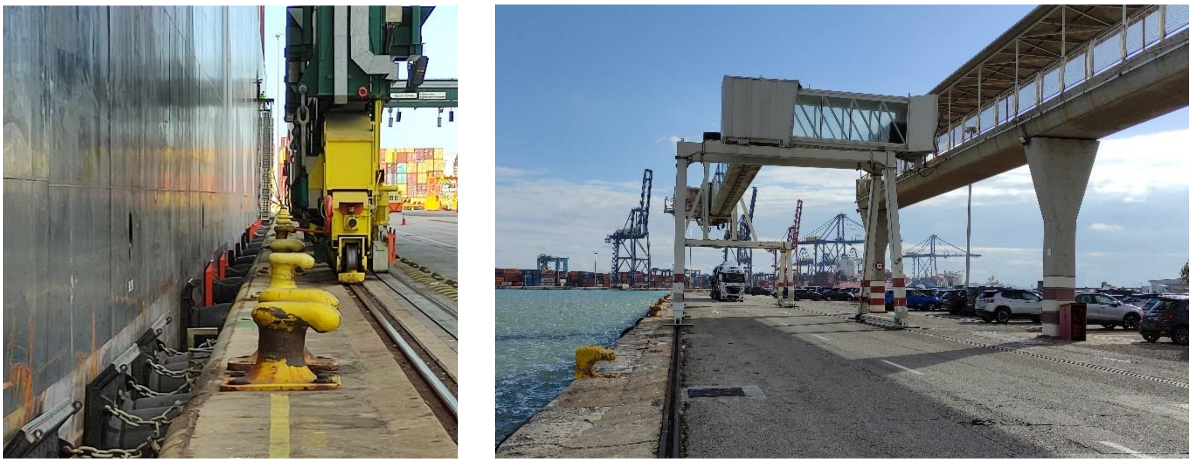

Figure 6-3: Space considerations - interference with other port operations and equipment

Source: Port of Valencia

Probability: Medium

Space consideration for OPS deployment in existing terminals and port infrastructure depends on the size of port and the types of terminals they support. This issue can be very port specific, but similarities in port design reveal that adequate space for OPS infrastructure will be a challenge for several ports. Ports that plan to include onsite renewable energy generation and battery storage will probably face this challenge.

Impact: High

If OPS cannot be deployed due to lack of adequate space, the port might not be able to comply with the OPS mandates or may require relying on expensive solutions increasing the already high capital investments.

Mitigating actions

Some ports will have the option to purchase additional land or expand the quay whereas other may not. Floating solutions can also be investigated for ports with significant lack of space. Space requirements will be considered in new construction plans and terminals can be designed to support this infrastructure. Working with technology providers to incorporate space restrictions could also in time mitigate the lack of space. Redesigning parts of the port and adding more service galleys where possible can be a costly, but viable option.

Probability after mitigation: Low

The probability that the lack of adequate space at the port remains an issue after mitigations is low. Some ports will not be able to expand or implement some of the solutions, but as OPS and electrification supporting technologies such as battery storage mature, space needed for the technologies may decrease. New terminals will include these needs in the design.

Impact after mitigation: Medium

Most ports will be able to implement solutions and work with technology providers to deploy these systems. But there can be a number of ports that are not able to overcome this challenge and for those ports, the impact will remain high. The overall impact of this challenge is therefore medium.

6.2.7 Challenge: Electricity Supply and Provision Rule Limitations

Introduction/context

Depending on the Member State and the local rules relating to electricity supply, the price of electricity and the ability to support and recover electrification investments through the sale of electricity can be difficult. The EU rule of unbundling between electricity supply and network activities also plays a role in these investments.

Observations

This problem may be exacerbated by the need for ports to recover their OPS investment costs by the sale of electricity at a margin. Some ports in Europe indicate that the current rules for electricity supply and provision are difficult to work with, and not always well-suited to the business of providing OPS to ships. More specifically, the reselling of electricity may be prohibited in some countries, such as Sweden, and thus charging ships for OPS utilisation involves specific difficulties. In some countries, the port authority can supply or consume energy within its own electricity network if it owns the grid, but to deliver electricity via the local DSO or TSO grid to other off-takers, the port would have a different role (e.g. become a utility). Generally, whether a port can (re)sell electricity that has been bought from a retailer, on the wholesale market, or self-generated depends on the roles and responsibilities the port has been assigned/chosen.

Electricity generation and sale is a challenge in several countries since, depending on the country licencing laws, they could require ports to apply for a licence as electricity supplier. Currently, independent producers in the Netherlands and Belgium are struggling with the rules of selling electricity “outside their fence”, an issue that ports can face too.

Probability: High

The probability ports will have to deal with electricity rules that are not designed for electrification in ports and OPS business models that allow for return on investment is high as most EU countries have similar electricity sector regulations.

Impact: Medium

This challenge will especially affect ports that own and operate the distribution grid and want to (re)sell electricity to OPS customers and terminal tenants. It will require all ports to change the way they have been approaching the electricity supply and grid activities in the past, especially if they are interested in self-generating power and selling it. Depending on the Member State this activity could require them to become retailers of electricity which includes certifications, licenses, additional staff, and understanding a new business that is non-traditional to port operators. This can be costly and time consuming.

Mitigating actions

Restructuring electricity sector rules and regulations at national level or proving specific electricity network tariffs or programmes ports can participate in could alleviate some of the challenges resulting from electricity rules.

Regarding OPS, there is some precedence in shore power supplied at a markup, for example at Dutch onshore power facilities for ships at ports, canals and waterways[89,90]. This solution is similar to public electric vehicle (EV) charging paying schemes. Third parties could provide these services. For example, at the port of Gothenburg the port authority is not responsible for designing, building, maintaining or operating OPS systems, but only agrees to the use of the land, neither does it act as electricity supplier; this approach can be used in ports and countries with strict regulations on electricity resale.

Selling excess electricity that ports do not self-consume without obtaining a supply license, could be achieved by sharing the excess electricity against a price as active customers (which is part of the political agreement on the Electricity Market Design reform in the new Article 15a "right to energy sharing").

Energy collaboratives that bring together utilities, technology providers and terminal operators can bypass some of these challenges by assigning the roles and responsibilities of power supply or provision to non-port authority parties. This mitigation though could remove part of the income of providing such services from the port managing authorities, which could affect OPS payback periods if the port authorities were the investing entities. Ports operating as some type of utility (e.g. network or supply activity) could lease this operation to a third party and focus on their core activities where their competences already lie.

Probability after mitigation: Medium

Though there are a number of mitigating actions available, some will be more difficult to implement as they require external intervention, such are electricity regulation restructuring. The challenges and the mitigating solutions are also Member State dependent, and some ports may still face difficulties that reduce their options for providing OPS services after mitigations.

Impact after mitigation: Low

The mitigation actions can remove most of the impact these rules have on successful port operations relating to electrification and OPS services, thus the impact assessed after mitigation actions can be considered low.

6.2.8 Challenge: Lack of Global Regulations for OPS and Carbon Pricing

Introduction/context

No global regulations have been adopted for mandatory provision of OPS installations or for carbon emission reductions which can affect European ports' competitiveness.

Observations

The EU has established OPS standards and regulations to promote the use of onshore power and reduce emissions and air pollution from ships while at berth. However, there are currently few (e.g. California and China) non-EU international OPS mandates in place. This means that ports in non-EU countries may not have the same level of infrastructure or requirements for OPS. If EU ports have to adhere to strict OPS mandates, while ports outside the EU have less stringent or non-existent regulations, this imbalance can create an unfair advantage for non-EU ports, as ships docking there would not need to comply with the same environmental standards or incur the additional costs associated with OPS. This is particularly a possible threat from neighbouring countries, though it may not materialize from the UK, as in February - April 2022 the UK Department for Transport had a "Call for evidence on shore power"

[89] Easy2Pay Walstroom, https://walstroom.eu/en/

[90] Connect 4 Shore, https://connect4shore.nl/tarieven/

requesting information from ports and other stakeholders regarding the use of maritime shore power in the UK. The results expressed that 73% of responders were supportive of shore power. However, this may not be the case with North African ports where such interests are currently not published nor expressed.

Some EU ports are concerned that the European Emissions Trading System (ETS) can negatively affect them especially regarding transhipment traffic[91]. From the perspective of the ports, routes originating in Asia and America are most likely to be impacted. Vessels on these routes can stop at sites close to Europe to pay lower emissions taxes. For example, they could stop at the Turkish ports of Tekirdag, Ambarli, Aliaga, and Mersin, Tanger Med in Morocco, East Port Said in Egypt, Ashdod and Haifa in Israel, and Beirut in Lebanon.

Probability: Medium

The probability that European ports will face challenges and become less attractive for international vessels due to the lack of global regulations that promote emissions reduction via OPS and carbon taxes is medium. A number of non-EU countries such as China and the US are also promoting the deployment of OPS and the reduction of port emissions. Thus, ships that originate from these countries will likely have to conform to similar emissions reduction requirements at the point of origin. The probability that other vessels will bypass European ports due to the ETS is also medium-high since emission rights are based on the route of the ship, meaning ships originating from further away will pay more. Ports located in the Mediterranean basin will more likely face the issue of ships choosing alternative ports to berth.

Impact: Medium

The impact of the lack of global regulations to ports is medium. Some ports (Mediterranean basin) will be impacted more and could face reduction of port calls from specific types of vessels. This can impact the port's economic performance and growth.

Mitigating actions

Establishing global regulations for OPS would ensure a level playing field for ports worldwide. It would accelerate deployment and encourage the adoption of OPS practices, regardless of the geographical location, thereby reducing emissions from ships and minimizing the competitive advantage gained by ports with weaker or no OPS regulations.

Similarly for the ETS, the European Commission could apply environmental taxes to ships that stop at the ports in close proximity to European ports. Currently, one existing mitigation measure is that stops by container ships at 'neighbouring (300 nautical miles) container transhipment ports' do not count to determine the start or the end of a voyage covered by the EU ETS. The Commission has identified Tanger Med (Morocco) and East Port Said (Egypt) as 'neighbouring container transhipment ports'.

Probability after mitigation: Low

The mitigations would mostly resolve this challenge for the majority of European ports and will significantly reduce the probability ports will lose completeness. It is thus reduced to low.

Impact after mitigation: Low

Similarly, the impact would also be reduced. Some vessels could still choose non-European ports for other reasons such as lower electricity procurement costs, but that is no longer due to the lack of global regulations.

6.2.9 Other Challenges

Though industry consortia and collaboration between ports exist, lessons learned are not always translated to actionable steps. The in-between decisions which are made case-by-case and play a significant role in the end results, are typically not shared widely. Time is required to understand the operation of new technologies, together with possible

[91] Valenciaport warns of the diversion of traffic to non-EU ports to evade payment for emissions, https://www.valenciaport.com/en/valenciaport-warns-of-the-diversion-of-traffic-to-non-eu-ports-to-evade-payment-for-emissions/

issues, meaning that initially ports will have to trust technology providers and make an effort to share lessons learned with their peers. The IMO could also help communicate the needs for implementation on the shoreside and not only the vessels. Electrification of ports may require changes to port operations, such as adjusting schedules (e.g. for battery recharging). Ports need to operate and provide services that are not typically provided by most ports.

Renewable electricity generation capacity shortages can be a challenge as different parts of the economy electrify and decarbonise simultaneously. Ports will heavily depend on renewable energy either sourced by third parties such as utilities, or self-generated. Most ports do not have the capability of becoming self-sufficient by generating all their electricity requirements, especially considering the increase in electricity demand due to OPS and electrification. A concern is that ports will need to compete with other end-users to procure renewable energy as the entire economy is electrifying and decarbonizing.

6.2.10 The most significant barriers to OPS and electrification

Table 6-2 below provides the magnitude of the barriers and challenges after the proposed mitigations. The most significant issues are those that were marked as red pre-mitigation (see Table 6-1) and are still marked as orange post-mitigation. These are the barriers believed to be the most difficult and/or costly to manage.

The table also includes whether the mitigation is primarily an internal issue for ports, or an external issue for outside organisations to manage. It also provides a view on whether the mitigation is likely to be costly. The cost implication does not only refer to port associated costs, but overall costs needed to implement the proposed mitigations.

Table 6-2: Summary of barrier and challenge magnitude after mitigations

Barrier	Probability	Impact	Overall magnitude	Internal / External	Cost Implication
Electricity grid capacity limitations and upgrade delays	M	M	MM	External	High
Infrastructure investments - high costs and access to capital	M	M	MM	Internal / External	High
Lack of workforce availability and technical skills	M	M	MM	Internal / External	Low/ Medium
Challenge					
Implementation of suitable business model for OPS	L	L	LL	Internal / External	Low
Electricity costs and grid tariffs	M	M	MM	External	Medium
Lack of available space	L	M	LM	Internal	Medium
Electricity supply / provision rule limitations	M	L	ML	External	Medium
Lack of global regulations for OPS and carbon pricing	L	L	LL	External	Low

6.3 Renewable and Low-carbon Fuels

Low-carbon fuels means recycled carbon fuels as defined in Article 2, point (35), of Directive (EU) 2018/2001, low-carbon hydrogen and synthetic gaseous and liquid fuels the energy content of which is derived from low-carbon hydrogen, which meet the greenhouse gas emission reduction threshold of 70% compared to the fossil fuel comparator for renewable fuels of non-biological origin set out in the methodology adopted according to Article 29a(3) of Directive (EU) 2018/2001". In this report, renewable hydrogen (and derivatives) is the main area of focus – biofuels can generally be blended in existing infrastructure and are therefore not a challenge for ports to handle. Ports are interested in the hydrogen opportunities that may materialise for them including onsite usage for port operations and handling of hydrogen and derivatives.

The starting point is that **direct electrification of port operations is the priority.** Literature review, feedback from two workshops and individual interviews with ports indicate that most ports that are not industrial ports or ports connected to Hydrogen Corridors will not be utilising hydrogen, at least not in large quantities. The reason is that electrification is already underway and more economical, and hydrogen is not required to further decarbonise operations in most cases. Where electrification is not an option for port operations, or where there are substantial barriers to its adoption, then hydrogen may be a good alternative. In practice, we may see a combination of direct electrification with a smaller amount of complementary hydrogen usage in some ports. Due to lower efficiency, hydrogen is likely to be more expensive than direct electrification, but in some cases may bring operational advantages, for example faster refuelling times and lower peak electricity demand. The “Study on hydrogen in ports and industrial coastal areas”[92] by the Clean Hydrogen Joint Undertaking provides more information on outlooks of the potential hydrogen demand and supply in European ports, the required non-technical enablers, areas of priority for research and innovation projects and required safety regulations, codes, and standards and the techno-economic feasibility of developing a range of hydrogen-related activities and infrastructures.

For the purposes of this report, the barriers and challenges are mainly focused on port operations and are predominately applicable to ports that expect to use larger volumes of hydrogen, including hydrogen production and storage at the port:

- Fuel bunkering for ships is not in scope.
- The role of ports in handling large volumes of hydrogen and derivatives for use in local industrial clusters is in scope but the use within the clusters and the onward transport to inland locations, is also not in scope.

Some barriers, however, will also be relevant for the role of the port in handling fuels for use in local industry. These include safety distances for hydrogen and ammonia storage at scale, high investment costs in infrastructure for storage and bunkering of green fuels, transport of hydrogen by sea at a large scale, and the technical maturity and economic feasibility of GW-scale hydrogen production facilities.

There are other barriers relating to clean fuels - including investments in green fuel bunkering infrastructure, uptake of green fuels in shipping, resilience of e-fuels, space and safety of handling green fuels onboard ship, efficiency of e-fuels, and competition within Europe - but these will not be examined in depth in this report as they relate more to maritime and bunkering activities. Table 6-3 provides a summary of the main barriers and challenges relating to hydrogen.

[92] Study on hydrogen in ports and industrial coastal areas – Reports, https://www.clean-hydrogen.europa.eu/media/publications/study-hydrogen-ports-and-industrial-coastal-areas-reports_en

Table 6-3: Summary of main barriers and challenges to hydrogen by severity

Barrier	Probability	Impact	Overall magnitude
Cost of renewable hydrogen	H	H	HH
Space for hydrogen production and handling, including safety distances	M	H	MH
Technical maturity and economic feasibility of GW-scale hydrogen production facilities	H	M	HM
Electricity grid capacity upgrades for renewable hydrogen	M	M	MM
Challenge			
Permitting	H	H	HH
Transport of hydrogen to the port	L	M	LM

6.3.1 Barrier: Cost of Renewable Hydrogen

Introduction/context

Switching to renewable hydrogen may be an expensive decarbonisation pathway for ports. While converting equipment or purchasing new hydrogen-fuelled equipment such as reach stackers may not be prohibitively expensive, purchasing or producing hydrogen could be. Terminals and port authorities will have to either invest in hydrogen production or secure an economic hydrogen supply for their operations. As DNV concluded in its 2023 “Transport in Transition” report,[93] “What electrifies will be cheaper, but hydrogen and sustainable biofuels cannot compete cost-wise with oil.” This will also be an issue for stationary machinery at ports, which is currently generally powered by diesel. Of course, very high EU ETS prices would improve the business case for switching to renewable hydrogen, but this would also improve the business case for electrification – as the relatively high cost of hydrogen would remain a barrier.

Observations

Discussions with ports such as Valencia, and Rijeka show different approaches to hydrogen. The Port of Valencia is involved in a hydrogen pilot and has expressed interest in the business model of a small onsite electrolyser (operated by a 3rd party). They argue that onsite production could be more economical since logistics costs of purchasing and transport are removed. The Port of Rijeka has a strong grid connection and argues that electrification is a better solution for the port both technologically and economically.

DNV research finds that hydrogen fuel cell commercial vehicles are likely to cost significantly more than either diesel or battery electric commercial vehicles, as detailed below. DNV expects a similar cost differential for terminal equipment (compared with mobile vehicles). In terms of operating costs, renewable hydrogen will likely cost more than direct electricity since part of the electricity will be lost in hydrogen conversion.

DNV’s Energy Transition Outlook (ETO) 2023 report provides a detailed model of energy production, transportation and end-use in ten global regions, including Europe. The model compares the cost of various commercial vehicle types out to 2050,[94] and finds that hydrogen fuel cell commercial vehicles are considerably more expensive than battery electric and internal combustion engine commercial vehicles:[95]

[93] 2023 Transport in Transition, https://www.dnv.com/Publications/transport-in-transition-242808

[94] This is based on factors such as expected electricity, hydrogen and oil prices, battery and fuel cell technology learning rates, and electrolyser costs

[95] Energy Transition Outlook (ETO) 2023, https://www.dnv.com/energy-transition-outlook/download.html

- **Total cost of ownership:** Fuel cell vehicles are expected to be 1.5 times as expensive as internal combustion vehicles and 1.7 times as expensive as battery electric vehicles in 2030. In 2040, fuel cell vehicles are 1.4-1.5 times as expensive as combustion and battery electric vehicles.
- **Operating cost:** Considering only operational costs, fuel cell vehicles are expected to be 1.6 times as expensive as combustion vehicles and almost twice as expensive as battery electric vehicles in 2030. By 2040, the gap narrows, but fuel cell vehicles are still nearly 1.4 times as expensive as combustion vehicles and nearly 1.6 times as expensive as battery electric vehicles.

The category “commercial vehicles” covers a wide range of vehicle types, and so the comparison figures should be seen as averages. The cost comparison also ignores other relevant factors such as refuelling/recharging times and storage requirements. Nevertheless, there is a persistent gap between hydrogen vehicle and battery vehicle costs. The picture is likely to be similar for fixed.

The production and use of H_2 for terminal equipment with onsite produced RES electricity case presented in Chapter 5.5 also demonstrates the increased costs of hydrogen-fuelled equipment compared to BaU.

Large-scale renewable hydrogen production

Levelised costs of renewable hydrogen production are expected to fall over time, as electrolysers become less expensive and the number of hours of low-priced electricity rises. For Europe as a whole, DNV’s Energy Transition Outlook (ETO) finds that renewable hydrogen production costs currently average over 5 EUR/kg but predicts that costs will fall to around 2 EUR/kg in 2030. Research from the Boston Consulting Group is more pessimistic, finding that projects currently in development are likely to show renewable hydrogen production costs of 5-8 EUR/kg in 2030 for Central Europe.[96] The report identified a number of drivers for cost increases relative to previous projections, including:

- Higher capital costs, as can be seen more generally in the market at present.
- Fewer electrolyser full-load hours than previously assumed, as wholesale power markets offer higher prices for wind farms.
- Supply chain constraints for wind turbines generation and electrolyser manufacturing.
- Lack of infrastructure to cost-effectively transport the hydrogen.

This implies that the cost of large-scale renewable hydrogen production will also be a challenge for ports that wish to install large electrolyser projects on their land.

Probability: High

We assess the likelihood of this barrier occurring as high. Regions with low renewable hydrogen production costs are also likely to have lower electricity prices, so the relative cost gap between operating battery electric and fuel cell vehicles will remain. Improvements in electrolyser efficiency and reductions in electrolyser CAPEX and fuel cell costs will reduce the gap in both operating costs and total cost of ownership, but we still expect batteries to be the cheaper solution.

Importing hydrogen by ship from parts of the world that have lower electricity and hydrogen production costs is unlikely to be a viable solution for ports’ own use, given the high costs of shipping and processing hydrogen.

[96] Boston Consulting Group, Turning the European Green Hydrogen Dream into Reality: A Call to Action, October 2023 https://media-publications.bcg.com/Turning-the-European-Green-H2-Dream-into-Reality.pdf

Impact: High

Relative costs will prove to be a major barrier to the adoption of renewable hydrogen in port operations, limiting hydrogen usage only to those operations that are more difficult to electrify, or providing an alternative if the port's electricity grid connection is congested and there are viable means of transporting hydrogen to the port.

Mitigating actions

It is hard for a port to mitigate the cost gap by itself since battery and fuel cell vehicle costs will be largely determined by global markets and local electricity and hydrogen production facilities.

The main mitigating actions for ports are to:

- Find uses for hydrogen which offer operational advantages that outweigh the higher fuel costs, for example faster refuelling times supporting continuous operation.
- Use hydrogen to mitigate electricity grid capacity constraints, which limit direct electrification of port activities. For example, if the port's electricity grid connection capacity is fully used by OPS, then port cargo activities could be powered by hydrogen transported to the port via a pipeline connection.

The main external mitigation is subsidies to reduce the cost of renewable hydrogen for consumers. The first European Hydrogen Bank auction was launched in November 2023, and a further auction is planned for spring 2024.

Probability after mitigation: Medium

Hydrogen may still have a cost disadvantage compared to electrification, but subsidies for renewable hydrogen will help to reduce the gap. Ports will also need to find a targeted role for hydrogen, where it offers operational or other benefits.

Impact after mitigation: Low

Targeting hydrogen use for specific activities in the port will greatly reduce the impact of relatively high hydrogen costs. A high hydrogen cost may also be a barrier to the port handling larger volumes of hydrogen for industrial clusters. In this case direct electrification may not be a suitable alternative to hydrogen (e.g. very high temperature industrial processes and feedstock uses), but high costs may slow down the adoption of renewable hydrogen in industry.

6.3.2 Barrier: Adequate Space for Hydrogen and Ammonia, including Safety Distances

Introduction/context

Both the physical space required for hydrogen and ammonia storage, and the regulatory safety distances, may present barriers to **large-scale** hydrogen and ammonia handling and storage at some ports. Regulatory safety distances, and the high cost or energy requirements of hydrogen liquefaction and ammonia cracking, may present barriers to liquid hydrogen and ammonia storage at scale in some ports.

Note that ports are unlikely to store hydrogen in ammonia form for use within the port. However, they may store and handle ammonia imports for use in local or regional industry.

Note that we refer to "safety distances" below, which could be described as the necessary spatial distance between environmentally taxing functions and environmentally sensitive functions to protect facilities and the environment.

Observations

DNV has carried out various work on the space and safety requirements of hydrogen production and storage options, some of which present a greater barrier than others. Electrolysers themselves require a significant amount of space and safety distance zones for large systems.

- **Space**: 8-17 ha for a 1 GW plant (depending on alkaline or PEM), including electrolyser installation and building, gas compression and treatment, and utilities[97] or around 7-10 ha for a 500 MW plant.
- **Safety distances:** The safety zone for a 500 MW electrolyser is about 300m around the installation, and the sound zone is 500m.

The space requirement and safety distance barrier severity can be considered low if ports are only interested in hydrogen for their own use, in which case a smaller electrolyser would be needed. Hydrogen and ammonia storage have their distinct requirements regarding space and safety distances as shown in the table below. In all cases, mitigation actions, which may be costly, would reduce the size of the safety zones.

Safety distances will be site-specific, and will also depend on various mitigating (costly) measures that may be possible. As shown in the table below, the unmitigated safety distance for both hydrogen and ammonia storage (above the Seveso threshold) is 700m.

Seveso III (2021/18/EU) is a European Directive which aims to prevent major accidents involving dangerous substances from happening, but ensuring 'reasonable distances' to any areas to be protected. But as accidents cannot be ruled out entirely, the directive also ensures that a company is appropriately prepared and will respond should an accident occur. It also requires measures to limit the consequences of such accidents on human health and the environmental and to identify the causes and learn lessons.

- For hydrogen storage, the directive (and the unmitigated 700m safety distance) applies to storage volumes of between 5 and 50 tonnes of hydrogen.
- For ammonia storage, the directive applies an (unmitigated) 700 m safety distance to storage volumes of 100-200 tonnes of ammonia.

Note that, although the unmitigated safety distances of hydrogen and ammonia are the same, their characteristics differ – hydrogen will rise in the air and is highly flammable, and ammonia will stay at ground level and is highly toxic, meaning that the spread and consequence pattern in the event of a leak will be different.

For ammonia bunkering, safety distances are defined following ISO 18683 and ISO 20519. However, matters are a bit more complex as ammonia also requires toxic zones and protection zones. These zones can be defined using the same methodology (ISO 18683), however risk acceptance criteria (risk based) or maximum concentrations (consequence based) need to be defined and agreed with port authorities to proceed.

Table 6-4: Hydrogen and ammonia storage barrier summary

	Gaseous hydrogen storage	Liquid hydrogen storage	Ammonia storage
Space	1,000 tonnes of gaseous hydrogen storage (compressed at 21 bar) would need around 9 ha and 135 storage vessels.	1,000 tonnes of liquid hydrogen storage would need around 0.3 ha and around 4 storage vessels.	• 1000 tonnes of hydrogen stored in ammonia form would require around 5,500 tonnes of ammonia storage, which would require less than 0.1 ha and 1 storage tank. • A 50,000 ton ammonia storage tank would be around 50m in diameter, or 0.25ha[98].
Safety distances	The safety zone is about 700m around the storage facility. Note that this is for storage capacity above the Seveso threshold, and is before any mitigating measures are applied.		
Economic challenges		Current state of the art liquefaction technology requires at least 30% of the energy contained in hydrogen for the liquefaction process, making it an energy-intensive and costly process[99].	• If the end use is gaseous hydrogen, an ammonia cracker would need to be installed, requiring considerable additional cost and land. Ammonia cracking is expected to cost EUR1-2 per kg of hydrogen[100]. • Hydrogen produced by onsite electrolysis is unlikely to be converted into ammonia for storage, to be reconverted back into gaseous hydrogen when needed.
Barrier severity	**Medium:** • DNV assesses that storage facilities would need to hold around 10% of annual consumption if the electrolysers are connected to an offshore wind generation profile. Adding solar PV to the wind would reduce the storage requirements to around 5% of annual consumption. • On this basis, Valencia would need around 225-450 tonnes of hydrogen storage, (based on 5-10% of 4,500 tonnes of H2 demand per year, or 150 GWh – see electricity grid capacity barrier) requiring around 2-4 ha, plus the safety distance	**High:** • DNV assesses that storage facilities would need to hold around 10% of annual consumption if the electrolysers are connected to an offshore wind generation profile. Adding solar PV to the wind would reduce the storage requirements to around 5% of annual consumption. • On this basis, Valencia Port would need around 225-450 tonnes of hydrogen storage, (based on 5-10% of 4,500 tonnes of H2 demand per year, or 150 GWh – see electricity grid capacity barrier) requiring around 0.07-0.14 ha, plus the safety distance. • Although the land requirements are smaller than for gaseous hydrogen, to liquefy the hydrogen, considerable additional energy would be required, which may be impacted by the grid connection barrier, and in any case is costly. Therefore, we assess the barrier to liquid hydrogen storage to be higher than for gaseous storage.	**Medium:** • Ammonia storage does not require large space, although the safety distances are large. • However, the energy and cost required to convert hydrogen to ammonia for storage, and back to gaseous hydrogen for end-use, is likely to be prohibitive, compared to onsite gaseous hydrogen storage. • If the end use is ammonia, for example as a feedstock in local industrial clusters, then no cracking is required, making it a cost-effective option for ship transport. In this case, large-scale ammonia storage tanks can be installed on port land (subject to safety distances). • In some cases, ports already handle grey ammonia, and their existing storage facilities will be able to handle green ammonia without modification.

98 See, for example https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks

99 Hunt et al, Solid air hydrogen liquefaction, the missing link of the hydrogen economy, International Journal of Hydrogen Energy, 1 September 2023 https://www.sciencedirect.com/science/article/pii/S0360319923015720#:~:text=The%20liquefaction%20of%20hydrogen%20consumes,the%20hydrogen%20gas%20%5B8%5D.

100 Ortiz Cebolla, R., Dolci, F. and Weidner Ronnefeld, E., Assessment of hydrogen delivery options, EUR 31199 EN, Publications Office of the European Union, Luxembourg, 2022 https://publications.jrc.ec.europa.eu/repository/handle/JRC130442

For certain ports, it is possible that the safety distances for large-scale hydrogen and ammonia storage may simply be too great, given their proximity to residential areas. This will make it very difficult for some ports to be able to handle hydrogen and ammonia at scale. Examples are the Port of Hamburg and the Port of Amsterdam. For other ports, such as the Port of Rotterdam, safety distances are unlikely to be a major barrier.

There is also a trade-off between hydrogen production cost and hydrogen storage volumes. Up to a certain point, higher storage capacity will allow to reduce the required load hours of the electrolyser, ensuring that hydrogen is produced when low-cost electricity is available, and therefore reducing the levelised cost of hydrogen. If there is little hydrogen storage capacity, then the electrolyser will need to run for more hours, including during times of higher electricity prices, and therefore the average cost of hydrogen production will increase.[101]

Probability: Medium

The probability of this barrier occurring, with respect to hydrogen storage for the port's own use, will depend on the port in question, with a high probability for ports located near residential areas, and a low probability for ports with more space – we therefore assess the probability of this barrier to be medium overall.

Nevertheless, there is a high probability of this barrier occurring for the storage and handling of large volumes of hydrogen and ammonia, for use in local industrial clusters.

Impact: High

For ports facing this barrier, safety distances may make it almost impossible to store hydrogen and ammonia at sufficient scale.

Equally, where mitigation actions to reduce the safety distance are possible, they may be costly. It is not possible to provide a guideline cost, as the mitigations will be very location specific, and will depend on the volumes of hydrogen and ammonia being stored.

Mitigating actions

Firstly, careful site and port selection for ammonia and hydrogen storage and handling needs to be made by the ports (internal mitigation).

Secondly, under AFIR, Member States need to start planning for the entry into the market of alternative fuels (including hydrogen, ammonia and methanol). These national policy frameworks need to be submitted by January 2025. This is an external mitigation as it requires Member States to make locational decisions. The cost implication depends on the port, and the required and available space, but the cost could be low since this mitigation primarily concerns strategic port and location selection.

A third mitigation is for the port to make connections to wider hydrogen transport and storage infrastructure, such as a national backbone pipeline linked to salt cavern storage. This would greatly reduce the volume of hydrogen needing to be stored at the port.

Finally, ports can put in place mitigating measures to reduce safety distances. These will be site-specific and will depend on the volumes being stored – a barrier wall may be one example. Mitigations may also be costly.

Probability after mitigation: Medium

[101] Note that there are other trade-offs, including the required electricity grid connection to the port (which incentivises higher running hours), and the trade-off between electrolyser capex (which incentivises higher running hours) and electricity prices (which incentivises lower running hours). The optimum load-factor for electrolysers will vary by location depending on these characteristics.

For certain ports, the barrier is still likely to occur post mitigation, even if fewer ports will be affected. We therefore still assess the probability of this barrier occurring to be medium.

6.3.3 Barrier: Technical Maturity and Economic Feasibility of GW-Scale Hydrogen Production Facilities

Introduction/context

For ports that plan to install major renewable hydrogen production facilities, the limited technical and commercial maturity of GW-scale electrolysis is still an important barrier, given that relatively few large-scale projects have taken final investment decisions.

Observations

A number of European ports have plans for large-scale electrolysis facilities. For example, the Port of Rotterdam Authority has the aim to install 2-2.5 GW of electrolysis by 2030 and is developing an 11 ha site suitable for the construction of an electrolyser facility of up to 1 GW.[102] The risk of GW-scale electrolyser technology is that it takes longer than expected to mature, which delays the commissioning of GW-scale electrolysis plants in the EU. Delays in GW-scale projects in non-EU countries may also delay the large-scale handling of hydrogen and hydrogen derivative fuels arriving by ships at European ports – this could also mean that the EU's target of 10 million tonnes of renewable hydrogen imports per year by 2030 is not achieved on time.

Note that, using an average offshore wind turbine load factor, 1 GW of electrolysis capacity would produce around 100,000 tonnes of hydrogen a year, which is still relatively small compared to the tonnages of fuels handled by many ports.

Electrolysers are a proven technology, but they are at present in operation at a much smaller scale than expected. For example, the largest electrolyser in operation today in Europe is 20 MW, the largest under construction in Europe is 200 MW – ambitions, however, are for electrolysis at the hundreds of MW or at the GW-scale.

Key findings from recent studies and market surveys include:[103]

- Globally, planned low-carbon hydrogen investments to 2030 total USD 320 billion, but only USD 29 billion has taken a final investment decision (FID). Global electrolyser production in 2022 is estimated to be around 1 GW. Manufacturers have announced plans to reach 155 GW/year of manufacturing capacity by 2030, but just as overall planned hydrogen investments, only 8% of this capacity has taken a FID.
- Annual global production of low-carbon (blue) hydrogen could reach 38 million tonnes in 2030, if all announced projects are realised. But only 4% of this potential production (nearly 2 million tonnes) has taken a FID.
- Higher prices for equipment and higher interest rates are negatively affecting project financing. As the IEA has pointed out, an increase of 3 percentage points in the cost of capital could raise total project cost by nearly one third. Several project developers have revised their initial cost estimates upwards by up to 50%. This means that government subsidies are likely to support a smaller number of projects.
- The EU's ambition of 10 million tonnes per annum of renewable hydrogen production in Europe by 2030 would require the delivery of 500 projects of equivalent size to the largest such project to achieve financial close in Europe to date (the 200 MW Holland Hydrogen 1 project in Rotterdam).

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[102] See https://www.portofrotterdam.com/en/news-and-press-releases/port-of-rotterdam-authority-site-green-hydrogen-plant-1GW#:~:text=Several%20companies%20have%20plans%20to,4%20GW%20nationwide%20by%202030.

[103] Hydrogen Council, Hydrogen Insights 2023, May 2023 https://hydrogencouncil.com/en/hydrogen-insights-2023/; IEA, Global Hydrogen Review 2023, September 2023 https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aaa175d/GlobalHydrogenReview2023.pdf; Worley, From Ambition to Reality 3: Steps to accelerate net zero delivery, 2023 https://comms.worley.com/From-Ambition-To-Reality-3-Download; DNV, Energy Transition Outlook 2023, October 2023 https://www.dnv.com/energy-transition-outlook/download.html

- DNV forecasts that the total hydrogen production from electrolysis in Europe (including Norway and the UK) will reach around 3 million tonnes in 2030, considerably below the EU's 10 million tonne target.
- Delays in electrolyser projects globally will also impact the volumes of hydrogen and ammonia imported to European ports via ship. DNV forecasts that only around 100,000 tonnes of hydrogen will be imported by ship into Europe (including Norway and the UK) by 2030 – although ammonia imports are likely to be much larger.

Probability: High

The probability of this barrier occurring is high for the ports planning for large scale electrolyser capacity. As the IEA confirmed in its most recent Global Hydrogen Review, a number of investment decisions for hydrogen projects are being delayed[104], and delays will impact GW-scale projects in ports across Europe[105]. Developers in Europe mention difficulties and long waiting periods to access European subsidies that are in turn delaying project development. Without government funding these projects will not be developed as renewable hydrogen deployment is a nascent sector and private investors are reluctant to take on the risk.

Impact: Medium

The barrier will have a moderate impact on smaller-scale electrolyser projects to provide hydrogen for the port's own use, with hydrogen likely available somewhat later and at higher cost than expected, whether the hydrogen is produced onsite or transported to the port.

For ports that plan to produce renewable hydrogen at GW-scale (or import large volumes of hydrogen) for use in local industrial clusters, the barrier will have a greater impact, potentially significantly delaying their ambitions.

Mitigating actions

Support schemes at EU and Member State level would help to fund the investment and operational costs of large-scale electrolysis projects in Europe. The EU's support through the Innovation Fund, including the planned auctions, is a good start, but significantly more resources would need to be committed at both EU and Member State level to offset the high costs and encourage offtake, sufficient to reach the EU targets.

Probability after mitigation: Medium

Additional government support will help to ensure a positive business case for large-scale hydrogen production, but we still expect hydrogen projects to take longer to scale than anticipated.

Impact after mitigation: Medium

We expect that hydrogen will take somewhat longer than expected to scale, even with significant support. Support schemes to bridge the gap between the cost of hydrogen production and the cost of existing and low-carbon alternatives will encourage the adoption of hydrogen for port use, and in industry, providing more secure offtake for production projects and for port investments in dedicated terminals and other equipment for hydrogen (and ammonia) handling.

6.3.4 Barrier: Electricity Grid Capacity Upgrades

Introduction/context

For renewable hydrogen to be used to decarbonise port equipment, such as cranes, forklifts, reach stackers and yard trucks, the hydrogen will either need to be produced from onsite electrolysis, or produced offsite and transported to the

[104] IEA, Global Hydrogen Review 2023

[105] Hydrogen Insight, https://www.hydrogeninsight.com/policy/european-green-hydrogen-projects-are-being-delayed-due-to-torturously-slow-eu-subsidy-processes-say-developers/2-1-1483308,
Procorre, https://www.procorre.com/blog/hydrogen-project-delays-mean-massive-shortfall-looks-set-by-2030/

port. Onsite hydrogen production (similarly to OPS and port electrification) could be supported from onsite renewable electricity generation but would most likely need additional electricity grid capacity.

Observations

The volume of hydrogen required to decarbonise port operations will depend greatly on the volume of cargo handled, and the penetration of hydrogen (versus direct electrification). A recent report by Deloitte for the Clean Hydrogen Partnership estimated that 0.58 MWh of hydrogen would be needed per TEU if all cargo handling was fuelled by hydrogen.[106] We assume in line with this report and the TNO case study for the Port of Rotterdam, hydrogen use in cargo handling would rise to around 5% (0.03 MWh per TEU) by 2030. In this case, the 5 million TEUs handled annually by the Port of Valencia would require 150 GWh of hydrogen, or at least 200 GWh per year of input electricity (assuming an electrolyser efficiency of 75%). This would require an electricity grid connection of nearly 25 MW if the electrolysers ran full load, or about twice this capacity if the electrolysers ran at partial load (e.g. about 4000 full load hours).

Nevertheless, without conversion efficiency improvements, onsite hydrogen production for port operations may require substantially larger electricity grid connections:

- If the electrolyser ran full load, it is possible that not all the hydrogen would meet the EU's definition of renewable hydrogen, given that at certain times grid electricity is mainly fossil-based. Also, this would mean producing hydrogen at times of high power prices, which would be uneconomic. So, it is more likely that the electrolyser will run partial-load, although storage of hydrogen would then be needed to meet demand from sectors such as industry, which generally requires a consistent load.
- It is, however, also unlikely that an electrolyser could only operate at times of lower OPS demand, as these may not coincide with periods of cheaper and greener electricity. Ships need to use OPS when they are at port regardless of the proportion of renewable electricity in the grid at that particular time. A grid connection capacity may therefore need to be large enough to accommodate both hydrogen production and OPS.

This leads to the same electricity grid capacity barrier described earlier for the deployment of OPS and electrification of port activities – please refer to this barrier for further details.

Probability: Medium

As per the electricity grid connection barrier for OPS and port electrification described earlier, the probability of this barrier occurring is medium. Grid congestion and long lead times for new connections of reinforcement of existing connections are currently problems in 3 out of 8 ports studied.

However, within this "medium" category, the probability of this barrier occurring is lower than for OPS and port electrification. This is because hydrogen could be produced offsite and transported to the port – if this was the case, then there would be no need for a hydrogen-related electricity grid capacity upgrade.

Impact: Medium

The impact of this barrier is very port-specific and would depend on the planned volume of hydrogen. But the time taken to increase the grid connection, and the associated cost, may significantly affect deployment.

Given that there is no regulation to supply hydrogen for port operations by 2030, it may be difficult to have certainty on hydrogen demand and therefore electricity demand requirements for onsite hydrogen production. This means that the work to upgrade the electricity grid connection for hydrogen will either be based on an estimate, or it will take place later than the upgrades required for OPS (which has a 2030 deadline, and so cannot be delayed).

[106] Clean Hydrogen Partnership, Study on hydrogen in ports and industrial coastal areas, Report 1, March 2023 p.65 (note that this does not include the port vessel fleet) https://www.clean-hydrogen.europa.eu/system/files/2023-04/Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf

Mitigating actions

There are four possible mitigations to address this barrier:

- Target hydrogen use for areas that offer operational advantages over direct electrification, for example faster refuelling times to support continuous operation. Using hydrogen in a targeted way will reduce the overall volumes of hydrogen needed.
- Carry out the electricity grid capacity upgrades for onsite hydrogen production at the same time as for OPS and port electrification. If the planning for all three purposes can be carried out jointly, then grid capacity upgrades for hydrogen production can be delivered in parallel, with no further delays, and with some cost saving compared to grid upgrades in sequence.
- Purchase hydrogen produced offsite, and transported to the port, avoiding the need for additional electricity grid capacity for hydrogen production. Of course, the hydrogen transport would come at a cost, and so a cost comparison would need to be made.
- Onsite electricity generation (including offshore wind) can alleviate the need for capacity upgrades (see 6.2.1).

Probability after mitigation: Low

Given that these mitigation options are all highly plausible, it is likely that one or more of them would be adopted, reducing the likelihood of electricity grid capacity barriers preventing hydrogen projects from being realised.

For instance, a port could choose to minimise hydrogen requirements by directly electrifying as much as possible; deploy a smaller capacity of onsite electrolysis that mainly operates during times of lower power demand for OPS; and purchase hydrogen produced offsite.

Impact after mitigation: Low

The mitigation actions described above may not be sufficient to completely avoid the barrier of electricity grid upgrade delays, but applying just one of the mitigations would result in a greatly reduced impact.

Note that if ports were to produce hydrogen for use in local industrial clusters, then the grid connection barrier would be of a higher order of magnitude.

6.3.5 Barrier: Permitting of Hydrogen Facilities

Introduction/context

Currently there is no specific regulatory framework in the EU covering the production, transportation, storage or use of renewable hydrogen making the permitting process for hydrogen facilities difficult. In June 2022 the European Clean Hydrogen Alliance Permitting Working Group published a report that identified the main barriers to hydrogen project permitting[107] and provided recommendations for regulators and policy makers. The EU's Hydrogen Strategy[108] also mentions the need for the streamlining of permitting and administrative hurdles.

Observations

One of the main observations the report made is that in most Member States the regulatory framework to authorise hydrogen projects is not adequate or absent. Any existent permitting frameworks lack clarity, timelines, and applicable processes.

[107] Paving the Way for Permitting of Hydrogen Projects in the European Union: Barriers and Recommendations, https://ec.europa.eu/docsroom/documents/50514

[108] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, A hydrogen strategy for a climate-neutral Europe, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

Most existing legislation is based on fossil-based hydrogen production associated predominantly with chemical processing. Newer, clean ways of producing and using hydrogen are not yet defined in permitting rules making permitting hard both for developers and government authorities. The lack of specific (mandatory) timeframes for issuing permits is also a major barrier for hydrogen development. There are cases where permitting processes take longer than 2 years before construction can begin and even then, local authorities may still need to provide their own authorizations.

Often, permitting of such facilities falls under regional or local authorities which lack the knowledge of emerging technologies like clean hydrogen production, increasing permitting times. Furthermore, many municipalities have not considered hydrogen production or use and therefore do not have applicable permitting regulations. Similarly to renewable energy projects, the lack of skilled staff at permitting authorities increases delays and can severely affect project deployment. This becomes even more challenging for energy hubs and thus also ports, that are part of areas where multiple hydrogen and other clean energy projects will be deployed in short timeframes.

The lack of clarity on which government authorities are responsible for permitting these facilities and which standards and frameworks apply add to permitting issues and delays.

As most Member States do not have approved technical standards for clean hydrogen, inconsistencies and errors in project classifications are unavoidable. For example EU legislation mentions hydrogen proofed/ready technologies but there are no clear guidelines as to what that refers to. Vague and unclear language adds to permitting complexities.

The European Federation of Inland Ports also reports difficulties with public permitting procedures that are long and cumbersome which creates challenges for ports interested in developing hydrogen projects[109]. It states the need to obtain permits and approvals from multiple agencies and stakeholders which requires time, is complex, and needs coordination between different parties.

Probability: High

The probability of this barrier occurring is high. Most Member States lack permitting standards and guidelines for hydrogen projects, but efforts at the EU level to create permitting standards are being made to help resolve the issues.

Impact: High

The impact of permitting inconsistencies and delays on project deployment is high. Ports that are (planning to become) energy hubs may face longer delays and difficulties in being granted permits especially since larger stored capacities of hydrogen or ammonia lead to increased risks.

Ports that are interested in hydrogen for local port operations will still face permitting difficulties in most Member States, but the impact should be lower as these are less complex projects compared to large electrolyser and hydrogen or ammonia storage facilities.

Mitigating actions

The Clean Hydrogen Alliance Permitting Working Group report[110] provides specific recommendations to mitigate the barriers relating to permitting of clean hydrogen facilities. The most important mitigating action is the clarification and streamlining of legislative and regulatory frameworks at the EU and Member State levels for hydrogen production, transport, storage and usage. Legislation that is applied consistently across the different Member States will ensure the stability needed by project developers and end users.

The development of EU common technical standards will also help mitigate permitting uncertainties and delays, especially by supporting local permitting authorities with guidelines and knowledge sharing on these new technologies.

[109] Making hydrogen a success for Inland Ports, https://www.inlandports.eu/media/Making%20hydrogen%20a%20success%20for%20Inland%20Ports.pdf

[110] Paving the Way for Permitting of Hydrogen Projects in the European Union: Barriers and Recommendations, https://ec.europa.eu/docsroom/documents/50514

At the administrative level, a national point of contact at each Member State will allow project developers to access relevant information and ensure smoother overall processes throughout the countries.

Streamlining the permitting process by having clear procedures on how to treat different hydrogen projects will facilitate project development. Having the same process, when possible, at all Member States will increase efficiencies and clarity, in particular for operators that deploy activities in several Member States. Allowances for smaller or less complex projects for simpler permitting processes are an efficient way of facilitating deployment.

Setting mandatory maximum permitting time limits will also allow for more clarity and certainty for project developers, who are significantly affected by long and uncertain permitting timeframes. The longer the permitting processes last, the more costly a project becomes, and it can lead to projects being abandoned. The recently adopted RED III includes measures to speed-up the granting of permits for renewable energy projects, including a maximum of 12 months for onshore projects in designated renewables acceleration areas (RAAs) and a maximum of 24 months for onshore projects in other areas.

Knowledge sharing and building throughout the EU can reduce this barrier by increasing permitting staff technical and regulatory competencies.

Probability after mitigation: Medium

If all mitigating actions are adopted the probability of this barrier can be reduced to medium. To achieve all mitigations, a significant EU and national effort to coordinate permitting procedures is required. In this context, the RED III permitting measures are helpful, but transposing directives to the Member State level can be time consuming, especially for complex projects such as these.

Larger hydrogen projects will still be faced with lengthy permitting times, especially as technology continues to mature and permitting requirements will need to be updated as this happens.

Finally, the Net-Zero Industry Act (NZIA) (expected to enter into force in July 2024) sets up streamlined permitting processes for net-zero technology manufacturing projects. All net-zero technology manufacturing projects will benefit from Member States designating a national competent authority acting as a single point of contact, in charge of coordination and facilitation of permitting, guiding economic operators, ensuring that information is publicly accessible and that all documents can be digitally submitted. The Regulation sets detailed timelines for permitting procedures according to the nature of the project developed.[111]

Impact after mitigation: Medium

After the above mentioned mitigations, the impact can be reduced to medium. Since permitting procedures will likely develop over time as the technology matures and risks and safety issues are better understood, the impact permitting has on project development will be reduced. But, until more projects are deployed at scale, permitting issues and delays may still play a significant role to (large-scale) hydrogen project development and deployment.

6.3.6 Barrier: Transport of Hydrogen to The Port

Introduction/context

As described above, an obvious mitigation action to the electricity grid capacity barrier would be for a port to minimise onsite hydrogen production and instead purchase hydrogen produced offsite. However, this solution would present a new barrier, that of transporting hydrogen to the port, which may require new infrastructure.

Observations

[111] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) - COM/2023/161 final

Options for transporting hydrogen to the port vary, and will depend on the volumes required:

- For small volumes, compressed containers via road transport may be most suitable, but this can be an expensive transport option. A recent paper found that, for 350 bar cylinders transported 50 km by road, transport costs would range from around 0.7 EUR/kg for 10 MW (7.2 tonnes per day) to 1.0 EUR/kg for 2.5 MW (1.8 tonnes per day). For a distance of 150 km, the costs would amount to around 1.0 EUR/kg and 1.25 EUR/kg, respectively.[112]
- For larger volumes, pipelines are the most cost-effective option, but the actual feasibility and cost will depend on the proximity to a larger hydrogen backbone, from which a smaller offtake pipeline can be connected. A 25 MW demand may not be large enough for a longer-distance pipeline, and in this case, demand for hydrogen for port activities would need to be coupled with larger demand for hydrogen from local industry or fuel bunkering. A further challenge for pipelines is the need for purification of the delivered hydrogen to fuel cell grade (99.99%), as in many cases purity requirements for hydrogen in pipelines are lower (around 98%)[113] – purity requirements would be lower for hydrogen combustion engines.
- Further work to define costs of various hydrogen transport options is being carried out by Cigre.[114] This work will provide an up-to-date picture of the levelised cost of various hydrogen transport options, for various loads and distances.

Aside from cost, a key barrier for hydrogen road transport is the number of trucks required and associated local impacts. For instance, Cigre's ongoing work is showing that for 100km and a hydrogen load of 100tH2/day, a fleet of approximately 40 trucks would be required – and these would need to be arriving and departing 24/7. This may, however, be higher than needed by ports, if hydrogen only accounts for a small share of the port's energy use. Taking the scenario explained in the grid connection barrier of a 5% hydrogen share in energy used for container handling, the Port of Valencia would need around 12.5 tonnes of hydrogen per day.

For pipelines, the main barrier will be the time taken to obtain permits. Taking the Netherlands as an example, each part of the planned hydrogen backbone is expected to take around 3 years to progress through the permitting steps – assuming that there are no delays in the process.[115]

Probability: Low

The probability of this barrier occurring is very port-specific and would depend on the planned volume of hydrogen and whether this can be produced onsite. Given that there are no targets for port utilisation of hydrogen and that onsite production is a viable option (notwithstanding the electricity grid connection barrier described above), we expect that the probability will be low overall.

Impact: Medium

The impact of this barrier is also very port-specific and would depend on the planned volume of hydrogen. But given that the cost of hydrogen transport by road is quite considerable, and the pipeline alternative would require high volumes and lengthy permitting times, difficulties in transporting hydrogen to the port would have at least a medium impact.

Mitigating actions

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[112] Markus Hurskainen and Jari Ihonen, Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers, International Journal of Hydrogen Energy 45 (2020)

[113] DNV, NPL, Element Energy, Loughborough University, Health and Safety Laboratory, Hydrogen Purity – Final Report, 2019. The report recommended a minimum purity standard of 98% for UK pipelines. DNV and KIWA, Kwaliteitseisen voor waterstof t.b.v. het transportnet, 2022. The report also recommended a minimum purity standard of 98% for Dutch pipelines.

[114] Cigre, Role of green hydrogen in energy transition: opportunities and challenges from technical and economic perspectives https://www.cigre.org/share/article/6005/role-of-green-hydrogen-in-energy-transition-opportunities-and-challenges-from-technical-and-economic-perspectives

[115] See https://www.rvo.nl/onderwerpen/bureau-energieprojecten/lopende-projecten/waterstofnetwerk-nzkg

The most obvious mitigation action for ports is to produce hydrogen onsite, although this may lead to the electricity grid connection barrier described above.

The second mitigation is to use hydrogen for applications that offer operational advantages over direct electrification, for example faster refuelling times to support continuous operation. Using hydrogen in a targeted way will reduce the overall volumes of hydrogen needed.

Probability after mitigation: Low

Producing hydrogen onsite and targeting port hydrogen usage would reduce the likelihood of this barrier occurring. Although we assessed the probability already to be low, the mitigations would further reduce the probability.

Impact after mitigation: Low

The impact of this barrier post-mitigation would also be low, as the volume of hydrogen needing to be transported to the port would be smaller, reducing the economic and environmental impact of transport with trucks.

Note that if a port were to handle large volumes of hydrogen for use in local industrial clusters, then the barrier of transporting hydrogen to the port would be of a higher order of magnitude.

6.3.7 The most significant barriers to low-carbon fuels

The table below provides the magnitude of the barriers and challenges after the proposed mitigation actions. The most significant issues are those that were marked as red pre-mitigation (Table 6-3), but still marked as red or orange post-mitigation. These are the barriers that are the most difficult and/or costly to manage.

Table 6-5: Summary of clean fuel barrier and challenge magnitude after mitigations

Barrier	Probability	Impact	Overall magnitude	Internal / External	Cost Implication
Electricity grid capacity upgrades	L	L	LL	External	High
Technical maturity and economic feasibility of GW-scale hydrogen production facilities	M	L	ML	Internal / External	High
Cost of hydrogen	M	L	ML	External	High
Space for hydrogen production and handling, including safety distances	M	M	MM	Internal / External	Medium / Low
Challenge					
Permitting	M	M	MM	External	Medium
Transport of hydrogen to the port	L	L	LL	External	Low

6.4 Conclusions

The hardest barriers and challenges to be mitigated to facilitate OPS and electrification are the electricity grid upgrades that may be needed to support the increased electricity demand, the high energy infrastructure costs and access to capital, the electricity price level and grid tariff structure that result in high electricity procurement costs and the lack of available and skilled workforce.

It is important to address the barrier of adequate power supply to ports so that they can electrify and decarbonize more promptly. Overcoming this barrier is crucial for ports and shipping companies. By upgrading and extending the electricity grids, the ports can access reliable power supply, enabling them to provide onshore power to ships, reduce emissions, comply with regulations, and enhance energy and operational efficiency. Local electricity production in ports through for instance solar and wind energy installations could be part of the solution, especially in areas where expanding or upgrading the grid is challenging. Electricity generation that is not directly used for OPS can be stored or used for other port operations. The required batteries to balance intermittent electricity production will add to the already high CAPEX of wind and solar energy. This storage capacity can also be used to reduce peak demand taken off from the grid (peak shaving and load shifting) and to offer flexibility or adequacy services to the electricity market, as well as to grid operators.

Energy infrastructure costs are a barrier which requires significant investments. The costs are associated with building new substations and adding transmission lines, OPS, and electrification equipment. Limited funding or budget constraints can make it harder to allocate resources for electricity grid development and equipment purchases. Combining business models such as OPS, electrification, onsite electricity generation, energy storage, etc. can increase funding options and improve return on investment. Additionally, external factors are the regulatory frameworks and permitting processes which add to the complexity of mitigating the barrier.

Current electricity price levels and grid tariff structures are not favourable for equipment with high peak demand such as OPS used by large cruise or passenger vessels. In addition, the complexity of electricity markets can pose challenges in mitigating the barrier. Navigating these market complexities, securing favourable Power Purchase Agreements (PPAs) with electricity suppliers, and ensuring stable and predictable electricity prices can be difficult. Demand side management and integration of renewables and storage can help alleviate some of the issues. Collaboration with local utilities, regulators, and 3rd party electricity providers to agree on terms and tariffs appropriate for these new port needs is essential.

To facilitate the deployment of OPS, electrification, and low-carbon fuels, port personnel need to be able to operate and maintain systems based on these new technologies, but existing personnel typically does not have adequate knowledge or competencies relating to these technologies. As these technologies are increasingly being implemented by ports and other industries for their decarbonisation efforts, the lack of skilled workforce will become more evident and competition for these workers will increase, leading to ports facing a potential lack of skilled personnel. Actions, such as port training programmes to facilitate the transfer of knowledge and skills and new vocational programmes, must be taken now to prevent the knowledge and skills gap.

There are several key barriers/challenges to use of hydrogen:

The cost of hydrogen production, transportation and storage can be considerable, and is likely to be more expensive to use in port vehicles than diesel and batteries.

The availability of space can be an important barrier affecting local renewable hydrogen production, storage and bunkering activities. Hydrogen needs considerable space to store at the surface in gaseous form, or considerable energy to liquefy. There are also regulatory safety distances for hydrogen and ammonia handling at scale. For some ports, safety distances overlap with residential areas, which makes it almost impossible for them to import green ammonia (ammonia production process is 100% carbon free) for end-use either as ammonia or reconversion to hydrogen.

The risk of GW-scale electrolyser technology is that it takes longer than expected to mature, which delays the commissioning of GW-scale electrolysis plants. It may also delay the large-scale handling of hydrogen and hydrogen derivative fuels arriving or departing by ships at ports. Electrolysers are a proven technology, but they are in operation at a much smaller scale at present. For example, in Europe, the largest electrolyser in operation today is 20 MW and the largest under construction is 200 MW – ambitions, however, are for electrolysis on the hundreds of MW or at the GW scale.

If renewable hydrogen is produced at the port, it will also require an **electricity grid connection**, which may already be constrained due to the installation of OPS. In this case, onsite hydrogen production may exacerbate the electricity grid connection barrier.

Permitting for hydrogen (and ammonia) facilities can take a long time, presenting a challenge to realising the 2030 targets. This of course is also a barrier to electricity infrastructure development. The recently adopted RED III includes measures to speed-up the granting of permits, including a maximum of 12 months for onshore projects in designated renewables acceleration areas (RAAs) and a maximum of 24 months for onshore projects in other areas. Nevertheless, this barrier is considered hard to mitigate due to the need for technology maturity relating to large scale hydrogen projects before permitting becomes straightforward.

If renewable hydrogen is produced outside of the port, infrastructure to transport the hydrogen to the port may be a barrier. Transport of hydrogen via truck is expensive, and a pipeline would likely need other uses in addition to port operations to justify its construction, unless there is already a hydrogen backbone very close.

7 IMPLEMENTATION OF THE CLEAN ENERGY BUSINESS MODELS FOR TWO TYPICAL PORT TYPES

This Chapter presents an integrated view of the impact of relevant energy business model combinations for two model ports - a **transport port** and an **industrial port**. The model ports contain all defined elements of real ports. The information from the business models presented in chapter 5 will serve as key input.

7.1 Selection of two typical port types and business models

In order to analyse the impact of implementing multiple business models in a port, a set of two representative ports, or model ports, was used: the transport port and the industrial port. The model transport port has a focus on the transport of passengers and containers. The industrial port has a combination of industrial activity, logistics and power generation (amongst others). The typical transport port is based on the Port of Valencia. The typical industrial port is based on the Port of Rotterdam.

The combination of the business models is non-exclusive. Hence, all the different business models are combined in both the model transport port and the model industrial port.

7.2 Introduction of the methodology

In order to represent the two model ports and assess the impact of decarbonisation business cases, a scaling factor is used. Rotterdam and Valencia are relatively big ports in terms of cargo and container handling, therefore both ports are scaled down to an “average” industrial and transport port. The scaled ports are more representative of the average European port. The amount of cargo tonnage (for the industrial port) or containers (TEU) (for the transport port) is used as scalars to scale down to the average port. The calculation of the scaling factors is presented in Appendix F.

The assessment of the different business cases is performed for the years 2030, 2040 and 2050. To represent the two model ports during the study horizon, the data of the ports of Valencia and Rotterdam is used as the basis to which the scaling factors are then applied. Both ports, Valencia and Rotterdam, are characterised by the data of estimated OPS supply, number of e-RTGs, H_2 reach stackers, and installed renewable energy generation capacity in 2030, 2040 and 2050. The quantification of the associated costs and benefits of implementing each business case is calculated based on the real investment costs from the ports and estimated EU average grid emission factors, energy and emission prices in 2030, 2040 and 2050. The use of EU averages facilitates the comparison of the results of the two ports. The resulting per unit cost and benefit is then scaled to the port’s future outlook (2030-2050), and to the dimension of the “average” port. Appendix F presents the methodology for the implementation of an average port and Appendix D the assumptions and financial inputs.

7.3 Cost benefit analysis for a typical transport port

In this Section, the costs and benefits of implementing several decarbonisation business models in a model transport port (“average” port) are described. The Valencia Port is used as the basis for the assumptions regarding the outlook for 2030, 2040 and 2050 and average EU data is used for the calculation of cost and benefits.

7.3.1 Port specific assumptions

To evaluate the business case of implementing OPS, RTG electrification, hydrogen usage for terminal equipment, and renewable energy production, the following assumptions and developments are considered for the port of Valencia.

- **The TEU handled** are based on the yearly global fleet rates for containerships. Note that the above estimation does not account for changes in ship size.

- **OPS capacity** is calculated based on the future OPS demand for the port of Valencia, and the assumption of an average load of 3.09 MW per OPS, with a utilisation time of 25.7%. The maximum power per OPS is assumed as 7.5 MW.
- **The number of electric RTG cranes and H_2 reach stackers** are based on the number of RTGs and reach stackers per TEU, currently in Valencia port. The future development is scaled by the expected TEUs handled by Valencia port.
- **Renewable energy capacity** is estimated from the current and planned installations up to 2030. Renewable energy capacity in 2040 and 2050 follows the deployment of Rotterdam port. The ratio of solar PV and onshore wind installed capacity per land area is calculated based on Rotterdam's forecast, the same ratio is then applied for Valencia port.

Scaling factor (10%)

The scaling factor for the transport port is based on containers handled (TEU) in 2022. An average EU port handled 10% of the TEU the port of Valencia handled in 2022).

Scaled transport port

The model port is scaled to a more representable European transport port using the scaling factor. The port characteristics are compiled in the following Table 7-1.

Table 7-1: Specific port inputs – Scaled transport port

Specific port input	2030	2040	2050
TEU handled	700,328	741,930	787,650
OPS capacity (MW)	14.5	15.3	16.2
Electric RTG cranes	11.0	12.0	13.0
H_2 reach stackers	4.0	4.0	4.0
Onshore solar PV capacity (MW)	0.7	1.1	1.1
Onshore wind capacity (MW)	1.8	1.8	1.8

7.3.2 Costs analysis

In this Section, the economic costs of combining the business cases of OPS, RTG electrification, H_2 machinery and renewable energy production, in an "average" transport port are analysed. The financial indicators used in the CBA are the ones previously used for the individual business cases i.e. in the implementation of Port of Valencia, with updated values for the OPS case, based on the average of the previously analysed OPS business cases (Marseille and Gothenburg). Kristiansand port has not been considered as its OPS case is not representative, due to its low utilisation rate. Only the OPS financial inputs are provided (see Table 7-2), since the other financial inputs are similar to the inputs used in the individual business cases (see Chapter 5). For other general assumptions on energy prices and electricity mix forecasts used, please refer to Appendix D.

Table 7-2: Financial input - OPS

Financial input	OPS
Investment cost for port (MEUR/MW)	0.6
Investment cost for ships (MEUR/vessel)	1.8
Maintenance of OPS (% of CAPEX)	5%
Maintenance of engine (EUR/h/engine)	1.6

The total costs per year are 8.9 MEUR in 2030, 9.3 MEUR in 2040 and 9.1 MEUR in 2050 (see Figure 7-1). The rise in costs by 2040 is mainly driven by the increase in OPS capacity and e-RTGs in the transport port, as presented in Figure 7-1. The projected fleet growth raises the energy demand, and thus OPS capacity after 2030. The assumed decrease in electricity prices after 2040 reduces annual OPS costs in 2050, and the increment in TEUs handled by the port, raises the required number of RTGs. The implementation rate of H_2 reach stackers is also linked to the growth in TEUs. However, the rate of reach stackers per TEU is lower than in the case of RTGs, and hence no material difference is seen across the years. The renewable capacity is expected to increase from 2030 to 2040, and remain constant until 2050, thus the same trend is reflected in the costs associated to the business case.

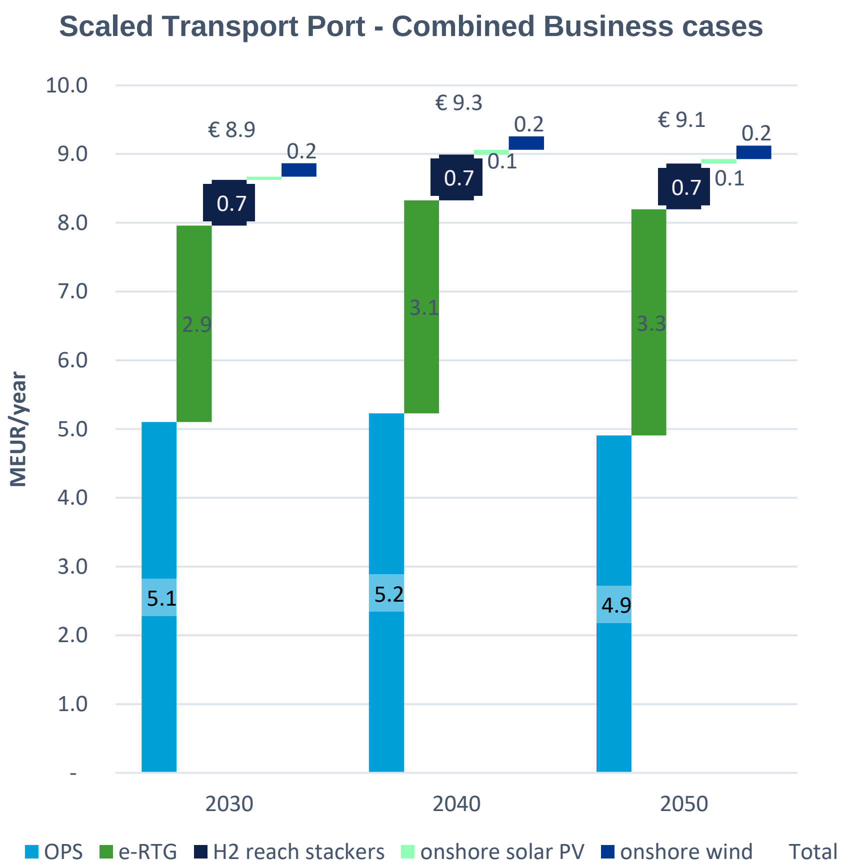

Figure 7-1: Yearly costs scaled transport port - Combined business cases

7.3.3 Analysis of benefits

The economic benefits of combining the business cases of OPS, RTG electrification, H_2 machinery and renewable energy production in an "average" transport port are analysed based on the cost of the decarbonisation alternatives as presented in Chapter 5, in comparison to the cost of the BaU case, where decarbonisation does not take place. The financial indicators used to calculate the cost of the BaU option are already presented in Chapter 5.

Overall, the combination of the decarbonisation business cases presents net economic benefits, in comparison to the BaU case, see Figure 7-2. The main drivers for the positive financial impact are the business cases of OPS and RTG electrification. In these two cases the decarbonisation alternatives achieve higher cost saving compared to the BaU than the other business cases. The required investment cost of OPS and e-RTGs is higher than for the BaU case, however the operational and pollution cost savings enabled by the alternatives compensate for the higher investment. The H_2 reach stackers business case is the only decarbonisation alternative that is not financially viable. The H_2 reach stackers require higher investment and operational costs than the fossil fuel option, and the pollution cost savings are not sufficient to compensate for these higher costs.

The techno-economic feasibility of the business cases does not change materially towards 2050. The main driver for this outcome is the increment over time in net benefits from the different business cases, especially OPS and e-RTG cases, in contrast with the stable net cost of the H_2 reach stackers case. The OPS capacity increases over time with the expected fleet growth, and similarly for the number of RTGs based on the TEUs forecast, while renewable installed capacity also experiences an increment from 2030 to 2040. This rise in capacity results in higher net benefits.

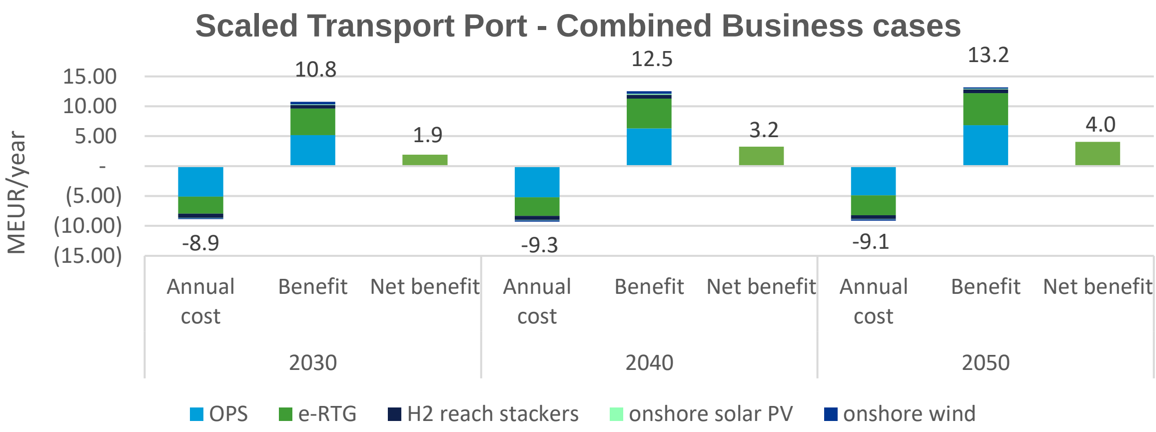

Figure 7-2: Cost-benefit results combined business cases - Scaled transport port

In addition to the economic benefits, DNV has analysed the benefits related to the reduction of emissions, as shown in Figure 7-3. The BaU case emissions are calculated considering the associated emissions of fossil fuel RTGs, reach stackers, and auxiliary engines (used when berthed) and grid electricity sized to the demand/generation of alternative options. The emissions considered in the analysis are CO_2 (well-to-wake), NOx, PM and SO_2. The implementation of the decarbonisation business cases results in a reduction of overall GHG emissions, in comparison with the BaU case. The scaled transport port reaches 13.1 ktonnes of emissions reduction in 2030 and up to 15.8 ktonnes by 2050. The OPS and electrification of RTGs business cases are the only decarbonisation alternatives that produce emissions. The emissions of these two business cases are linked to the electricity offtake from the grid required for the electric RTGs and the onshore power supply. The emission factors assumed for the electricity mix are based on the EU average electricity in the years 2030, 2040, 2050, therefore the analysis will vary by country. The business cases of H_2 reach stackers and renewable energy production, assume the onsite generation of electricity through renewable energy sources, i.e. onshore wind and solar PV, no offtake of electricity from the grid is considered, which results in no emission incurred by these business cases. The majority of the emissions are attributed to CO_2, which in 2050 represent 99.8% of total emissions in the decarbonisation case, and 99 % in BaU. The BaU case also shows 0.8% of the emissions from NOx gases. The share of other pollutants is marginal.

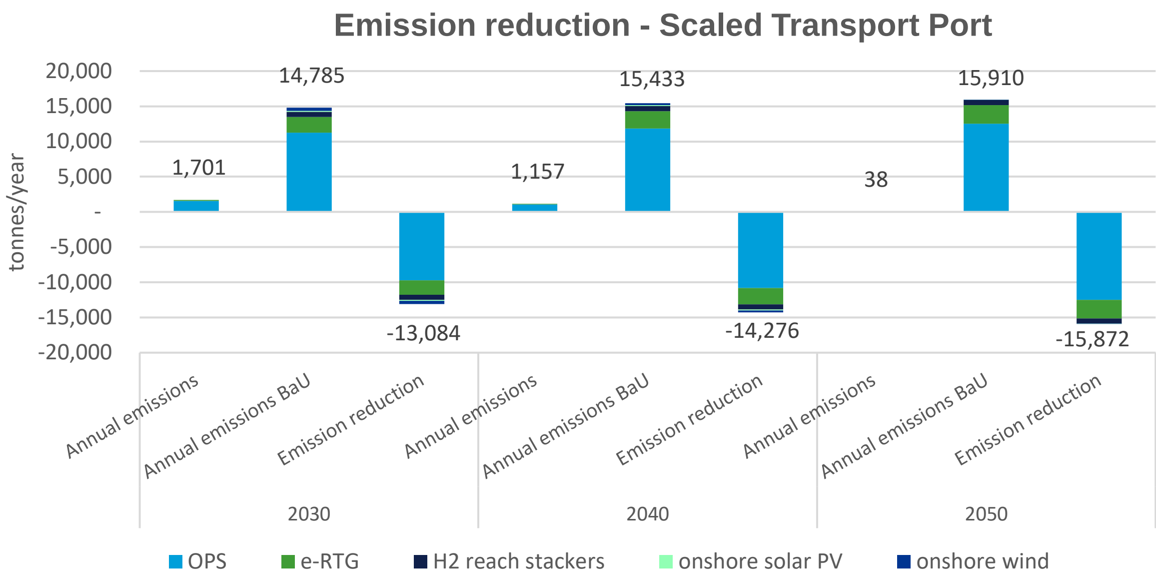

Figure 7-3: Emission reduction per business case - Scaled transport port

7.4 Cost benefit analysis for a typical industrial port

In this Section, the costs and benefits of implementing several decarbonisation business models in a model industrial port ("average" port) are described. The Port of Rotterdam is used as the basis for the calculation of the assumptions regarding the outlook for 2030, 2040 and 2050 and average EU data is used for the calculation of cost and benefits.

7.4.1 Port specific assumptions.

To evaluate the business case of implementing OPS, RTG electrification, use of H2 for terminal equipment, and renewable energy production, the following assumptions and developments are considered for the port of Rotterdam:

- **The TEU handled** are based on the Port of Rotterdam TEU growth projection.
- **OPS capacity** is calculated based on the future OPS demand for the port of Rotterdam, and the assumption of an average load of 3.09 MW per OPS, with a utilisation time of 25.7%. The maximum power per OPS is assumed as 7.5 MW.
- **The number of electric RTG cranes and H2 reach stackers** are based on the number of RTGs and reach stackers per TEU, currently in Valencia port. The same ratio is applied for the Port of Rotterdam. The future development is scaled by the expected TEUs handled by Rotterdam port.
- **Renewable energy capacity** is estimated from the current and planned installations. The maximum solar PV potential is expected to be reached in 2040, while the onshore wind capacity is kept constant based on higher restrictions on the use of land for onshore wind deployment.

Scaling factor: 2.9%

The scaling factor for the industrial port is based on the cargo tonnage in 2022 (or 2021 when 2022 data are not available). An average EU port handled 2.9% of the tonnage the port of Rotterdam handled.

The detailed calculation of the scaling factors is presented in Appendix F.

Scaled industrial port

The model port is scaled to a more representative European industrial port using the scaling factor. The port characteristics are as follows:

Table 7-3: Specific port inputs - Scaled industrial port

Specific port input	2030	2040	2050
TEU handled	457,150	524,008	578,830
OPS capacity (MW)	9.2	9.7	10.3
Electric RTG cranes	8	9	10
H2 reach stackers	3	3	3
Onshore solar PV capacity (MW)	2.6	4.3	4.3
Onshore wind capacity (MW)	5.7	5.7	5.7

7.4.2 Costs analysis

In this Section, the economic costs of combining the business cases of OPS, RTG electrification, H_2 machinery and renewable energy production, in an “average” industrial port are analysed. The financial indicators used in the CBA are the ones previously used for the individual business cases i.e. for the implementation of Port of Rotterdam, with updated values for the OPS case, based on the average of the previous analysed OPS business cases (Marseille, Gothenburg). The OPS financial inputs are provided only (see Table 7-2), since the other financial inputs are similar to the inputs used in the individual business cases (see Chapter 5). For other general assumptions on prices and electricity mix forecasts used please refer to Appendix D.

The total costs per year are 6.6 MEUR in 2030, 7 MEUR in 2040 and 7 MEUR in 2050 (see Figure 7-4). The rise in costs between 2030 and 2040 is mainly driven by the increase in OPS capacity and e-RTG in the industrial port, as presented in Figure 7-4. The projected fleet growth increases the energy demand, and thus OPS capacity after 2030, and the increment in TEUs handled by the port raises the required number of RTGs. The implementation rate of H_2 reach stackers is also linked to the growth in TEUs, however the rate of reach stackers per TEU is lower than in the case of RTGs, and hence no material difference is seen across the years. The renewable capacity, solar PV, is expected to increase from 2030 to 2040, and remain constant until 2050, thus the same behaviour is reflected in the costs associated to the business case.

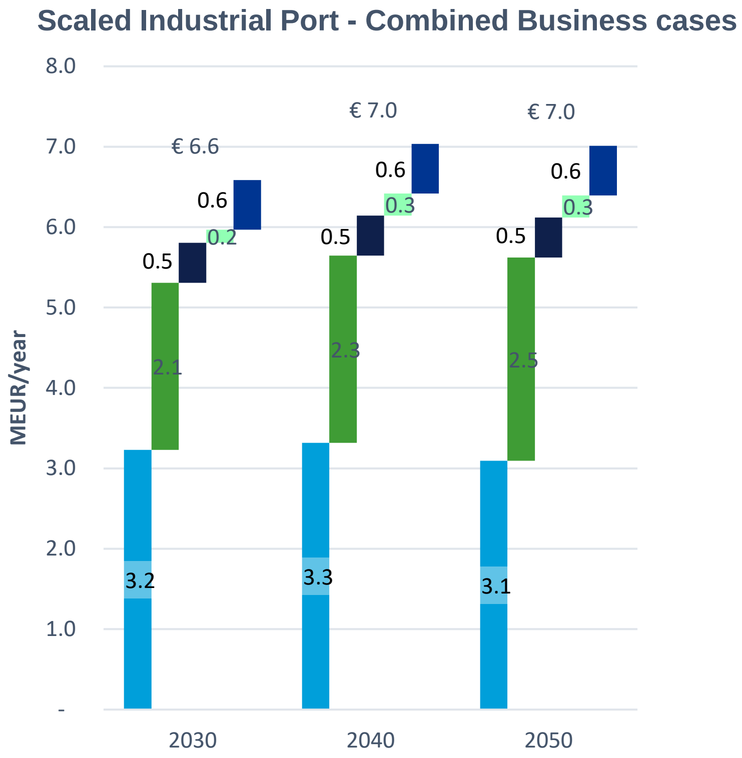

Figure 7-4: Yearly costs scaled industrial port - Combined business cases

7.4.3 Analysis of benefits

The economic benefits of combining the business cases of OPS, RTG electrification, H_2 machinery and renewable energy production in an “average” industrial port are analysed based on the cost of the decarbonisation alternatives as presented in Chapter 5 (the BaU case).

Overall, the combination of the decarbonisation business cases presents economic benefits in comparison to the cost of the BaU case (see Figure 7-5). The main drivers for the positive financial impact are the business cases of RTG electrification and renewable energy production, especially wind. In these two cases, the decarbonisation alternatives yield higher cost savings with respect to the BaU compared to the other business cases. The required investment cost of e-RTG and onshore wind is higher than for the BaU case. However, the operational and pollution cost savings introduced by the alternatives compensate for the higher investment. The H_2 reach stackers business cases are not financially viable. In these two cases the decarbonisation alternatives require higher investment costs than the BaU and the operational and pollution cost savings introduced by the alternatives are not sufficient to compensate for the higher investment.

For 2030, 2040 and 2050 a similar net benefit is calculated, up to 3.2 MEUR in 2050. The main driver for this outcome is growth in cost saving over time from the different business cases, especially e-RTG and renewable generation, in contrast with the nearly stable additional cost of the H_2 reach stackers and OPS cases. The number of RTGs increases over time with the expected growth in TEUs, while renewable installed capacity also experiences an increment from 2030 to 2040. This rise in capacity of the financially viable business cases, results in an increment in the absolute net benefits.

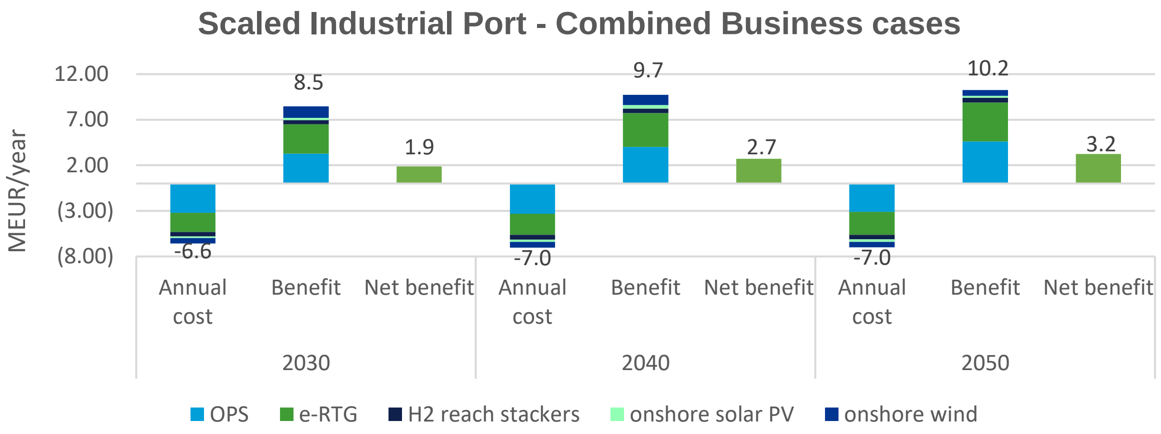

Figure 7-5: Cost-benefit results of combined business cases - Scaled industrial port

In addition to the economic benefits, DNV has analysed the benefits related to the reduction of emissions, as shown in Figure 7-6. The BaU case emissions are calculated considering the associated emissions of fossil fuel RTGs, reach stackers, and auxiliary engines (used when berthed) and grid electricity sized to the demand/generation of on shore solar PV and on shore wind. The emissions considered in the analysis are CO_2 (well-to-wake), NOx, PM and SO_2. The implementation of the decarbonisation business cases results in a reduction of overall emissions, in comparison with the BaU. The scaled industrial port reaches 9.8 ktonnes of abated emissions in 2030 increasing slightly to 10.7 ktonnes in 2050. The OPS and e-RTG business cases are the only decarbonisation alternatives that produce emissions. The emissions of these two business cases are linked to the electricity offtake from the grid required for the e-RTGs and the OPS. The business cases of H2 reach stackers and renewable energy production, assume the onsite generation of electricity through renewable energy sources, i.e. onshore wind and solar PV, no offtake of electricity from the grid is considered, which results in no emission incurred by these business cases. The majority of the emissions are attributed to CO_2 gases, which represent 99.8% of total emission in the decarbonisation case, and 99.1% in BaU. The BaU case also shows 0.8% of the emissions from NOx gases. The share of other pollutants is marginal.

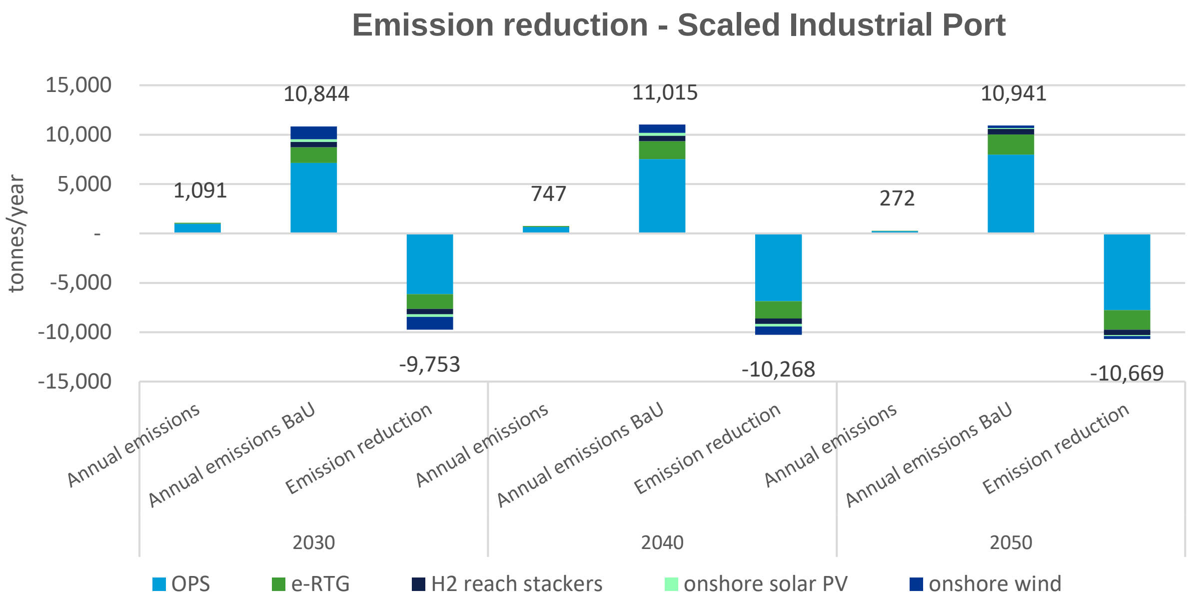

Figure 7-6: Emission reduction per business case - Scaled industrial port

7.5 Summary and main findings of the cost benefit analysis

This chapter presents an integrated view of the impact of relevant energy business model combinations for two model ports - the **transport port** and the **industrial port**. The transport port is scaled to 10% of Valencia Port to represent an average EU port. The industry port is scaled to 2.9 % of the Port of Rotterdam to represent an average EU port. The combination of the business models is non-exclusive. Hence, all the different business models are combined in both the model transport port and the model industrial port.

The **annual costs** of the combined business cases of the transport port are substantially higher than in the industrial port. The costs are growing from 2030 to 2040 (refer to Table 7-4**Error! Reference source not found.**). This growth is caused by the higher OPS electricity demand and the higher number of e-RTG's. The annual costs are dominated by the cost of the OPS and e-RTG business model with a share of almost 90% in 2050 in the transport port and a share over 80% in the industry port.

Table 7-4: Evolution of annual costs in transport and industrial port (in MEUR)

	2030	2040	2050
Transport port	8.9	9.3	9.1
Industrial port	6.6	7.0	7.0

The net economic benefits of the two model ports are comparable in 2030 (1.9 MEUR/year) and are growing to 3.2 MEUR in 2050 for the industry port and 4.0 MEUR/year for the transport port. In both ports, all business models except H_2 reach stackers show a positive net benefit for 2030 and 2040 (see Figure 7-7). In 2050, the business case of the H_2 reach stackers is zero for the transport port and slightly positive for the industry port. The positive impact is caused by the low 2050 grid electricity prices compared to the 2040 electricity prices.

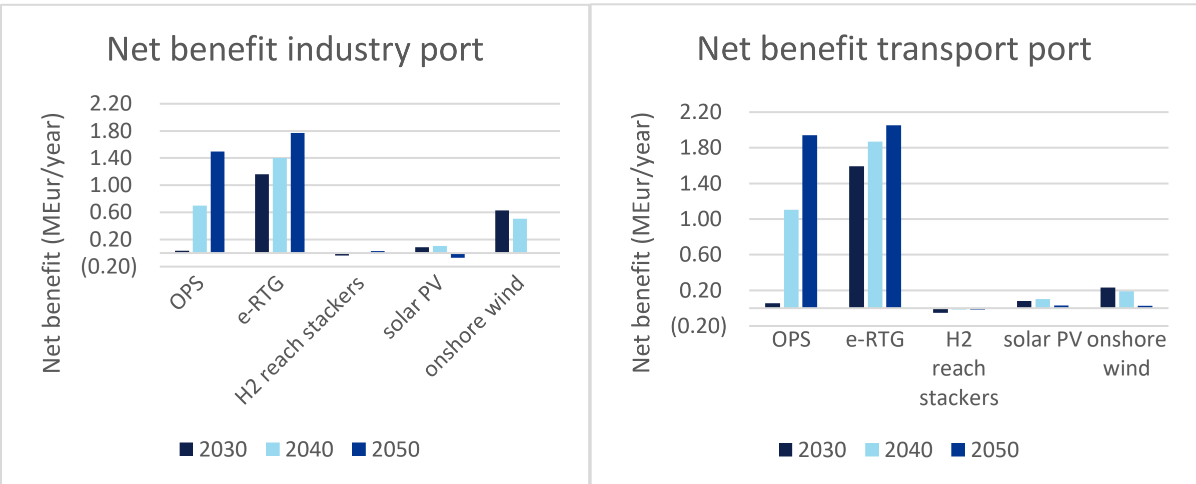

Figure 7-7: Evolution of net benefits in the transport and the industrial port

On average for 2030-2050, the model transport port has higher energy-related costs than the industrial model port. The higher costs are driven by the larger implementation of OPS capacity, e-RTGs and H_2 reach stackers in the model transport port in comparison to the industrial port.

The renewable electricity production capacity is higher in the model industrial port than in the transport port, therefore incurring higher costs and higher benefits for those business cases.

However, there are differences in the net benefits resulting for each business case.

- In both model ports, the net benefit of the OPS is growing considerably after 2030 due to the higher pollution cost (and the higher number of vessels using OPS).
- In both model ports, the net benefit of e-RTG business case grows over time due to the growth in cargo handled and the higher pollution cost. The e-RTG case achieves higher benefits in the model transport port than in the industrial port, due to the higher number of e-RTG's.
- The implementation of H_2 reach stackers is not economically viable in both model ports, yet the transport port shows larger net costs than the industrial port. The larger net costs are due to a higher number of H_2 reach stackers in the model transport port.
- Renewable energy production presents higher benefits in the model industrial port since the renewable capacity considered in this port is greater than in the transport port. The net benefits of renewable energy production decline in both model ports after 2040 because the declining electricity grid emission factor leads to lower pollution costs in the BaU case.

The transport model port achieves higher emission abatement than the industrial model port, almost 50% more reduction. This results from the higher reduction caused by OPS and to a lesser extent the higher numbers of e-RTGs and H_2 reach stackers. The renewable energy production is the only case that reaches higher emission reduction in the industrial model port, which is a result of the higher RES capacity of the industrial model port.

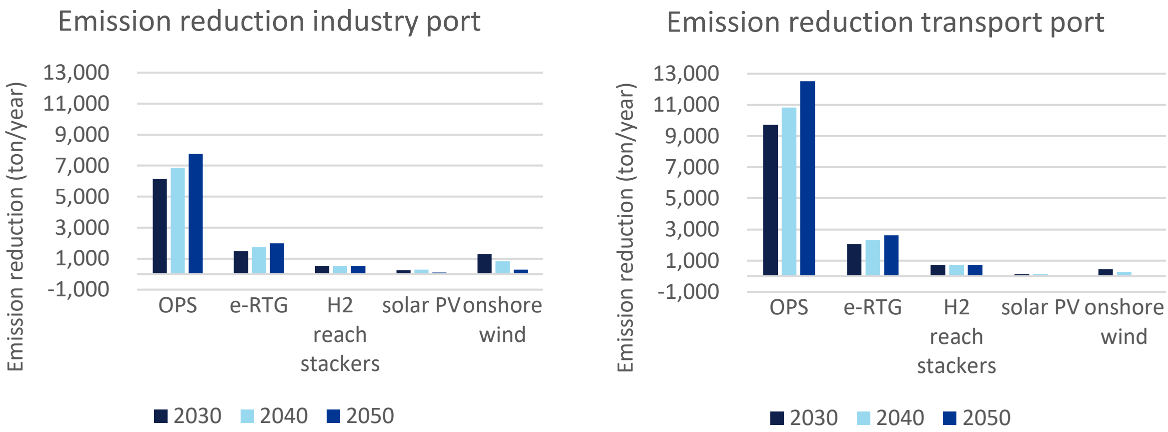

Figure 7-8: Evolution of emission reduction in transport and industry port

As indicated by the sensitivity analyses of the individual business cases in Chapter 5, as well as the impact of the grid emission factor on the net benefit in the model industrial port and the model transport port, the results should be interpreted carefully, also taking into account that the investment costs and energy prices might differ substantially from country to country and in time.

When generalizing the results to other ports, the port specific characteristics should be considered:

- Ports located in a country with a high electricity grid emission factor should properly consider this factor when evaluating investments in OPS and e-RTGs. The emission intensity of the electricity grid mix highly influences the financial viability of these business models. However, these ports will likely benefit more from deploying onsite renewable energy capacity to cover their electricity demand.
- Ports with a higher land availability, and in particular industrial ports with high energy consumption, likely benefit more from building and operating onsite renewable energy production capacity due to economies of scale (both in terms of electricity production potential and reduced network costs and losses).

- Transport or industrial ports with a high container throughput, could benefit from investing in a higher number of e-RTGs and OPS systems (which would in particular provide substantial environmental benefits if the electricity used has a low grid emission factor).
- Ports with mostly dry bulk/ liquid bulk throughput are likely not to substantially benefit from the studied business models, unless OPS will become available also for these types of vessels.

8 PORTS AS INDUSTRIAL NEXUS FOR THE ORES AND TEN-E IMPLEMENTATION

8.1 Policy overview

8.1.1 TEN-E

Overview

The Trans-European Networks for Energy (“TEN-E”) is an EU policy with the key objective to achieve a more integrated internal energy market by linking energy infrastructures between Member States and with third countries. This is to be achieved by accelerating the modernisation and expansion of Europe's cross-border energy infrastructure, which should at the same time help to cost-efficiently achieve the energy and climate objectives. The TEN-E policy supports this transformation namely through the so-called ‘Projects of Common Interest’ (PCIs).

The first version of the TEN-E Regulation dates from 2013; it identified priority corridors across different geographic regions in the field of electricity, gas and oil infrastructure to strengthen cross-border interconnection and help integrate renewable energy. The concerned investments are supported by the selection and implementation of PCIs, which can benefit from specific funding from the EU budget (Connecting Europe Facility) and from a fast track permitting procedure.

On 30 May 2022, the European Union adopted the revised Regulation on guidelines for trans-European energy infrastructure (No. 2022/869). The revised TEN-E Regulation continues to work towards developing better connected energy networks while shifting the focus more on the latest energy and climate policies and concrete targets and ensuring consistency with the climate neutrality objectives set out in the EU Green Deal.

Details

The TEN-E regulation pursues several key objectives:

- Integration of renewables and new clean energy technologies into the energy system.
- Development of new and reinforcement of existing cross-border energy infrastructure and interconnections: To this end, the TEN-E Regulation defines eleven priority corridors for electricity, offshore grid, and hydrogen infrastructure covering different geographic regions. The development of a cross-border CO_2 transport network is one of the three priority thematic areas in TEN-E, together with the deployment of smart electricity grids, helping to integrate renewable energy and allowing consumers to better regulate their energy consumption, as well as gas grids to efficiently integrate cleaner gas sources into the gas network, support the uptake of innovative and digital solutions for network management and facilitate smart energy sector integration and demand response.
- Energy market integration and competition: By reinforcing internal grid infrastructures and facilitating cross-border interconnections, the TEN-E policy aims to promote market integration. This is expected to lead to more competition and potentially lower energy system costs through the integration of renewable energy sources and completion of the EU internal energy market.
- Offshore Renewable Energy Expansion: The revised TEN-E Regulation comprises a new chapter with specific provisions to accelerate deployment of offshore renewable energy through coordinated long-term integrated offshore and onshore grid planning. It aims for joint long-term commitments for the deployment of offshore renewable energy per sea basin up to 2050 with non-binding agreements for installed capacity in Member States, including intermediate steps in 2030 and 2040.

The revised TEN-E Regulation of 2022 also extends the EU energy market boundaries to third countries by introducing a new cooperation mechanism for so-called Projects of Mutual Interest (“PMIs”). Similar to PCIs, they can be selected if they contribute to the EU’s overall energy and climate policy objectives in terms of security of supply and decarbonisation.

The European Commission adopts a list of PCIs and PMIs every two years (the “EU list”), with the first EU list of the revised TEN-E published on 28 November 2023.[116] In order to assist with the significant investment costs, PCIs and PMIs on the EU list may be eligible for public co-funding via the ‘Connecting Europe Facility’ (CEF) at EU level on the one hand and national state aid on the other hand.

Role of ports in TEN-E

While the TEN-E policy covers various energy infrastructure components, including electricity, hydrogen and CO_2 (which is needed for Power-to-liquids products like methanol) grids as well as storage facilities, the role of ports is particularly crucial in the context of liquefied natural gas (LNG), CO_2 and hydrogen (and derivatives) transport.

Ports play a significant role in the import and export of energy resources, such as electricity interconnection (link with offshore) and hydrogen (including its derivatives such as ammonia and methanol). They serve as vital hubs for the transshipment and storage of these energy carriers, allowing for the efficient transport of energy between different regions. Diversification of energy sources and supply routes is a key objective of the TEN-E policy. Ports, by serving as entry and exit points for different energy carriers, contribute to the overall energy supply security of the European Union. They can also be key nodes for the integration of renewable energy sources. They provide a gateway for the import and distribution of renewable energy, such as renewable hydrogen, produced in areas with abundant renewable resources to regions with high energy demand. They also often serve as intermodal hubs, connecting various modes of transportation, including ships, trucks, and pipelines. This interconnectedness is crucial for the seamless movement of energy resources throughout the European network.

8.1.2 ORES

Overview

On 19 November 2020, the European Commission published its EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. This Offshore Renewable Energy Strategy (ORES)[117] has been updated through the EU communication “Delivering on the EU offshore renewable energy ambitions”, adopted on 24 October 2023[118].

The ORES aimed to significantly increase the EU's offshore production capacity of power from renewable energy sources from currently 12 GW to over 60 GW by 2030 and 300 GW (excluding the UK) by 2050. The Offshore Communication takes stock of the actions taken and identifies actions on how to deliver on the increased ambition level. For 2030 the ambition level agreed by Member States has almost doubled to 111 GW. In the 2050 timeframe the ambition level is on par with the ORES.

Whereas wind power is the only offshore renewable energy technology that is currently being operated on an industrial scale, the European Commission sees relevant potential in other offshore renewable technologies, such as tidal and wave power, floating solar energy, and macro-algae for biofuels, which are therefore also addressed in the strategy. In terms of offshore wind power, the commercial development of floating technologies will allow exploitation of a much wider range of potential offshore locations.

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116 See https://energy.ec.europa.eu/publications/delegated-regulation-first-union-list-projects-common-and-mutual-interest_en

117 See https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0741

118 See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0668

The TEN-E included a provision, which is also referred to in the EU Renewable Energy Directive (RED, EU 2023/2413), that obliges Member States to cooperate on the amount of offshore renewable energy generation to be deployed within each sea basin by 2050 and increase the cross-border cooperation on renewable energy through offshore hubs.

Details

The ORES seeks to facilitate the necessary investment in offshore renewable energy-related projects by increasing certainty for investors and smoothing the path for investments, easing bottlenecks, and finding the best combination of public and private financing. One important element identified by the ORES for this is regional cooperation in order to cost-efficiently reach this goal while ensuring that renewable technologies are developed not only in the North Sea (where most offshore wind projects are currently located) but also in the Baltic Sea, Mediterranean Sea, Black Sea, Atlantic Ocean, and outermost regions and overseas territories. The goal is to promote a supply chain involving multiple regions in coastal and inland areas, and to enhance maritime spatial planning for a successful large-scale deployment of offshore renewable energy.

For this, the strategy states that it is essential to provide a clear and supportive legal framework, like clarification of the electricity market rules or revisions of the State aid guidelines on energy and environmental protection. The strategy also includes aspects to mobilise relevant funds to support the sector's development, such as the Recovery and Resilience Facility or the European Investment Bank (EIB).

As part of the EU communication published in October 2023, the EU has defined actions to be taken, building on existing policies and legislation, focusing on six main areas:

1) Develop cross-border offshore grids
2) Fast-track permitting
3) Strengthen maritime spatial planning (MSP)
4) Strengthen the resilience of offshore renewable energy infrastructure
5) Sustain research & innovation efforts to ensure EU’s technological leadership
6) Support the EU supply chains to develop their capabilities to remain or become more competitive and able to help realize the higher ambitions levels for installed offshore power production capacities in the EU as well as in third countries through dedicated trade dialogues also with the involvement of industry.

Role of ports in ORES

By leveraging the capabilities of ports, the EU aims to create a robust and interconnected ecosystem that fosters the deployment of offshore renewable energy while addressing economic, logistical, and environmental considerations. Within the framework of ORES, the EU focuses, with regard to the ports, primarily on their promotion of infrastructure and their potential role as hubs for offshore energy equipment assembly, maintenance and servicing. The importance is also reflected in the communication on delivering on the EU offshore renewable energy ambitions.

Alongside this, the EU considers ports as one of the important building blocks when it comes to strengthening the supply and value chain across Europe, as the offshore renewable energy supply chain must be able to ramp up its capacity. Therefore, some ports will need upgrading and new vessels must be built and put into operation. This initiative would also include component suppliers which would also need to upgrade. According to the ORES update communication, the ports are within the supply chain considered as “unique gateways to offshore energy installations”.

8.2 Enhanced implementation of TEN-E and ORES

8.2.1 Potential role of the ports

EU ports, positioned as pivotal nodes in the maritime transport sector, are integral to the energy landscape. Managing vast quantities of goods annually, these ports serve as essential connections in European and global supply chains. Consequently, their significant role extends to the effective implementation of both the TEN-E and ORES, highlighting their relevance in advancing energy-related initiatives.

Ports in relation to TEN-E

Ports can play a key role in the implementation of the TEN-E policy, which is aimed at developing and modernising energy infrastructure to ensure secure, sustainable, and interconnected energy networks across the European Union. Therefore, ports are important in the context of the TEN-E policy in several ways:

- Already nowadays, ports play a central role when it comes to cross-border transport of energy. Ports serve as gateways for import and export of energy resources, including liquefied natural gas, oil, or renewable energy equipment. They facilitate the transhipment of energy resources between ships, pipelines, and other transportation modes, contributing to a reliable supply of energy to the EU member states.
- Ensuring efficient port infrastructure and energy transportation networks is crucial for the growth of renewable energy capacity in the EU. This also works the other way around, in the sense that ports can act directly as centres for the development of renewable energy infrastructure themselves (see also following sub-chapter).
- The TEN-E aims to improve the interconnection of energy networks across EU member states. Ports can serve as key nodes in these interconnected networks, enabling the transfer of energy between different regions and countries. Ports that are equipped with the necessary infrastructure, such as high-voltage direct current (HVDC) converter stations, can facilitate the transmission of electricity over long distances.
- Furthermore, ports can contribute to the development of CO_2 transport networks and innovative energy technologies. Research centres and test facilities located in or near ports can support the testing and demonstration of new energy technologies, such as wave energy converters or offshore wind turbines.
- The development and expansion of port infrastructure related to energy can create jobs and stimulate economic growth in the surrounding regions, contributing to the overall objectives of the EU policy.

In conclusion, ports are essential components of the European TEN-E policy, as they facilitate the import, export, conversion, storage and distribution of energy resources, support renewable energy deployment offshore and on the port’s site, thereby enhancing energy supply security, and promoting economic development. As the EU continues to pursue its energy transition and infrastructure development goals, ports will play a central role in achieving these objectives.

Ports in relation to ORES

Ports can play a crucial and multifaceted role in the EU’s strategy on offshore renewable energy, which aims to harness the potential of offshore wind, wave, tidal, and other marine renewable energy sources to meet the EU's ambitious clean energy and climate goals. The following key roles for ports can be identified:

- Deployment and Maintenance Hubs: Ports can serve as deployment and maintenance hubs for offshore renewable energy projects. They can provide the necessary infrastructure for assembling, transporting, and installing offshore wind turbines, wave energy devices, and other renewable energy infrastructure. This includes heavy-lift cranes, specialized vessels, and storage facilities for equipment and spare parts.
- Manufacturing and Supply Chain Support: Ports can host manufacturing facilities and supply chain logistics for components of offshore renewable energy systems. This includes manufacturing wind turbine components,

foundations, and subsea cables. Beyond that, ports can also serve as locations for the assembly of offshore platforms and substructures.

- Logistics and Transportation: Ports are critical for the transportation of renewable energy equipment and materials. They facilitate the movement of wind turbine blades, tower sections, and other large components from manufacturers to offshore project sites. Ports provide access to maritime transportation and can be equipped with roll-on/roll-off ramps and heavy-lift infrastructure to handle oversized cargo.
- Offshore Operations and Maintenance (O&M) Bases: Ports can establish O&M bases for offshore renewable energy installations. These bases are essential for regular maintenance, repair, and monitoring of offshore wind farms and other marine energy installations. They provide a convenient location for crews, equipment, and spare parts to support ongoing operations.
- Grid Connection and Power Export: Ports can be used for connecting offshore renewable energy projects to the onshore electricity grid. Subsea cables can be routed through ports, which may host converter stations and other electrical infrastructure to manage the power flow from offshore installations to the mainland.
- Hosting electrolysers powered by offshore electricity: Ports can serve as strategic locations for hosting electrolysers that utilise offshore-generated electricity, offering a solution to alleviate stress on onshore electricity grids and contributing to a more efficient and decentralized energy infrastructure.
- Research and Innovation Centres: Some ports may host research and innovation centres focused on offshore renewable energy technologies. These centres can support research, testing, and development of new technologies and solutions, such as improved turbine designs, marine energy converters, or grid integration innovations.
- Environmental Monitoring and Mitigation: Ports can play a role in environmental monitoring and mitigation efforts associated with offshore renewable energy projects. They can support research on the ecological impact of these projects and facilitate the implementation of measures to minimize environmental harm.
- Job Creation and Economic Development: The development of offshore renewable energy projects and associated port infrastructure can create jobs and stimulate economic growth in port regions and nearby communities.
- Integration with Other Modes of Transportation: Ports can be integrated with other modes of transportation, such as rail and road networks, to ensure the efficient movement of goods and equipment, as well as of energy, to and from offshore energy sites.

In summary, ports can substantially contribute to the EU's offshore renewable energy strategy, as they can provide essential infrastructure and services for the deployment, operation, and maintenance of offshore wind, wave, tidal, and other marine energy projects.

8.2.2 Potential impact of the considered business models on ORES and TEN-E implementation

In the following section, the relevance of the considered business models for the implementation of ORES and TEN-E are explored and described.

8.2.2.1 Relevance of Onshore Power Supply (OPS): The ports of Marseille, Kristiansand and Gothenburg

TEN-E

Initially, it is important to note that TEN-E is not directly linked to OPS. This is primarily due to the scope of the TEN-E as well as to the difference in scales addressed. Therefore, there is no direct application or relevance here.

However, the question of a robust infrastructure in the immediate vicinity plays a major role. OPS business cases can significantly be influenced by the presence or absence of nearby available infrastructure, namely the availability of high-voltage lines. If this is not available, there is a significantly greater onsite effort.

The Trans-European Networks for Energy (TEN-E) policy represents the European Union's ambitious commitment to create an integrated and interconnected energy network, facilitating cross-border exchange of energy, enhancing energy supply security, and promoting sustainable and competitive energy markets.

ORES

Integrating Offshore Renewables into the Grid: Where ports develop into energy hubs, they could serve as an advantageous landing point with strong grid nodes. In this case, shore power systems in ports can be directly integrated with offshore renewable energy sources. This allows vessels to utilise clean, green energy directly from offshore installations when docked, promoting the use and relevance of offshore renewable energy.

Emission Reduction in Port Cities: As offshore (and onshore) renewable energy sources are expected to increasingly contribute to the electricity supply, onshore power systems in ports draw from a cleaner energy mix. This means that docked ships using shore power would contribute to emission reductions, and urban air quality initiatives.

Infrastructure Synergy: Ports can serve as strategic hubs for both offshore renewable energy operations and onshore power supply systems. Shared infrastructure, such as substations or storage systems, can optimize costs and operational efficiency.

Enhancing Resilience and Security: Diversifying the energy mix with a significant portion from offshore renewables and integrating it with onshore power systems in ports can contribute to energy security. This aligns with the EU's broader goals of reducing dependence on fossil fuel imports and mitigating potential energy supply disruptions.

Encouraging Sustainable Maritime Operations: As the maritime industry moves towards greener operations, ports as landing points from offshore renewables can be better equipped with shore power systems that will be attractive for ships focusing on sustainability. This can position European ports as frontrunners in sustainable maritime operations.

8.2.2.2 The port of Valencia: RES generation, electrification of RTG cranes and energy management solutions

TEN-E

Enhancing interconnectivity and resilience: The European TEN-E policy emphasizes interconnectivity, resilience, and a transition to cleaner energy sources to fuel Europe's growth sustainably. The Port of Valencia implements renewable energy initiatives, diversifying sources, and showcasing how critical infrastructures can integrate clean energy, contributing to European sustainability aspirations, while reducing the port's carbon footprint.

Implementation of smart grid solutions: A specific key thematic area of the TEN-E Regulation are smart grids. The port's plans for the implementation of smart grid solutions can be seen as how maritime infrastructures can seamlessly integrate fluctuating renewable energy sources. Smart grids ensure that energy, whether produced onsite or sourced from broader European networks, is consumed efficiently and sustainably. Moreover, these grids bolster the resilience of the port's operations, ensuring uninterrupted energy supply — a goal that resonates with the core of the TEN-E policy.

Ports are natural nodes of interconnectivity, linking sea, land, and sometimes even air routes. By adopting renewable energy and smart systems, the Port of Valencia can potentially become a hub for green energy distribution, connecting maritime energy sources with onshore grids, further supporting the TEN-E policy's goals of establishing interconnected energy networks across Europe.

ORES

Collaborations with offshore renewable projects: The initiatives taken by the Port of Valencia can potentially bolster the entire offshore renewable energy supply chain. Ports can play a central role in the deployment, maintenance, and operations of offshore energy farms. By fostering a renewable-friendly infrastructure, the Port of Valencia can attract collaborations with offshore renewable projects, further driving the industry's growth.

Integration of renewable energy installations: By integrating renewable energy installations within the port's precincts, the Port of Valencia serves a dual purpose. On the one hand, it showcases the viability and efficiency of renewable energy solutions in maritime and port logistics settings. On the other hand, it establishes a foundation for potentially connecting to offshore renewable energy farms, serving as an energy hub that can channel offshore-generated power to onshore facilities and users.

Incorporation of smart grid solutions: The incorporation of smart grid solutions is also a testament to the port's foresight in anticipating and managing fluctuating energy inputs, especially from renewable sources. Offshore renewables, such as wind farms, produce intermittent energy outputs and require other sources (back-up supply, storage, demand response) and specific technologies including smart grids to manage these fluctuations.

8.2.2.3 Energy hubs and new business models: the future role of hydrogen production, conversion and refuelling

Numerous ports already act as hubs for large quantities of energy. This will also be the case in the future, yet with other forms of energy, in particular low-carbon and renewable molecules. Hydrogen and its derivatives will play an increasing role in the future. This is also reflected in the projects of the ports of Rotterdam, Valencia and Gothenburg.

TEN-E

Among the avenues of exploration, the production of hydrogen using electricity generated within the port stands out as a promising and impactful strategy.

Within the context of the Hydrogen and Electrolysers corridors outlined in the TEN-E regulation, covering diverse geographic regions in electricity, offshore grid, and hydrogen infrastructure, hydrogen and its derivatives can emerge as efficient energy storage solutions. Ports, strategically positioned in these corridors, can optimize electricity usage, producing hydrogen during low demand periods and deploying it during peaks, aligning with the TEN-E policy's objective of balancing the broader European energy grid. As ports engage in hydrogen production and import/export activities, they play an important role in developing hydrogen transport networks, encompassing pipelines, refuelling stations, and storage facilities, contributing directly to the TEN-E's mission of modernizing energy infrastructure across the continent. (Energy) ports with an interest in H_2 should here also consider whether they are located near the European Hydrogen Backbone or whether a connection to it would be possible in the vicinity. This becomes all the more important the larger the scaling is. While this may play a lesser role in the consideration of the business case on a smaller scale, it is all the more important for large ones.

By being at the forefront of hydrogen production (and import/export), ports can attract investments, partnerships, and industries focused on hydrogen and other renewable technologies. By serving hydrogen derivatives, especially ammonia and synthetic hydrocarbons, ports can attract industries fertilisers, plastics and green chemistry This amplifies their economic significance and positions them strategically within the European energy landscape envisaged by enabling the diversification of Europe's energy sources. Furthermore, some of these derivatives can be stored and transported under less stringent conditions than pure hydrogen.

Finally, as the energy transition unfolds, the demand dynamics for various energy carriers might shift. Having the infrastructure to produce, convert, store, and import various hydrogen derivatives provides the flexibility to adapt to changing market needs. This flexibility is crucial for ensuring a resilient energy infrastructure, a core principle of the TEN-E policy.

ORES

Ports, as key interfaces between the maritime and terrestrial domains, are well positioned to contribute to harnessing the vast energy potential of the EU's seas and oceans.

The ports can utilise electricity generated from offshore wind, wave, and tidal installations to electrolyze water and produce green hydrogen. This aligns with the objective to tap into offshore renewable energy sources and creates a tangible link between offshore energy generation and onshore energy consumption. In case of offshore electrolysis through energy islands or offshore platforms, which would lead to lower network costs and transport losses, ports can act as corresponding landing point of these products.

Converting hydrogen into derivatives like ammonia or methanol can also simplify storage and transport challenges. These derivatives, often more energy-dense, can be used as alternative fuels or feedstocks in various industries, further integrating offshore renewable energy into the European energy mix.

The installation of hydrogen bunkering for ships or refuelling stations for heavy-duty applications, transforms ports into holistic green energy hubs. For example, in the case of Gothenburg, maritime vessels bring in goods, and trucks powered by hydrogen — a byproduct of offshore renewable energy — can transport these goods inland, reducing carbon emissions from freight transport and optimising the seamless integration of green maritime and terrestrial operations.

Finally, ports can serve as real-world laboratories. Successful implementation of these integrated hydrogen solutions can offer replicable models for other coastal regions, amplifying the impact of the EU's Offshore Renewable Energy Strategy.

8.3 Additional energy infrastructure and its impact on business models

Before discussing the impact of additional energy infrastructure on the different business models, it has to be identified first what infrastructure types could be additional to those already explored in the preceding chapter. As a starting point for this identification, the focus will lie on the discrepancy between the plans and the scope of the business models analysed on the one hand, and the possible development beyond that on the other hand, also considering the potential impacts on TEN-E and ORES discussed before.

8.3.1 Identification of additional energy infrastructure and relevance for business models

In the following sections, the relevance of the additional energy infrastructure identified and described will be analysed. The determination of this relevance is structured on the basis of a cost-benefit analysis. The aspect of costs will be interpreted more specifically in terms of the additional effort required for implementation on the one hand and the additional costs incurred on the other. These costs, which in the framework of this analysis are referred to as effort, are divided into three categories: low, medium and high. A similar subdivision is used for the description of the benefits.

8.3.1.1 Onshore Power Supply (Marseille, Kristiansand, Gothenburg)

The installation of Onshore Power Supply (OPS) in ports can serve as a steppingstone towards a broader spectrum of benefits and further infrastructural advancements. Local generation of renewable electricity, e.g. from wind and/or solar within/nearby port premises, increases control of electricity supply costs where sufficient space and production potentials are available.

Electrical power generation onshore is typically also more energy efficient than power generation by ship-based diesel engines. This higher efficiency stems from larger scale generation, and advanced technologies used in onshore power generation. Additionally, the integration of renewable energy sources can further enhance energy efficiency.

With an OPS infrastructure, ports have the opportunity to integrate locally generated renewable energy into their power supply system. This can be achieved by either sourcing renewable energy from local providers or by installing renewable energy generation systems like solar panels or wind turbines within or near the port area.

The identified additional energy infrastructure and its relevance for the business model is portrait in the following table.

	Costs	Benefits
Expanding substation capacity	High (Procurement of additional infrastructure & installation)	High (Meet growing energy demand & improved resilience)
Hydrogen based power barges	Medium (Initial investment & operation and maintenance)	High (Enhanced Operational Efficiency & preventive maintenance)
Connection points	Low (Depending on number & capacity of new connection points)	Low (Improved accessibility & enhanced flexibility)
Grid upgrades	High (Can involve substantial reconstruction and installation)	High (Improved reliability and capacity)
Smart grid technology	High (Procurement of hard- and software & integration costs)	High (Enhanced energy management & operational efficiency

Figure 8-1: Costs/ Benefits for OPS cases

Expanding substation capacity

Expending substation capacity requires capital expenditure, operational expenditure, and additional effort. Significant investment is required for upgrading existing substations or constructing new ones, which includes the cost of transformers, switchgear, protection devices, and other necessary equipment. Furthermore, there are costs related to the installation of new equipment and infrastructure. If the expansion requires additional land, there may be associated acquisition costs as well. Operational expenditure includes regular maintenance, to ensure the reliability and safety of the substation, and additional staffing to operate and maintain the expanded substation capacity. When it comes to the additional effort, managing the expansion project requires significant effort in terms of planning, coordination, and oversight which falls under project management. Existing staff may require training to handle the new or upgraded systems. Ensuring compliance with local and international electrical and safety standards requires effort in terms of documentation, inspections, and possibly system modifications, categorized under regulatory compliance.

The primary benefit is the accommodation of increased power demand which ensures reliable power supply to vessels, and contributing to lower emissions. Adequate substation capacity supports smoother port operations, reducing the risk of power outages and associated operational disruptions. Transitioning to onshore power significantly reduces emissions from vessels while berthed, contributing to improved local air quality and alignment with environmental regulations. Over time, the cost of onshore power may be lower compared to the cost of fuel for onboard generators, leading to cost savings for both the port and the vessels.

Hydrogen based power barges

Hydrogen based power barges generate electricity from hydrogen, providing a reliable and flexible clean energy source for both the port and the docked vessels, and first pilot projects in this sector such as the one realized by Teco.[119] are already planned. They can be deployed where and when needed, without requiring significant permanent infrastructure.

119 Teco (2023): TECO 2030 launches new product concept TECO 2030 Power Barge. URL: https://kommunikasjon.ntb.no/data/attachments/00132/bd0ddf67-53d1-400b-9177-62468d5b78a4.pdf . Accessed on 23.10.2023.

This flexibility makes them particularly useful in ports that may not have the necessary infrastructure for OPS, or in situations where demand for onshore power exceeds the available supply. To fully realize the benefits of hydrogen-based power barges, hydrogen production, storage, and distribution facilities will be necessary. These facilities should ideally be located close to the ports to minimize transportation emissions and costs. Establishing a reliable supply chain for hydrogen is crucial to ensure the continuous operation of the power barges.

Furthermore, the ports will need to have the necessary infrastructure to connect the power barges to the onshore power grid and the docked vessels. This includes electrical substations, transmission lines, and the required connectors and cables. The integration should be done in a way that ensures the safety and reliability of the power supply, adhering to the relevant standards and regulations.

Connection points

The capital expenditure in this case primarily involves the procurement and installation of state-of-the-art connection equipment and systems that ensure safe and efficient connections to the OPS. There might also be costs associated with the development or procurement of specialized software that facilitates quick and secure connections and disconnections. Operational expenditure includes routine maintenance to ensure the reliability and safety of the connection points, and possibly staffing costs if additional personnel are required to manage these connection points. Besides this, further efforts needed are project management to ensure the smooth development and integration of the connection points within the existing port infrastructure. Training existing staff to proficiently operate and manage these connection points is another area where significant effort is required. Furthermore, ensuring compliance with local and international standards for safety and efficiency entails additional effort in terms of documentation, inspections, and possibly system modifications.

The main benefits are enhanced operational efficiency - quick and easy connections and disconnections significantly reduce the turnaround time for ships, promoting a smoother flow of maritime traffic within the port. Well-designed connection points will also minimize the risk of electrical accidents, which is beneficial both in terms of human safety and operational continuity. Efficient connection points lead toas quicker connections, reduced idling time for ships and consequently lowering emissions.

Grid upgrades

Grid upgrades require capital and operational expenditures. The capital expenditure includes the cost of new equipment, such as transformers, switchgear, and cables, and possibly the construction of new substations. It also encompasses the costs associated with the installation and integration of this new equipment within the existing infrastructure. Operational expenditures cover the routine maintenance and potential staffing costs if additional personnel are required to manage the upgraded grid infrastructure.

Besides that, project management effort is significant to ensure the smooth execution and integration of grid upgrades. The process of obtaining necessary permits and approvals for the upgrades is another area where relevant effort would be required, although it doesn't directly translate into a monetary cost.

With regard to benefits, it primarily enhances the reliability and capacity of the OPS, ensuring a steady supply of power to vessels and port facilities. This, in turn, significantly reduces the dependency on onboard generators, leading to lower emissions and aligning the port with environmental sustainability goals. The enhanced reliability and efficiency of electricity supply also translate into improved operational efficiency and potentially lower operational costs over time.

Smart grid technology

The financial efforts towards smart grid implementation encompass the procurement and installation of smart grid technologies, including advanced metering infrastructure, sensors, control systems, and communication networks. This has to be followed by routine maintenance, system updates, and potential staffing costs for managing and monitoring the smart grid infrastructure.

Beyond the direct financial horizon, additional effort is needed when it comes to project management steering the smooth integration of smart grid technologies. Training for the existing staff is needed in order for them to navigate the new systems.

The deployment of smart grid technology could cast a wide range of benefits. Primarily, it would orchestrate an optimized distribution of electricity, ensuring energy is utilised efficiently and reliably. This operational tune resonates with lower energy costs and reduced greenhouse gas emissions. The real-time monitoring and control capabilities of smart grid technology also accentuate operational efficiency and foresee potential issues before they escalate, thereby reducing downtime and maintenance costs.

8.3.1.2 Electrification of RTG cranes in the container terminal

The transition towards electrifying RTG cranes in container terminals represents a significant stride towards fostering sustainable and efficient port operations. While the initial phase of electrification brings forth substantial benefits including emission reduction and operational cost savings, further advancements can be implemented to multiply these advantages.

The infrastructure can be further utilised to integrate renewable solar or wind energy to power RTGs, thus further diminishing their reliance on fossil fuels.

The identified additional energy infrastructure and its relevance for the business model is portrait in the following table.

	Costs	Benefits
Advanced power distribution systems	**High** (procurement, installation and integration with existing systems)	**High** (Improved reliability and efficiency & future scalability)
Energy storage systems	**High** (Procurement of storage units, power electronics & installation)	**High** (Peak shaving, grid support and resiliency)
Enhanced Connectivity Infrastructure	**Medium** (Depends on the extent and technology)	**Medium** (Real-time monitoring, improved data analytics)

Figure 8-2: Costs/ Benefits for RTG crane case

Advanced power distribution systems

The integration of advanced power distribution systems in ports can bolster the reliable and efficient power supply to electrified RTG cranes. Given that in the business cases the electrified RTGs are already operational, the emphasis would lie on the enhancement of the power distribution infrastructure. On the financial front, the heart of an advanced power distribution system lies in the procurement of state-of-the-art equipment such as transformers, switchgears, and smart grid technologies, which demand a significant financial outlay. The journey from acquisition to operationalization incurs costs related to the installation and integration of the new equipment within the existing electrical infrastructure, presenting a notable financial commitment.

With regard to the effort dimension, the transition to advanced power distribution systems would require a significant effort in project planning, coordination, and oversight, which falls under the broad umbrella of project management. Training requires not just a financial investment but also a substantial amount of time and effort to ensure staff are proficient in operating the new systems. Coordination extends its tentacles to various stakeholders including contractors, utility providers, and regulatory bodies, making it an effort-intensive phase. Continuous monitoring and evaluation to ensure the system's efficiency and reliability demand an ongoing commitment of effort.

The horizon of benefits emanating from advanced power distribution systems on the other hand is broad. Foremost, these systems promise a more reliable power supply to electrified RTGs, reducing the risk of operational downtime due to power interruptions. Improved efficiency in power distribution potentially unfurls into lower energy costs and optimized operations, which is a significant stride. The narrative of environmental stewardship is also enriched as efficient power distribution aligns with environmental sustainability goals by potentially reducing energy wastage. Advanced systems often come with the boon of data analytics capabilities, enabling predictive maintenance and better decision-making.

Energy storage systems

Financially, the integration of energy storage systems would mean a notable investment in procuring the battery banks and related equipment. The financial footprint would extend to the installation and integration of these systems within the existing electrical infrastructure of the ports. Given the technical sophistication of modern energy storage systems, investment in advanced software for monitoring and managing the energy storage and distribution would also be indispensable. The operational phase unfolds further financial commitments in the form of routine maintenance, repairs, and possibly the need for specialized technical personnel to manage these systems.

On the effort spectrum, the project management to ensure smooth integration and operation of energy storage systems would mean a significant endeavour. It entails meticulous planning, coordination, and oversight across various stages of the project. Training and skill development for both existing and new technical personnel would require a significant amount of time and effort to ensure proficiency in managing the new systems. The dialogue with various stakeholders including contractors, utility providers, and regulatory bodies also signifies an effort-intensive phase.

With regard to the benefits, the incorporation would primarily help to enable a more reliable and efficient power supply to the electrified RTGs, especially during peak demand periods or power outages, ensuring operational continuity. The ability to store excess generated energy for later use is a significant stride towards optimizing energy utilisation, potentially leading to lower energy costs. The environmental narrative would also be brought forward, as efficient energy storage and utilisation would further contribute to lower greenhouse gas emissions.

Enhanced Connectivity Infrastructure

Firstly, additional infrastructure in the form of enhanced connectivity infrastructure would require a notable investment in procuring cutting-edge communication equipment and software. Installation and integration of these systems within the existing operational framework also carries a financial imprint. Given the technical nuance of modern communication systems, investment in sophisticated software that can harmonize the communication between electrified RTGs and control centres would be indispensable. Routine maintenance, troubleshooting, and potential upgrades of the communication systems encapsulate further ongoing financial commitments. Another facet would be to ensure compliance with communication, safety, and data security standards where financial resources are expended for inspections, documentation, and potential system adjustments to meet regulatory benchmarks. This would also come along with further efforts as for example thoughtful project management is indispensable to ensure the smooth integration and operation of upgraded communication systems.

On the benefits side, enhanced connectivity facilitates a seamless flow of information between electrified RTGs and control centres, potentially leading to better operational efficiency and real-time monitoring. This upgraded connectivity can lead to quicker response times to operational exigencies, and better-coordinated movements of electrified RTGs, which in turn could lead to reduced downtime and optimized operations. The modern communication systems also often come with data analytics capabilities, enabling better decision-making and predictive maintenance, which are important cornerstones in modern operational ecosystems.

8.3.1.3 Solar panels on terminal passenger roofs and smart grid (Port of Valencia)

The implementation of solar panels on passenger terminal roofs in combination with smart grid electricity solutions is a significant step towards harnessing renewable energy, reducing operational costs, minimizing the carbon footprint and to reduces the reliance on grid electricity. This is especially beneficial in case of grid outages or fluctuations, ensuring at least temporary continuous operations.

The smart grid's real-time monitoring and control capabilities ensure optimal utilisation of solar energy, adjusting the energy distribution based on demand and solar generation capacity.

The identified additional energy infrastructure and its relevance for the business model is portrait in the following table.

	Costs	Benefits
Energy storage systems	**High** (Costs of procuring, installing and ongoing costs)	**High** (Peak shaving, improved solar utilization, grid resilience)
Advanced Metering Infrastructure	**High** (Due to technology, installation, and integration costs)	**Medium** (Better energy management & possibly lower energy bills)
Grid-Interactive System	**Medium** (Integration with existing infrastructure & monitoring)	**High** (Selling excess energy & improved grid stability)
EV Charging Stations	**Low - Medium** (Depending on scale & technology of charging infrastructure)	**Medium** (Revenue Generation & foundation for further electrification)

Figure 8-3: Costs/ Benefits for solar panels on terminal passenger roofs and smart grid case

Energy storage systems

Financially, the integration of energy storage systems begins, just as described for the RTG cranes, with a sizable investment in procuring robust battery banks and related equipment. The financial spectrum is broadened by the costs associated with installing and integrating these systems within the existing solar and smart grid infrastructure. The required system components would encompass battery banks, inverters, controllers (to manage the flow of electricity into and out of the storage system), as well as protection equipment (like circuit breakers and surge protectors to ensure the safety of the system) and enclosures, as batteries and other equipment need to be protected from the elements.

Beside the financial investment, this would require respective site assessments, which are needed to determine the optimal location for the energy storage system together with the assessment of the condition of the existing electrical infrastructure to identify any upgrades that might be needed. Furthermore, the system would need to be commissioned to ensure it is operating correctly. This includes testing and adjusting the system as needed.

On the benefits side, energy storage systems give ports the ability to harness solar energy efficiently, making the most out of the sun's bounty by storing excess energy generated during peak solar hours for utilisation during non-solar periods. An energy storage system can be utilised to reduce peak demand charges by storing energy during off-peak times and discharging it during peak demand periods. This peak shaving capability can lead to significant cost savings. By reducing dependency on grid electricity, especially during peak demand times when electricity market prices are higher, ports can notably curtail their energy expenses. Further, the integration of energy storage systems fits seamlessly into existing smart grid solutions, providing a more robust energy management ecosystem. It would facilitate smoother demand-response coordination, allowing the port to respond adeptly to varying energy demands and supply scenarios. This energy management could also contribute to load shifting, resulting in reduced operational costs.

Advanced metering infrastructure

On the financial side, the initial investment required to integrate an advanced metering infrastructure might be substantial. This includes the costs for smart meters, communication networks, and data management systems, alongside any necessary upgrades to existing infrastructure to ensure compatibility and optimal functionality. Moreover, there could be ongoing operational and maintenance costs associated with these systems, which might strain the port's financial resources in the short term.

However, the incorporation of AMI could also unlock numerous financial savings and operational efficiencies in the longer term. For instance, the enhanced two-way communication between utilities and customers facilitated by AMI can lead to better demand-side management. This in turn can result in lower electricity costs due to more efficient energy usage and reduced peak demand charges. Moreover, the precise energy usage data collected can provide the port authorities with invaluable insights into energy consumption patterns, enabling more informed decision-making regarding energy management. Furthermore, the integration of AMI could enhance the effectiveness of the existing solar panel installations and smart grid solutions. By providing real-time data on energy production and consumption, AMI can help in optimizing the balance between solar energy generation, storage, and consumption, ensuring that the solar assets are utilised to their fullest potential. This improved management of solar resources can lead to further reductions in energy costs and potentially increase the self-sufficiency of the port in terms of energy supply. Moreover, the advanced metering infrastructure could also support the broader smart grid ecosystem within the port by enabling more sophisticated grid management and automation capabilities. This can lead to a more reliable and resilient energy infrastructure,

Grid-interactive systems

On the expenditure front, the primary costs associated with integrating a grid-interactive system would encompass the installation of the necessary equipment and possibly upgrading the existing electrical infrastructure to ensure it's apt for back-feeding electricity to the grid. Moreover, there may be regulatory compliance costs, as grid interconnection typically necessitates adherence to certain standards and might require approval from the local utility or grid operator. Additionally, ongoing maintenance and monitoring of the grid-interactive system could also incur operational costs to ensure that it functions optimally and complies with grid codes.

Nevertheless, the financial benefits could be noteworthy. By selling excess solar energy back to the grid, the port can generate additional revenue, which can be a significant financial boon over time. This extra income can offset the initial and ongoing costs of the grid-interactive system, and even the solar installations, thus improving the overall return on investment for the port's renewable energy infrastructure. Beyond financial considerations, the grid-interactive system can foster a more resilient and sustainable energy ecosystem within the port. By providing a mechanism to offload excess solar energy, it helps in managing the intermittent nature of solar power, thus contributing to grid stability. Moreover, by feeding clean solar energy back to the grid, the port contributes to reducing the dependency on fossil fuels and consequently lowers greenhouse gas emissions in the broader community. A grid-interactive system can also potentially pave the way for the port to participate in demand response programs, where it can further monetize its flexible energy assets by responding to grid demands during peak load periods or during times of grid stress. This not only could generate additional revenue but also further contribute to grid stability and reliability. And finally, the enhanced interconnectivity with the grid can provide valuable data and insights regarding energy production and consumption patterns. This data can be instrumental in optimizing energy management strategies, ensuring that the solar installations and smart grid solutions are utilised to their fullest potential.

EV charging stations

In the context of port, EV charging stations could address port specific equipment like charging system for forklifts, cranes or trucks. The primary costs associated with this initiative would involve the installation of EV charging stations, which includes the procurement of charging equipment, construction work for setting up the stations, and any necessary electrical infrastructure upgrades to ensure reliable power supply to the chargers. Additionally, there might be regulatory compliance costs to adhere to local and national electrical and safety standards. Operational and maintenance costs for the charging stations, as well as costs for managing and monitoring the charging network, are other expenditures that should be factored into the overall financial assessment.

The installation of EV charging stations can also open up new revenue streams for the port. By providing charging services to EV users, whether they are port employees, visitors, or nearby residents, the port can generate income that can help offset the installation and operational costs of the charging infrastructure. Furthermore, the smart grid solutions already in place can be leveraged to manage the electricity demand of the charging stations efficiently, which can lead to reduced energy costs. Existing solar installations can be a significant asset in this aspect. The solar-generated electricity can be utilised to power the EV charging stations, reducing the reliance on external electricity sources and minimizing the operational costs associated with charging services. This solar-powered charging setup not only cuts down electricity costs but also magnifies the environmental benefits by ensuring that the EV charging is powered by clean, renewable energy. Moreover, the enhanced electric infrastructure necessary for the EV charging stations could also serve as a foundation for other future electrification initiatives within the port, such as electric port vehicles and equipment.

8.3.2 Additional infrastructure beyond the business models

Waste-to-Resource/Energy Facilities

Waste-to-Resource processes are building blocks for a more circular economy in the future when waste is used as a resource (cradle-to-cradle). Waste-to-Energy (WtE) facilities present a pragmatic and sustainable solution to the growing challenge of waste management while also serving as a reliable source of energy. For ports and the neighbouring regions, establishing waste treatment facilities can represent an additional infrastructure within the port fostering resource circularity and regional integration.

The energy generated from waste management processes can be sold, creating a new revenue stream for ports. Moreover, the operation and management of waste treatment facilities necessitate both skilled and unskilled labour, which translates to job creation and a boost in local employment. Furthermore, by handling waste locally, ports along with local authorities can achieve cost savings on transportation and landfill fees.

Establishing WtE facilities requires a well-thought-out technical framework. Adequate waste collection, sorting, and preparation facilities are essential to ensure a consistent supply of waste suitable for recycling and energy generation (for the non-recyclable waste fractions). Advanced sorting equipment is necessary to segregate recyclables and remove non-combustible materials. Regarding energy generation technology, in terms of thermal valorisation of waste streams, a well-designed incinerator capable of high-temperature combustion is crucial to maximise energy generation and minimise emissions. Alternatively, gasification or anaerobic digestion technologies can be employed, suitable e.g. for plastic and biogenic types of waste, respectively. Resource recovery facilities equipped with advanced metal recovery systems and other recycling facilities are essential for recovering resources from waste ash, such as phosphate from the residues of anaerobic digestion.

Air pollution control is a critical aspect, necessitating the installation of systems to capture and treat emissions, ensuring compliance with environmental regulations. Continuous emission monitoring systems are required to ensure adherence to emission standards. The captured energy needs to be converted into electricity or heat using turbines and generators. Additionally, electrical infrastructure for connecting the WtE facility to the local grid is vital, encompassing transformers, switchgear, and metering equipment.

Logistics and Supply Chain Innovation Centres

With the urgent global shift towards cleaner energy sources, offshore renewable energy production, encompassing wind and solar energy, has been gaining substantial traction. Ports, with their strategic coastal positioning and robust infrastructure, are poised to play a central role in this green energy transition. They can serve as pivotal installation and maintenance centres for offshore renewable energy projects, acting as springboards from which renewable energy ventures leap from conceptualization to realization. This transformation, however, necessitates a concerted effort to augment existing port infrastructure to meet the demands of offshore energy projects.

This transformation would require several additional infrastructure which may be relevant for TEN-E, ORES as well as complementary regulatory frameworks that are not in the scope of this study:

1) **Specialized Dock Facilities**: Ports would need to develop specialized dock facilities capable of handling the unique requirements of offshore energy equipment. These docks should be designed to accommodate the loading, unloading, and assembly of large wind turbines, solar panels, and associated structures.

2) **Heavy Lift and Transport Equipment**: The scale and weight of offshore renewable energy equipment necessitate the availability of heavy lift cranes and specialized transport vehicles. This equipment is vital for the smooth transition of materials from the port to the offshore installation sites.

3) **Storage and Assembly Areas**: Adequate space for the storage and assembly of offshore renewable energy equipment is paramount. Ports would need to designate and develop open areas for the assembly of large structures like wind turbines.

4) **Workshops and Maintenance Facilities**: Dedicated workshops equipped with the necessary tools and technologies for the maintenance, repair, and potentially the fabrication of offshore energy equipment are crucial. These facilities would serve as the backbone for the ongoing maintenance and servicing of offshore renewable energy installations.

5) **Training and Certification Centres**: The specialized nature of offshore renewable energy projects necessitates a skilled workforce. Ports can host training and certification centres to nurture the required expertise for the installation, operation, and maintenance of offshore renewable energy facilities.

6) **Research and Development Facilities**: To stay abreast of evolving technologies and practices, ports can establish research and development facilities focused on offshore renewable energy innovations. These facilities could foster collaborations with academic institutions, industry stakeholders, and government agencies.

By morphing into hubs for offshore renewable energy installation and maintenance, ports not only contribute to the global clean energy agenda but also unlock new economic vistas. They can attract significant investments from renewable energy companies, create employment opportunities, and spur economic activity in associated industries like logistics, manufacturing, and services. Moreover, the proximity to offshore renewable installations reduces logistical challenges and costs, fostering a conducive environment for renewable energy ventures.

Furthermore, this transition paves the way for ports to reduce their carbon footprint significantly, aligning their operations with global sustainability aspirations. It also positions them as leaders in the green energy transition, enhancing their social license to operate.

Hydrogen production and distribution

With the growing shift towards clean hydrogen as clean fuel alternative, ports can play a crucial role in hydrogen production and distribution, given their strategic location and access to water - an essential input for electrolysis-based hydrogen production.

The infrastructure needed for this are firstly electrolysers for hydrogen production, hydrogen storage facilities to ensure a steady supply, and distribution infrastructure such as pipelines or hydrogen refuelling stations for fuel cell vehicles. Establishing a hydrogen infrastructure within the port could attract and establish a wider ecosystem in which hydrogen is used as feedstock and fuel for own operations, industries and fuel cell vehicle operations, respectively, thus facilitating business' clean energy transition while creating new revenue streams. Such an approach can already be seen today in the port of Duisburg (Germany), which tries to become the first inland container terminal in Europe to achieve climate neutrality through the installation of hydrogen- based power solutions.[120]

120 MTU (2022): Hydrogen-based energy for the port logistics of the future. URL: https://www.mtu-solutions.com/na/en/stories/power-generation/hydrogen-based-energy-for-the-port-logistics-of-the-future.html. Accessed on 31.10.2023

Regarding its wide range of possible fields of application, potential roles of hydrogen are laid out in more detail in the subsequent Section 8.4.

By-product heat from electrolysers

The great interest in hydrogen as a clean fuel and feedstock has spotlighted electrolysis as a key technology for the production of hydrogen and derivatives. Water electrolysis is the most efficient means to produce a chemical energy carrier (H_2) from renewable electricity with an electrical efficiency in the range of 60-70 $\%_{LHV}$ (or 71-83 $\%_{HHV}$). However, electrolysis is not just a source of hydrogen, but also a producer of low-grade by-product heat (often termed 'waste heat' as the temperature level is below 100°C). Where this heat can be utilised, it becomes a valuable energy source. Using the output heat increases the overall efficiency of electrolysers to some 80 $\%_{LHV}$ (or 90 $\%_{HHV}$). Ports, with their expansive infrastructure and proximity to industrial zones and/or urban areas, are uniquely positioned to make use of this waste heat, thereby augmenting their energy efficiency and reducing their carbon footprint. Valorising electrolysers' by-product heat necessitates the establishment of additional infrastructure designed to capture, transport, and utilise the waste heat generated from electrolysis operations within the port.

1) Heat Capture Systems: capable of handling varying temperatures of waste heat, segregating high-temperature heat from low-temperature heat efficiently.

2) Heat Storage Facilities: to ensure the captured heat is available for use when needed, thus decoupling production and consumption of heat. Modern heat storage solutions can store the heat in water, oil, thermal salts, or other media (subject to temperature level, scale, ramping, etc.), maintaining its temperature over time (days to months).

3) Heat Distribution Networks: for transporting the heat to various points of use within the port, nearby industries, and urban areas.

4) Heat Exchange, Conditioning and Utilisation Systems: for the efficient transfer of heat to the intended applications, be it for heating buildings, powering industrial processes, or other uses. Low-temperature heat can be elevated to higher temperature levels via heat pumps. This requires electricity for operating the heat pump, however, the efficiency is very high with a coefficient of performance[121] of e.g. 3 to 4 if using an industrial heat pumping system to elevate temperature from 40 to 90°C.

5) Monitoring and Control Systems: Robust monitoring and control systems are vital for ensuring the efficiency and reliability of the waste heat recovery and utilisation operations.

Harnessing the waste heat from electrolysis presents a gamut of economic and environmental benefits. For the port, it's a stride towards energy self-sufficiency, reducing the dependency on external energy sources and consequently lowering energy costs. The utilisation of high-temperature heat (>100°C) can particularly be beneficial for powering energy-intensive industrial processes within the port or in nearby industrial zones. Where only low-temperature heat sources are available (<100°C), industry heat pumps can increase the temperature spectrum to above 100°C. On the other hand, low-temperature waste heat can be employed for heating purposes within the port or nearby cities via heating grid.

For a seamless transfer and utilisation of waste heat, a collaborative approach towards infrastructure development is essential. Joint planning between the port authorities, local industries, and municipal bodies can ensure the establishment of efficient heat distribution networks, heat exchange systems, and monitoring controls that serve the collective needs effectively.

121 COP = ratio between useful heat output and required energy input

8.4 Special focus: Hydrogen (H_2) & derivatives

This part specifically considers the different dimensions in which ports could be involved. These are divided into:

(1) Production and use within the port area.

(2) Production and use involving the refuelling of landed vessels (bunkering).

(3) Production, exchange, and use beyond the port. This includes both the import and export of hydrogen and derivatives as a commodity, as well as the connection with industry and communities located nearby ports and in the farther hinterland.

This part is intended to highlight in particular the scaling and dimension of hydrogen and its derivatives.

The following analysis focuses exclusively on possible areas of application and technical feasibility with regard to the role of ports. This does not include safety distances that apply for safety aspects associated with the options described below (for this, see chapter 6.3.2 Barrier: Adequate Space for Hydrogen and Ammonia, including Safety Distances).

8.4.1 Ports and their potential role in the hydrogen value chain

Potential interfaces for ports exist within the hydrogen value chain, where they could function as central hubs for importing, exporting, and coordinating activities related to hydrogen, as can be seen in the following.

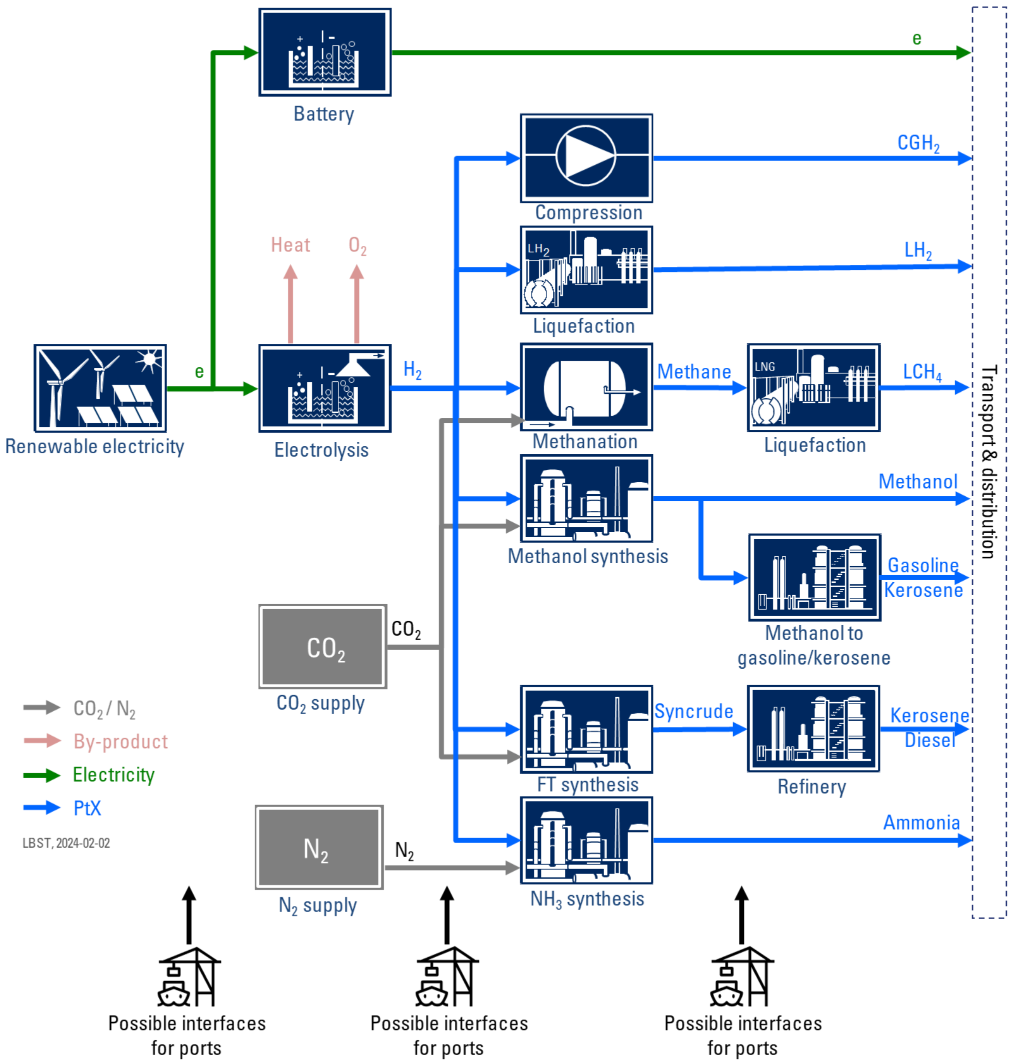

Figure 8-4: Overview of PtX production processes

8.4.1.1 Renewable electricity use

For the sake of completeness and relevance, the direct use of renewable electricity is hereafter briefly discussed. Where technically feasible and economically viable, direct and local use of renewable electricity is the best option for most low-temperature heating and passenger car transport applications, thus minimising conversion and transport losses across the energy supply chain. Direct use of electricity may comprise electricity transmission and storage, e.g. in batteries. Batteries are best utilised for short-term electricity storage (seconds, hours, up to few days). The need for converting renewable electricity into chemical energy carriers comes into play in cases like the following:

- Dispatchable power supply, i.e., during times of low renewable energy generation ("Dunkelflaute") or longer periods (seasonal storage)
- Transport of large amounts of energy (TWh/a) over long distances (>100s of kilometres) with insufficient grid connections, e.g., to valorise otherwise 'stranded' renewable power potentials
- Provision of renewable electricity-based fuels and chemicals for the transformation of otherwise hard-to-decarbonise industries

In such cases, renewable electricity can be first converted into hydrogen, and then potentially further converted into hydrogen-based derivatives (more details in the following section).

8.4.1.2 Compressed hydrogen (CGH_2) through electrolysis

Ports, with their strategic coastal locations and robust infrastructural capacities, can serve as vital hubs supporting the production of hydrogen through offshore renewable energy, while also crafting a sustainable business model that could significantly bolster their operational and financial portfolios.

Ports can provide logistical support and maintenance services during the development and maintenance of offshore wind, solar and wave installation and of underwater transmission lines and substations in the construction and operational phase and host onshore substations of the electricity grid and facilities within or near their premises.

Upon reaching the shore, the electricity is directed to electrolysis facilities where water is split into hydrogen and oxygen. This phase necessitates a reliable water supply and a well-equipped electrolysis facility. Ports could host these electrolysis facilities within or near their premises, providing the requisite water supply and ensuring a seamless electricity transmission to the electrolysers. This not only accelerates the hydrogen production process but also anchors the port as a critical node in the hydrogen value chain.

Post electrolysis, the produced hydrogen undergoes purification to meet the requisite purity standards and is then compressed. Ports could provide the space and infrastructure for these purification and compression facilities, possibly offering maintenance services, thereby further integrating into the hydrogen production ecosystem.

Besides H_2 production from water electrolysis, by-product heat (< 80°C) and oxygen are produced. These co-products have only rarely been used to-date because of smaller project sizes so far. With increasing volumes, attractiveness for utilising by-products (where feasible) is increasing.

By-product oxygen (O_2) from water electrolysis to-date is typically vented. O_2 can be used as a booster in waste-water treatment plants, in aquaculture, or in other industrial processes, e.g., in metal refineries and chemical manufacturing. The relatively small scales of early Power-to-Hydrogen (PtH_2) projects have so far hardly led to a positive cost/benefit for O_2 valorisation. The perspectives may improve with increasing project sizes. O_2 valorisation may be limited though as O_2 quantities from commercial (GW) scale hydrogen production will exceed established demand for O_2. Furthermore, O_2 users are preferably in proximity to the electrolyser as transport and distribution of large amounts of O_2 is best handled within industrial complexes and over short distances only for safety reasons.

8.4.1.3 Liquefied hydrogen (LH_2)

Following the electrolysis process, liquefaction can be a means to increase energy density for efficient distribution or to provide hydrogen in a liquefied state for dedicated consumption, e.g., for heavy-duty transport applications. Where space allows, ports can house the infrastructure necessary for hydrogen liquefaction and/or re-gasification processes, storage, and distribution. Furthermore, by becoming hubs for LH_2 distribution, they could generate revenue from hydrogen sales, refuelling services, or even leveraging the LH_2 for port operations.

8.4.1.4 Methane (gaseous and liquefied)

This route of methane is included here for the sake of completeness, as individual players are currently pursuing LNG as a promising marine fuel, such as shipping major CMA CGM [122] for container ships [123] or new cruise ships like the 'Icon of the Seas' [124].

Hydrogen can be transformed into methane through a catalytic process called methanation, where hydrogen reacts with carbon dioxide to form methane. Ports could foster this transition by housing the methanation facilities, providing the necessary infrastructure, and possibly obtaining the required carbon dioxide from suitable sources.

Following this is the methane liquification, transforming it into LNG. This transition is achieved through a cooling process where methane is cooled to -161°C, transforming it into a liquid form which is easier and more economical to store and transport. Ports could host these liquification facilities, ensuring the requisite cooling systems and storage tanks are in place to support the LNG production. Post liquification, the LNG is ready for storage and distribution. Ports, with their existing logistic networks and storage facilities, could establish dedicated storage tanks and distribution channels for LNG. Whether the LNG is utilised locally, distributed to nearby regions, or exported globally, ports could facilitate this distribution, ensuring a seamless supply chain.

Ports could monetise the infrastructure and services provided at each phase of the value chain, from electrolysis to LNG distribution. Moreover, the sale or export of LNG could become a significant revenue stream, positioning the port as a key player in the global clean energy market. Furthermore, ports could venture into ancillary services like maintenance, technical support, and training services related to methane and LNG production. They could also foster partnerships with nearby industries for carbon dioxide supply or even the utilisation of the produced LNG.

8.4.1.5 Methanol (MeOH, CH_3OH) and other liquid hydrocarbons

For the production of methanol, hydrogen is synthesised with carbon dioxide (CO_2) in a catalytic reactor to form methanol, a process known as methanol synthesis. Ports could further their role by hosting these reactors, possibly sourcing carbon dioxide from nearby industrial emissions, fostering a synergistic interaction that not only produces methanol but also mitigates carbon emissions. This methanol can be used as feedstock in chemical processes or further processed into longer-chain hydrocarbons (see next sub-chapter).

Gasoline / kerosene / diesel

There are two principal routes for the production of power-to-gasoline / kerosene / diesel as described in the following:

- Methanol route

Methanol can be processed in a series of chemical conversions into gasoline and kerosene. The role of ports within this process could be to host these conversion facilities that are similar to refineries. Post upgrading, the gasoline or kerosene is ready for storage and distribution. Ports, with their inherent logistic networks and storage facilities, could establish dedicated tanks and distribution channels. Whether the fuel is utilised locally or distributed to broader regions, ports could facilitate this distribution, ensuring a seamless supply chain. The confluence of methanol synthesis and upgrading processes with port infrastructure can lead to various business opportunities. Ports could monetise the

[122] Compagnie Maritime d'Affrètement (CMA) Compagnie Générale Maritime (CMG)

[123] https://sea-lng.org/2023/01/lng-as-marine-fuel-a-risky-or-future-proof-investment/

[124] https://www.theguardian.com/environment/2024/jan/26/icon-of-the-seas-largest-cruise-ship-human-lasagne-climate-fuel-lng-greenwashing

infrastructure and services provided at each juncture of the value chain, from electrolysis to fuel distribution. The sale or export of gasoline or kerosene could emerge as significant revenue streams. Ports could also extend their services to maintenance and technical support related to methanol synthesis and upgrading processes, thereby fostering partnerships with nearby industries for carbon dioxide supply or even the utilisation of the produced fuels.

- Fischer-Tropsch route

The Fischer-Tropsch (FT) synthesis is a catalytic chemical process that converts, through different catalysts, a mixture of hydrogen and carbon monoxide (CO)into hydrocarbons, such as synthetic crude oil or syncrude. This intermediate product can then be further refined into fuels like diesel and kerosene. Ports could extend their role by housing the FT synthesis reactors, possibly facilitating the supply of carbon monoxide through gasification of biomass or conversion of CO_2 into CO. This step not only transforms hydrogen into a more manageable and transportable form but also includes ports deeper into the syncrude value chain.

The syncrude can then be refined and upgraded to produce kerosene and/or diesel. Syncrude refining and upgrading commence with a process of fractional distillation, where the crude is heated and separated into various fractions based on differing boiling points, suitable for different fuel types. Following this, the fractions destined to become kerosene or diesel undergo further treatment and refining processes such as hydrocracking or hydrotreating. Finally, these refined fractions may be blended with additives or other hydrocarbons to meet specific fuel standards, ensuring the final products possess the desired combustion characteristics and are compliant with according standards.

As for the products described before, ports could monetize the infrastructure and services provided or profit from the sale or export of these commodities, which would in the first place require an according investment in additional infrastructure.

8.4.1.6 Ammonia (NH_3)

The production of ammonia is based on the Haber-Bosch process in which hydrogen (H_2) and atmospheric nitrogen (N_2) are synthesised into ammonia (NH_3). The process is established for decades at industrial scale. Its primary use is as a synthetic fertiliser in agriculture. Ammonia also serves as a raw material in the production of various nitrogen-based chemicals and pharmaceuticals. In the realm of clean energy, ammonia is being explored as a long-distance hydrogen carrier and as an alternative fuel for propulsion or thermal power plants.

Extending current uses of ammonia into other sectors, however, is subject to an ongoing discussion. Concerns are the very high human and also water toxicity of ammonia. Being a highly-toxic gas, safety and security aspects[125] have to be carefully considered versus risk levels of alternatives[126].

In the context of ports, ammonia can be utilised in several novel ways. Firstly, as a clean fuel, it is currently investigated as a potential future fuel to power ships. Ports could also serve as crucial nodes in the supply chain for ammonia, housing production facilities or serving as transit hubs for its global distribution where neighbouring communities and space requirements for safety distances allow for this (see chapter 6.3.2 on safety distances). Lastly, ports with nearby agricultural regions could act as integrated production and distribution centres for ammonia-based fertilisers. Integrated fertiliser production would reduce the lifetime of ammonia, thus inherently reducing safety and security risks compared to today's ammonia value chains. The scalability of renewable power generation technologies also provides the option for a more decentralised fertiliser production, thus increasing the resilience in regional agricultural production.

8.4.2 Use cases

In this second part, the use cases will be described again in more detail as well as the influence on the necessary quantities depending on the scope. Different studies will also be included, such as the study commissioned by the Clean

[125] Keinan, Ehud (Schulich Faculty of Chemistry, Technion – Israel Institute of Technology): An executive summary of the Professors' Report; The Israel Chemist and Engineer, Issue 3, June 2017; https://ice.digitaler.co.il/ice3/files/assets/common/downloads/publication.pdf

[126] Together in Safety: Future Fuels Risk Assessment; 2022

Hydrogen Partnership[127] which discusses the potential for hydrogen utilisation within port areas, primarily focusing on the European region.

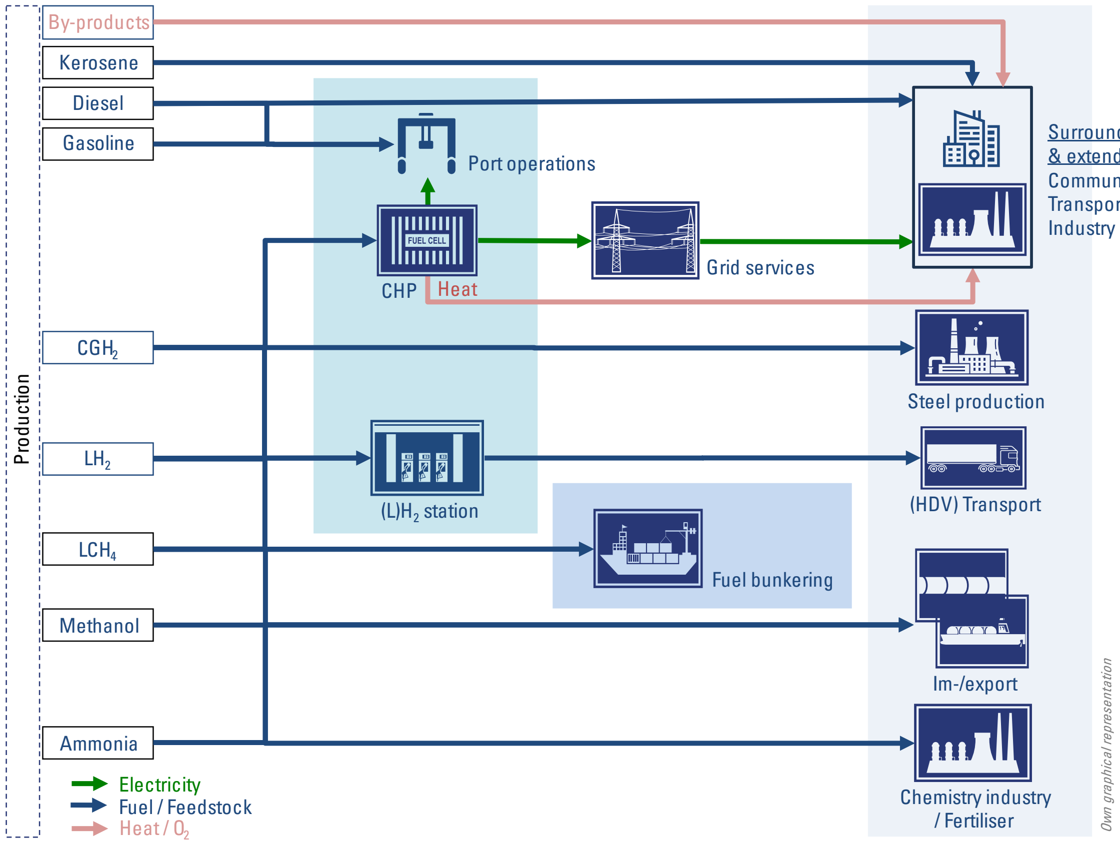

Figure 8-5: Overview of PtX use cases (including by-products)

8.4.2.1 Use cases within the port area

The availability of hydrogen and its derivatives in ports opens up a number of possibilities for enhancing port-internal processes and operations. Nonetheless, a majority of cargo handling and terminal equipment continue to pose challenges to electrification due to

(1) substantial power demands,

(2) diminished operational convenience, and

(3) extended charging durations.

Moreover, emissions from heavy machinery in ports and regions lacking sufficient renewable power supply potential or lacking a strong grid connection can be mitigated by adopting alternative energy carriers like hydrogen (in fuel cells or combustion engines) or H_2 derivatives (in combustion engines).

Currently, the application of hydrogen and hydrogen-derived fuels for port and terminal equipment remains a less substantiated technology with lower technological maturity when juxtaposed with electrification. Looking ahead, alongside batteries, the utilisation of low-to-zero carbon fuels such as hydrogen (either coupled with a fuel cell or engine) could witness a broader deployment for heavy-duty equipment and/or entail longer operating periods for e.g. trucks, forklifts, cranes, and tugs. Besides significantly reducing their greenhouse gas emissions, they could be refuelled quickly and minimising downtime compared to electrified alternatives. The high energy density of hydrogen can provide

127 Deloitte (2023): Study on hydrogen in ports and industrial coastal areas. URL: https://www.clean-hydrogen.europa.eu/system/files/2023-09/EN%20PDF%20-%20H2%20in%20Ports%20-%20Report%202%20-%20September%202023.pdf. Accessed on 23.10.2023.

sufficient power to handle the demanding tasks these pieces of equipment perform, while also reducing noise pollution. This use case can already be found today e.g. in the port of Duisburg where most of the electrical energy required to power the port's operations will be generated on demand on site using hydrogen. The planned power installation comprises cogeneration plants (both hydrogen motor and fuel cells) to fully cover loads. The applications in the terminal to be powered by electricity generated with hydrogen includes the bunkering of vessels with onshore power for unloading, storage and handling of containers.[128] The concept also foresees to supply upon demand hydrogen and/or by-product heat to other parts of the port and the surrounding area [129].

Hydrogen acts also as an effective medium for energy storage. Ports often have fluctuating energy demands, and the ability to store excess energy in the form of hydrogen can help manage these fluctuations efficiently. This is especially beneficial when ports have integrated renewable energy sources, as hydrogen allows for the long-term storage of excess electricity generated during periods of high wind or sun. Onsite hydrogen-based power generation therefore support a better integration of renewable energy sources. The stored hydrogen can be utilised via fuel cell (zero emission), motor engine or gas turbine to balance the electrical grid within the port (including co-generation of heat where need be), providing power during peak demand periods or during times when renewable energy generation is low. This enhances the energy resilience of the port and also helps in stabilizing the grid, ensuring a reliable power supply for port operations and reducing reliance on external power sources which might be fossil fuel-based.

8.4.2.2 Use cases involving the refuelling of landed vessels (bunkering)

Presently, nearly all fuel consumed in maritime engines is energy-dense oil fuels. In 2018, the International Maritime Organization (IMO) outlined its preliminary Greenhouse Gas (GHG) emissions reduction strategy (set for an update in 2023), aiming to curtail the carbon intensity of international shipping by a minimum of 40% by 2030 (striving for a 70% reduction by 2050) relative to 2008, and to diminish the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008. Given the lengthy lifespan of maritime vessels, typically exceeding 30 years, the pressing need for alternative (zero or low-carbon) maritime fuel vessels to achieve the 2030 and 2050 targets is palpable.

Although large-scale availability of alternative maritime fuels is yet to be realised, hydrogen and hydrogen-based fuels (such as ammonia or methanol) hold the potential to decarbonise and mitigate air pollution of the maritime sector. Under the EU Green Deal, the EU has initiated several legislative, regulatory, and programmatic measures to accelerate the development of alternative maritime fuels within the maritime transport domain (see chapter 2.2).

With a rising emphasis on enhancing environmental efficiency in European ports and amongst shipping firms, onshore power systems (OPS), emerge as a viable solution to furnish ships with (partial) shore-based power. Achieving a full elimination of direct GHG emissions is possible if the OPS is solely fuelled by renewable electricity, which can be produced nearby where sufficient suitable area is available.

The majority of onshore power systems are grid-connected, imposing a significant load on the electricity grid. This might pose a challenge for ports situated in smaller cities, isolated areas, or islands, where the regional power generation and grid capacity may be insufficient. Distributed dispatchable power generation (fuel cells, combustion engines) could be aptly suited for onshore power supply.

Given the overall challenges, the development of both mobile (installable on barges) and stationary (onshore) hydrogen-based systems encompassing fuel cells, dual and mono-fuel hydrogen-powered internal combustion engines represent viable options even though they are not extensively deployed yet. These innovations present possible means of supplying auxiliary power to vessels while also paving the way for ports to establish hydrogen refuelling infrastructures for both road and maritime uses.

128 MTU (2022): Hydrogen-based energy for the port logistics of the future. URL: https://www.mtu-solutions.com/na/en/stories/power-generation/hydrogen-based-energy-for-the-port-logistics-of-the-future.html. Accessed on 31.10.2023.

129 enerPort II: Optimierter Energieeinsatz im Hafen Microgrid @DGT [German only]. URL: https://green-terminal.ruhr . Accessed on 03.04.2024

8.4.2.3 Use cases beyond the port (local and extended region)

According to the hydrogen in ports study[127], it is expected that with the deployment of the REPowerEU plan over the next decade, large quantities of LH_2 and hydrogen carriers (ammonia, methanol) will be imported into European ports by sea tankers. Ports will have to play an active role in the development of this new international trade by providing import terminal capacities including cracking (where needed). This marks the first important use case for ports and beyond.

For the safe offloading and management of LH_2 or hydrogen carriers, ports would necessitate meticulous planning. This could either be at retrofitted LNG terminals, if feasible, or, more likely, at newly constructed or expanded dedicated liquid bulk terminals tailored for this purpose.

Terminals designed for the unloading and storage of LH_2 are equipped with loading arm systems, storage tanks, a boil-off gas management system, cryogenic pumps, and vaporizers, facilitating the supply of gaseous hydrogen to pipelines for balancing purposes. The equipment and infrastructure for LH_2 handling at import terminals have been demonstrated on a relatively small scale, as seen with the operation of the LH_2 terminal prototype in Kobe, Japan. Consequently, a substantial scaling up of the different terminal components is requisite for large-scale transport or for adapting the existing LCH_4 market infrastructure to accommodate LH_2 conditions. Among these components, storage tanks, boil-off-gas (BOG) management, and rotary equipment are identified as the most critical elements requiring attention for scaling and adaptation.

Ammonia, on the other hand, is mostly used in fertilizer production and is thus already transported in large quantities. A global shipping infrastructure exists with a high maturity of storage, transport, and distribution technologies. Ammonia import terminals store ammonia as a liquid at -33°C and atmospheric pressure in stainless steel tanks. Refrigerated storage at -33°C requires insulation and a boil-off gas system to mitigate heat ingress. According to the study from Deloitte Belgium, there are already 88 import ports for ammonia worldwide. OCI Global, an internationally operating Dutch fertilizer producer, has made an FID for the expansion of its ammonia terminal from 400 ktpa to 1200 ktpa in the Port of Rotterdam. In order to be able to handle the larger volumes in the future, ports will have to build and provide the corresponding infrastructure, as described above.

Ports can also become a nexus for industry in the hinterland, serving as crucial hubs in the hydrogen and derivatives supply chains. Their strategic location and infrastructure make them well-positioned to facilitate the import/export, production, storage, transportation, and utilisation of hydrogen and its derivatives. Industries in the hinterland that might be interested in hydrogen and its derivatives include:

- Chemical industry
- Steel industry
- Heavy-duty transportation
- Peak (back-up) power generation
- Aviation

Power-to-X (PtX) technology in general, shows a notable strength in its scalability, offering versatility across a wide range from megawatts (MW) to gigawatts (GW). This scalability allows PtX solutions to be tailored to diverse energy demands, accommodating both smaller, localized applications and larger, grid-scale implementations.

Ports have the potential to evolve into pivotal hubs in the **hydrogen ecosystem**, fostering a seamless integration of hydrogen and its derivatives across various sectors within the hinterland. This transformation can spur new business models, making ports not just transit points, but multifaceted energy hubs. In the chemical industry, ports can play a vital role by hosting electrolysers powered by renewable energy for green hydrogen production which in term can serve as a crucial feedstock for nearby chemical plants or be exported to other regions. Additionally, ports can facilitate the production of ammonia by providing the necessary hydrogen, which can then be used locally or exported, serving as a key component in fertiliser production and other chemical processes. The same idea applies to ports in regard to the steel industry, which also presents an interesting opportunity. By supplying hydrogen to steel mills in the hinterland, ports can foster a transition to hydrogen-based steel production or attract more relevant industry in the surrounding area, which in turn would stimulate local economics.

In the domain of **transportation**, ports can position themselves as relevant actor when it comes to the establishment of a hydrogen-based transport ecosystem. Hydrogen, either as compressed gaseous hydrogen (CGH_2) and/or liquefied hydrogen (LH_2), can be distributed as transportation fuel through H_2 refuelling stations to hydrogen-powered vehicles like buses, trucks, as well as inland barges and maritime vessels. Most industrial ports will also be connected to the hydrogen backbone, which will interconnect the large import/export and production facilities with the main industrial clusters. In this context, repurposing methane transport pipelines is being considered to carry 100% hydrogen; this option is a lower-cost alternative than building new hydrogen pipelines.

The **power generation** sector can benefit from the hydrogen capabilities of ports, as they can supply hydrogen to power plants or host their own hydrogen-powered generators, providing clean electricity to the grid, including heat where a district heating grid is in place. Moreover, the hydrogen supplied could also be used for electricity generation during periods of high demand or low renewable energy output, thus supporting system adequacy and grid stability.

For **heating**, ports could supply hydrogen for industry heat i.e. for high-temperature applications that cannot (yet) electrified. Hydrogen for low temperature heating purposes requires significantly more primary energy compared to e.g. heat pumps using electricity, hence this is not an adequate option from an energy perspective. However, low temperature by-product heat from water electrolysis can and should be used for any heating demands, and could be complemented with industry heat pumps to achieve temperature levels >100°C.

In **aviation**, ports can host facilities for producing synthetic aviation fuels from hydrogen, supplying nearby airports or exporting internationally. These synthetic fuels can serve as low-carbon alternative fuels, helping to reduce the carbon footprint of aviation.

Based on these different possibilities, ports could develop various business models. They would transform into **energy hubs**, producing, storing, and distributing hydrogen and its derivatives, and charge fees for these services. By investing in crucial infrastructure like electrolysers, storage facilities, refuelling stations, and pipelines, ports could also lease these facilities to energy companies or charge usage fees, establishing themselves as infrastructure providers.

Furthermore, ports could provide essential services like bunkering, fuelling, and maintenance, generating revenue from service fees. They can also facilitate the trade and export of hydrogen and its derivatives, earning revenue from handling and export fees. This would also lead to the establishment of new partnerships and joint ventures with energy companies, industrial clusters, and government entities to develop and operate hydrogen projects, sharing the risks and rewards.

What becomes clear from this analysis is that the development of new business models around the hydrogen value chain presents ports with exciting opportunities, yet it also brings attention to potential limitations, particularly concerning space constraints. Handling fuels and feedstock with different risk profiles demands careful spatial planning. The availability of sufficient space can be a critical factor for implementation. Furthermore, the necessity of safety distances, especially in the case of handling products like ammonia, adds an additional layer of complexity. The high toxicity of ammonia requires stringent safety and security measures and or novel approaches like fully-integrated fertilizer production.

8.5 Conclusions

The chapter “Ports as industrial nexus for the ORES and TEN-E implementation” highlights the critical role of ports in facilitating the deployment of offshore renewable energy and as central nodes in establishing and interconnecting global and local energy networks.

Upgrade of port infrastructure: Ports are recognized as indispensable for the deployment of offshore renewable energy. With the continuous evolution of technology, the components associated with these assets will be growing in size and weight. As a result, needs may arise to upgrade port infrastructure to handle these larger and heavier components. This involves investments in dock structures, cranes, storage facilities, and transportation capabilities to ensure the smooth flow of equipment and materials crucial for offshore energy projects.

Interconnecting energy networks and markets: Some ports have historically been energy hubs for biomass (wood) and even more so for fossil fuels. A transformative wave is ongoing and should be accelerated: Fossil/unmitigated energies will have to be replaced by low-carbon/renewable energies, the latter will primarily be based on renewable electricity from solar and wind power, power-to-hydrogen and derivatives. The characteristics of energy hubs at the interface of sea and shore are set to change accordingly. A strength of PtX technology is its scalability across the MW to GW range. This translates into opportunities where sufficient space is available in or near ports. The portfolio of energies and feedstocks is likely to increase – adding, e.g., power, heat, O_2, or CO_2 – thus linking global, regional, and local energy systems. By serving as hubs for energy exchange, ports can facilitate the efficient transfer of renewable energy between world regions and countries. Furthermore, at the local level, ports can integrate with surrounding areas, forming a cohesive energy network that benefits both the port and its adjacent regions.

Alignment with TEN-E regulation and ORES objectives: The expansion of energy-related port infrastructure aligns with the broader objectives of the Trans-European Networks for Energy (TEN-E) regulation and the Offshore Renewable Energy Strategy (ORES) and the more recent Offshore Communication. The TEN-E regulation seeks to create a seamless and integrated European energy market, and by enhancing port infrastructure there is a direct contribution to the development of this interconnected and integrated energy system. Simultaneously, the Offshore Communication aims to harness the potential of offshore renewable energy by delivering on new and more ambitious goals for installed capacity in 2030, 2040, and 2050. Well-equipped ports can indeed play a pivotal role in enabling the efficient installation, maintenance, and expansion of offshore energy production and transport assets.

Regional strengthening: The expansion of energy-related port infrastructure, where space allows for this in or near ports, is not only beneficial at a national and global scale but also contributes to the strengthening of adjacent regions. This regional development is a byproduct of increased economic activity, job creation, and improved infrastructure. Consequently, it complements the overall goals of the TEN-E regulation and ORES initiative by fostering sustainable development at both macro (global), meso (Europe), and micro (regional) levels.

Exploring new business models for ports goes beyond the conventional scope of shipping and trade activities, presenting an opportunity for port operators and policymakers to diversify revenue streams and contribute to sustainable development. Beyond the business model cases already discussed, several promising options emerge, including the integration of waste-to-energy/resource facilities, the establishment of logistics and supply chain innovation centres, and the utilization of electrolyser by-products in cases where hydrogen production is part of the development.

In the realm of new business models for ports, a focus on hydrogen and its derivatives presents a transformative opportunity. Ports, particularly those designated as energy/industrial hubs, stand as pivotal nodes in the entire value chain, functioning as key players in the production, storage, transportation, and distribution of hydrogen and its derivatives and by-products. While recognizing the potential limitations due to space requirements arising from safety considerations, ports are well-positioned to evolve into clean energy hubs, facilitating seamless shipment across regional and international corridors.

In addition, port operators can develop comprehensive logistics solutions for the seamless shipment of hydrogen and derivatives and implement advanced tracking systems, efficient loading/unloading infrastructure, and dedicated terminals for handling hydrogen shipments. This can be supported through the establishment of standardized procedures and regulations for the transportation of hydrogen, ensuring safety while promoting efficiency on the one hand, and fostering international collaborations to create harmonized standards, simplifying cross-border shipments on the other.

In order to address space limitations, port operators will have to strategically plan and optimize the utilization of available space within the port for hydrogen-related activities combined with investments in technologies that maximize storage density and optimize safety measures to handle bulk volumes, considering the specific characteristics of hydrogen and its derivatives. This can be complemented by dedicated collaborations with relevant authorities and regulatory bodies to establish guidelines for safe and efficient space utilization within or near ports.

Besides the challenge of space limitations, safety and security measures have also to be considered when talking about future business models based on hydrogen and its derivatives. Port operators should always prioritize safety measures in the handling of hydrogen and its derivatives, for example by implementing rigorous training programs for personnel, deploying cutting-edge monitoring systems, and adhering to international safety standards. This should be supported through a proper regulatory framework ensuring the enforcement and regularly update of safety regulations governing the handling and transportation of hydrogen. For this, collaboration with international organizations can be helpful to share best practices and enhance the necessary safety standards for the handling of hydrogen and its derivatives.

Looking at the integration of waste-to-resource/energy facilities, port operators should seek cooperations with waste management companies to establish waste-to-resource/energy facilities within or nearby port premises. This comprises converting imported, regional, and/or port-generated wastes into energy or extracting valuable resources through advanced recycling processes. Such activities resonate with the objective of moving towards more ‘circular’ economies, a concept also promoted by European policy.

Regarding ports as potential logistics and supply chain innovation centres, port operators could collaborate with technology and logistics companies to establish innovation centres focused on optimising supply chain processes. This may include implementing advanced technologies such as distributed ledger (blockchain) and artificial intelligence with the objective to enhance efficiency, transparency, and sustainability in logistics operations.

Embracing these findings enables port operators and policymakers to unlock new economic development avenues, thus contributing to environmental sustainability and technological innovation. Ports can thus strengthen their role as hubs at the interface between shore and sea.

APPENDIX A: LITERATURE REVIEWED FOR BARRIERS AND MITIGATIONS ANALYSIS

1. DNV (2022) Maritime forecast to 2050 – Energy Transition Outlook 2022, download at eto.dnv.com
2. DNV (2020) Barriers for implementation of carbon-neutral fuels.
3. DNV (2017) SUSTAINABLE DEVELOPMENT GOALS: EXPLORING MARITIME OPPORTUNITIES
4. DNV (2020) Ports green gateways to Europe. Available at: https://www.dnv.com/Publications/ports-green-gateways-to-europe-179372
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APPENDIX B: LIST OF ABBREVIATIONS

Abbreviation	Definition
A/E	Auxiliary Engine
AIS	Automatic Identification System
AFIR	Alternative Fuels Infrastructure Regulation
AMP	Alternative Maritime Power
CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CEF	Connecting Europe Facility
CGH2	Compressed Gas Hydrogen
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DSO	Distribution System Operator
DNV MASTER model	Mapping of Ship Tracks, Emissions and Reduction potentials (MASTER) model, the model uses user inputs, detailed ship specific information and supporting data tables to estimate the energy demand, fuel consumption and emissions of each individual ship while sailing and when in port.
EMA	Energy Market Authority (Singapore)
ESPO	European Sea Ports Organisation
ETU	Energy Taxation Directive
GHG	Greenhouse Gas
GT	Gross Tonnage
GW	Gigawatt
HHV	Higher Heating Value
HRS	Hydrogen Refuelling Station
HV	High-Voltage
HVSC	High-Voltage Shore Connection
LBG	Liquified Biogas
LH2	Liquefied Hydrogen

LHV	Lower Heating Value
LIDAR	Light Detection and Ranging
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MW(p)	Megawatt (Peak)
MS	Member State
OPS	Onshore Power Supply
ORES	Offshore Renewable Energy Strategy
PA	Port Authority
Pax	Passenger
PEM	Proton Exchange Membrane
PM	Particulate Matter
PPA	Power Purchase Agreement
PtH2	Power-to-Hydrogen
RES	Renewable Energy Sources
Ro-Ro	Roll-on/Roll-off
RTG	Rubber Tyred Gantry (crane)
SSE	Shore-Side Electricity
STS	Ship to Shore
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European transport network
TEU	Twenty-foot Equivalent Unit
TSO	Transmission System Operator

APPENDIX C: LIST OF PORTS

		Operational Experience Criteria					General Ports's Characteristics				
	Port	**OPS**	**Decar.**	**Energy Hub**	**New bus.**	**Smart grid**	**Type**	**Size**	**Location**	**Energy share**	**Industrial activities**
1.	Gothenburg, SE	5	5	3	3		Gen Purpose	Medium	Baltic Sea	10-30%	Industrial port
2.	Kristiansand, NO	5			4		Gen Purpose	Small	North Sea	<10%	None
3.	Stockholm, SE	5	1	5	2		Gen Purpose	Small	Baltic Sea	10-30%	None
4.	Oslo, NO	5	4				Passenger	Small	North Sea	<10%	None
5.	Bergen, NO	5	2				Energy	Medium	North Sea	<10%	None
6.	Kiel, DE	4	5	4			Passenger	Small	Baltic Sea	<10%	None
7.	Amsterdam, NL	3	2	2	2	1	Gen Purpose	Very L.	North Sea	30-50%	Energy industry
8.	Hamburg, DE	3				3	Gen Purpose	Very L.	North Sea	<10%	Industrial port
9.	Bilbao, ES	1	1				Gen Purpose	Medium	Atlantic		
10.	Rotterdam, NL	3	2	1	2	5	Energy	Very L.	North Sea	30-50%	Energy industry
11.	Valencia, ES	2	2	3		2	Container	Large	Mediterranean	<10%	Mixed bus. zone
12.	Le Havre, FR	3			2		Energy	Large	North Sea		
13.	Bremen-Bremerhaven, DE	2			2	2	Gen Purpose	Medium	North Sea	<10%	Industrial port
14.	Antwerp-Bruges, BE				2	3	Gen Purpose	Very L.	North Sea	30-50%	
15.	Brest, FR				1		Gen Purpose	Small	Atlantic	<10%	Mixed bus. zone
16.	Bordeaux, FR							Small	Atlantic		
17.	Las Palmas, Canary I., ES	4		3			Island port	Medium	Atlantic		
18.	Marseille, FR	5		3			Energy	Large	Mediterranean		
19.	Trondheim, NO				3		Passenger	Small	North Sea	<10%	None
20.	Copenhagen, DK			3	2		Cruise	Medium	Baltic Sea	10-30%	None
21.	Kyllini, GR	3				5	Passenger	Small	Mediterranean	<10%	None
22.	Vigo, ES	2					Fishery	Small	Atlantic		
23.	Viana do Castelo, PT			1			Leisure	Small	Atlantic		
24.	Saint Nazaire-Nantes, FR		2	1	1		Shipbuilding	Medium	Atlantic	55%	Energy industry
25.	Genoa, IT	5	1	2			Shipbuilding	Medium	Mediterranean		
26.	La Spezia, IT						Cruise	Medium	Mediterranean		
27	Pireaus, GR		2	2			Gen Purpose	Large	Mediterranean		
28.	Vancouver, CA	5	1		2		Energy	Large	Pacific		
29.	Los Angeles, US	5	2	5			Container	Very L.	Pacific		
30.	Singapore, SG		2	5	2	3	Trans-ship	Very L.	Asia		

Legend: 5 = at least 3 years operational, full coverage, 4 = partly or recently implemented, 3 = Pilot project operational, 2 = Feasibility phase/design/defined targets, 1= Ambitions/strategy plans

APPENDIX D: ASSUMPTIONS AND FINANCIAL INPUTS IN COST BENEFIT ANALYSIS

Calculations have been made using an interest rate of 6% and depreciation period of 20 years.
For all the calculations, assumptions have been made for energy prices and prices for CO_2, NOx, PM, and SO_2.

Financial inputs were gathered during the interviews with ports or assumed by DNV.

Concerning the power mix in the electricity grid, assumptions have been made on the power mix in the relevant countries, unless the port has concluded purchasing power agreements with supply of 100% renewable energy.

Table D- 1: General assumptions

Interest rate	6 percent	DNV assumption
Depreciation period	20 years	DNV assumption
Bunker fuel price	570 USD/ton	Average 2023 Rotterdam bunker prices
Electricity grid investment	24,27 EUR /MWh	Average network investment and O&M EU27 (2010-2018) per transported unit of energy

Table D- 2: Financial inputs – OPS business models

Financial inputs	Marseille: OPS-Ferry Line	Kristiansand: OPS-Bulk Goods Carrier	Gothenburg: OPS-Ferry Line
Depreciation period (years)	20	20	20
Interest rate	6%	6%	6%
Investment cost for port (MEUR/MW)	0.29	0.5	1
Investment cost for ships (MEUR/vessel)	1.5	1.8	2
Maintenance of OPS (% of CAPEX)	5%	5%	5%
Maintenance of engine (EUR/h/engine)	1.6	1.6	1.6

Table D- 3: Financial inputs CBA - other clean energy business models

Financial inputs	RTG Electrification	H2 Terminal Machinery	Renewable electricity case
Depreciation period (years)	20	20	20
Interest rate	6%	6%	6%
Investment cost new e-RTG (MEUR per unit)	1.79		
Investment cost retrofitted e-RTG (MEUR per unit)	0.13		
Maintenance costs e-RTG (EUR/ operational hour)	19.43		
Investment cost ‘normal’ diesel RTG (MEUR per unit)	1.70		
Maintenance costs ‘normal’ RTG (EUR/hour)	40.3		
Investment cost e-infrastructure MEUR	3.3		

Diesel price (EUR/L)	0.91[130]	0.91	
Investment cost electrolyser including stacks, rectifiers, gas treatment, cooling and containers + prepare site EUR/kW		1,500	
Maintenance cost H_2 Facility % of CAPEX		8.8%	
CAPEX Machinery (EUR per unit)		500,000	
Maintenance cost H_2 Reach stacker % of CAPEX		10%	
CAPEX Wind energy EUR/kWp		1,200	1,200
CAPEX Solar PV EUR/kWp		2,000	
OPEX RES (Wind, Solar) % of CAPEX		0.4%	0.4%
CAPEX normal reach stacker (EUR per unit)		350,000	
Maintenance cost normal reach stacker % of CAPEX		12%	
Investment cost solar PV (EUR/kWp)			693[131]
Investment cost floating solar (EUR/kWp)			776
Investment cost wave energy (EUR/kWp)			4,000
Maintenance floating solar (% of CAPEX)			2.5%
Maintenance wave energy (EUR/kW/year)			95
Capacity factor onshore wind Spain			25%
Capacity factor floating solar			11%
Capacity factor wave energy			35%

The following table presents the specific emissions per electricity mix (2023).

Table D- 4: Emissions per electricity mix per country

Electricity source	100% green certificates	Netherlands Mix	Spain Mix	Sweden Mix	Norway Mix	France Mix
CO_2 (g/kWhe)	0.0	421	131	19	18	39
NOx (g/kWh)	0.0	0.58	0.18	0.03	0.02	0.05
PM (g/kWh)	0.0	0.02	0.01	0.00	0.00	0.00
SO_2 (g/kWh)	0.0	0.31	0.10	0.01	0.01	0.03

Source: https://www.nowtricity.com/country/ and https://ce.nl/wp-content/uploads/2021/03/CE_Delft_4F65_defnotitieMO.pdf

[130] Spain average 2023

[131] According to www.sciencedirect.com/science/article/pii/S0960148123006250 , Port of Valencia did deliver the total cost of the project but this value aggregated the maintenance and the investment cost, for this analysis we would need the separate investment cost.

Table D- 5: EU average emissions projections

	100% green certificates	2023	2030	2040	2050[132]
CO_2 (g/kWhe)	0.0	231.2	114	73.3	25
NOx (g/kWh)	0.0	0.32	0.16	0.10	0.03
PM (g/kWh)	0.0	0.01	0.01	0.00	0.00
SO_2 (g/kWh)	0.0	0.17	0.08	0.05	0.02

Sources: https://www.nowtricity.com https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-14/#tab-chart_7 and https://www.iea.org/data-and-statistics/charts/average-co2-emissions-intensity-of-hourly-electricity-supply-in-the-european-union-2018-and-2040-by-scenario-and-average-electricity-demand-in-2018

Electricity prices

The following table presents the electricity prices used in the high, medium and low scenario. For the medium scenario ENTSO-e 2023 average wholesale prices were used. For the High and Low scenario, a 20% increase and decrease were taken into account.

Table D- 6: Electricity prices

Electricity prices (EUR/MWh)	The Netherlands	Spain	Sweden	Norway	France
High	115.0	104.5	59.0	72.6	116.2
Medium	95.8	87.1	49.1	60.5	96.9
Low	76.6	69.7	49.1	48.4	77.5

Source: ENTSO-e and DNV calculations.

The table below provides (unweighted) average EU electricity price projections.

Table D- 7: Average EU electricity price projections

Average EU Electricity prices (EUR/MWh) [133]	2023	2030	2040	2050
High	114.7	77.2	67.3	26.4
Medium	95.6	64.3	56.1	22.0
Low	76.5	51.5	44.9	17.6

Source: ENTSO-e and DNV calculations.

Table D- 8: Other fuel prices

Fuel	2023	2030	2040	2050
Bunkering fuel (USD/ton)	570	565	629	693
Diesel (EUR/l)	0.90	0.85	1.02	1.07

Sources: https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en , https://www.eia.gov/outlooks/steo/report/global_oil.php, CO_2-taxes, fuel prices and learning rates Contribution from Copenhagen Economics to the MarE-Fuel project

[132] 95% reduction in grid emissions compared to 1990.

[133] Up to 2040 the electricity prices includes costs to decommission fossil nuclear power stations. After 2040 with almost full renewable flexible generation there will be many hours with low prices.

Table D- 9: Emission costs

Emission	2023	2030	2040	2050
CO_2 (EUR/ton)	EUR 83.6	EUR 131.25	EUR 192.50	EUR 218.75
NOx (EUR/ton)	EUR 11.606	EUR 11.606	EUR 11.606	EUR 11.606
PM (EUR/ton)	EUR 197.630	EUR 197.630	EUR 197.630	EUR 197.630
SO_2 (EUR/ton)	EUR 16.643	EUR 16.643	EUR 16.643	EUR 16.643

Sources: www.CarbonCredits.com and Delft methodology report , and DNV projections

Table D- 10: Sensitivity analysis variables

Price	Low	Medium	High
Diesel fuel price (EUR/L)	EUR 0.7	EUR 0.91	EUR 1.1
CO_2 price (EUR/ton)	EUR 66.9	EUR 83.6	EUR 100.3
Electricity price	-20%		+20%
Bunker fuel (EUR/ton)	EUR 422	EUR 527	EUR 632
CAPEX	-20%		+20%

APPENDIX E: RESULTS AND ASSUMPTION MARITIME ANALYTICS

Ports Calls:

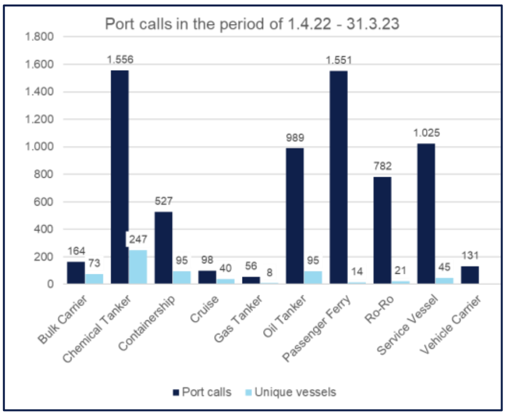

Figure E- 1: Port calls Gothenburg

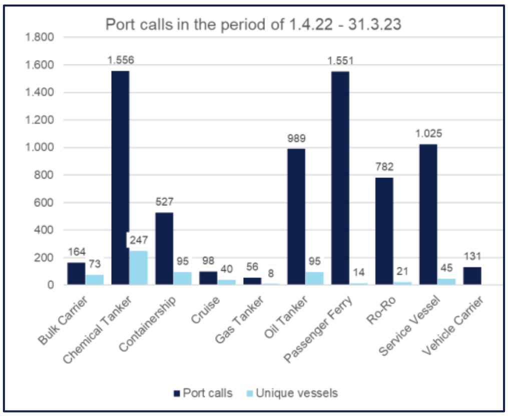

Figure E- 2: Ports calls Kristiandsand

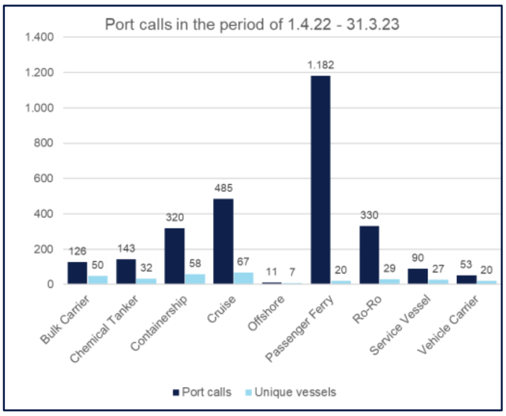

Figure E- 3: Ports calls Marseille

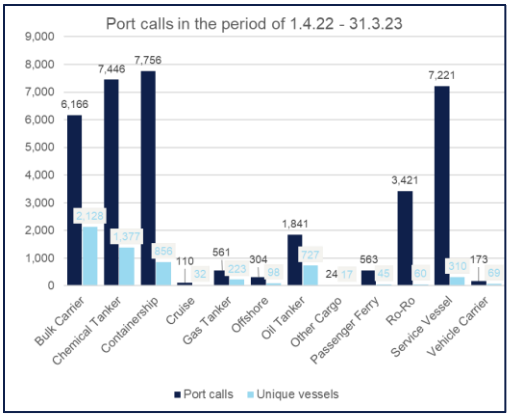

Figure E- 4: Ports calls Rotterdam

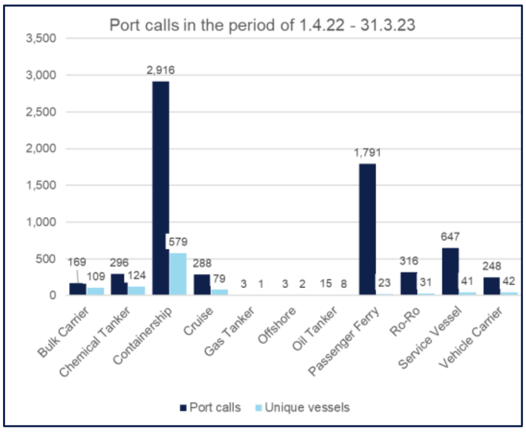

Figure E- 5: Port calls Valencia

Results

1. Evolution of total energy demand of all vessels:

Bulk Carrier Chemical tanker Container ship Cruise Gas Tanker Oil Tanker Passenger Ferry Service Vessel Ro-Ro Vehicle Carrier

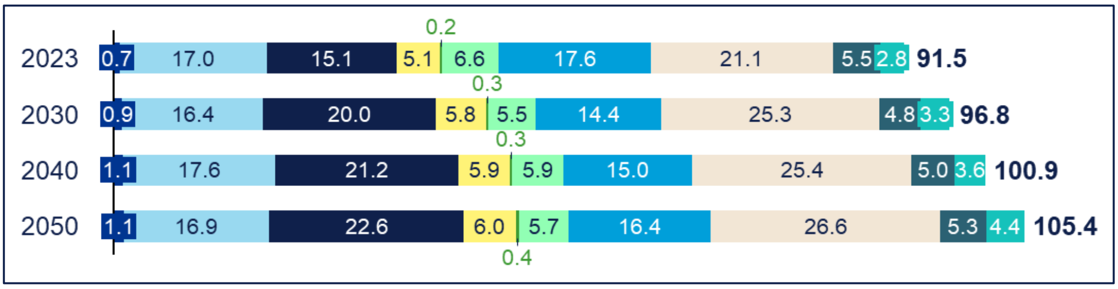

Figure E- 6: Evolution of total energy demand of all vessels at berth for Gothenburg, in GWh

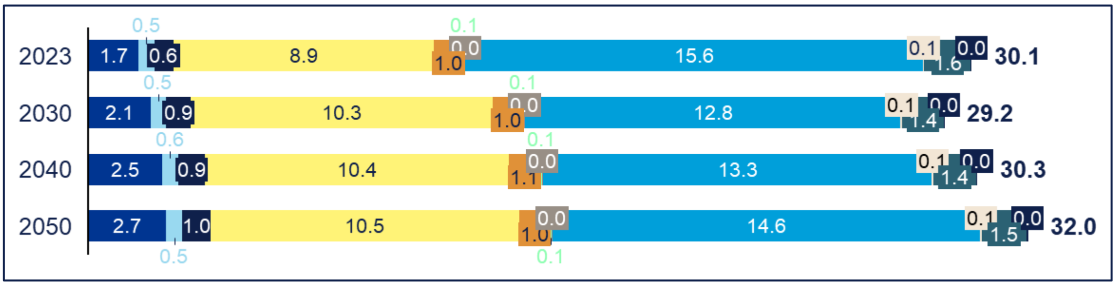

Figure E- 7: Evolution of total energy demand of all vessels at berth for Kristiansand, in GWh

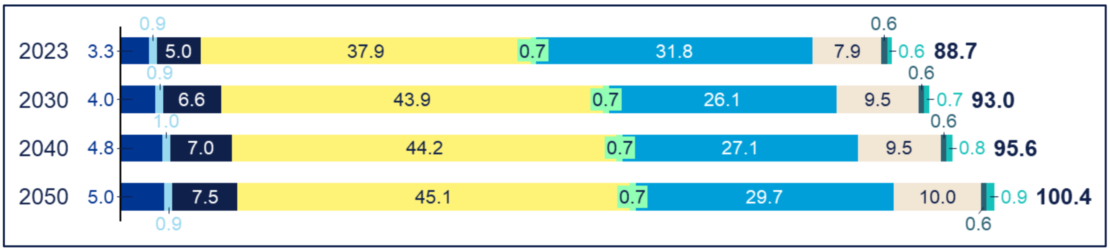

Figure E- 8: Evolution of Total energy demand of all vessels at berth in Marseille port, in GWh

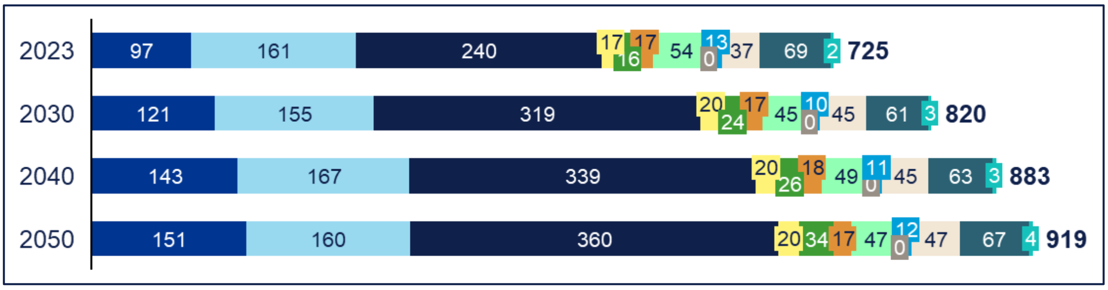

Figure E- 9: Evolution of total energy demand of all vessels at berth in Rotterdam port, in GWh

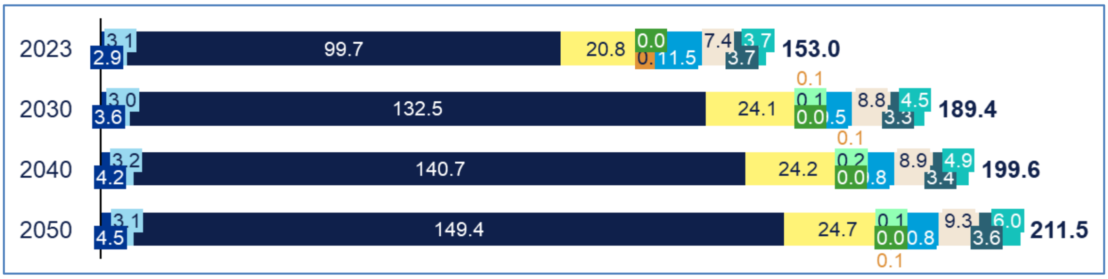

Figure E- 10:Evolution of total energy demand of all vessels at berth in Valencia port, in GWh

2. Evolution of energy supplied for shore power to vessels > 400 Gton:

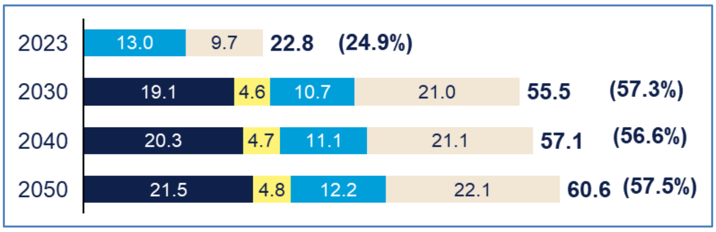

Figure E- 11: Evolution of energy supplied for shore power to vessels > 400 Gton in Gothenburg in GWh

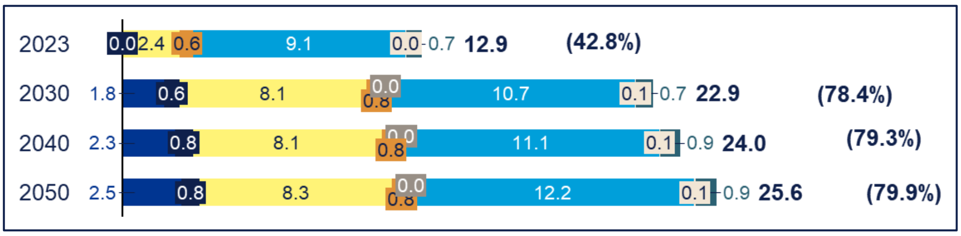

Figure E- 12: Evolution of electricity supplied for shore power to vessels > 400 Gton in Kristiansand port, in GWh

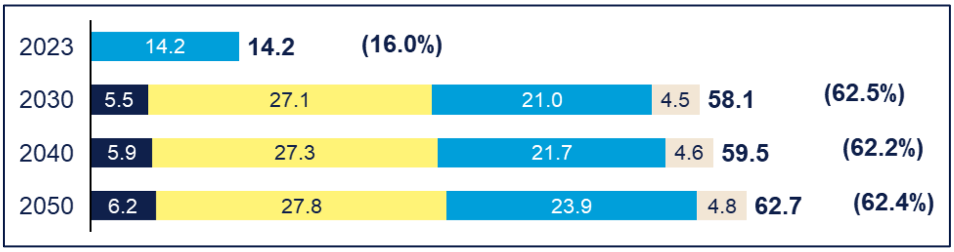

Figure E- 13: Evolution of electricity supplied for shore power to vessels > 400 Gton in Marseille port in GWh

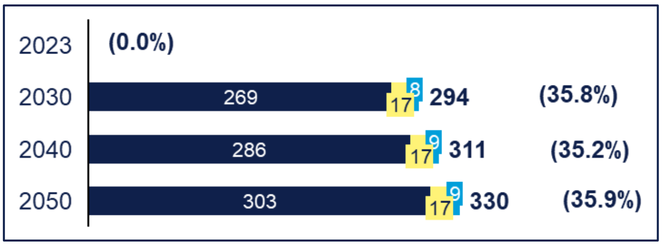

Figure E- 14: Evolution of electricity supplied for shore power to vessels > 400 Gton in Rotterdam port, in GWh

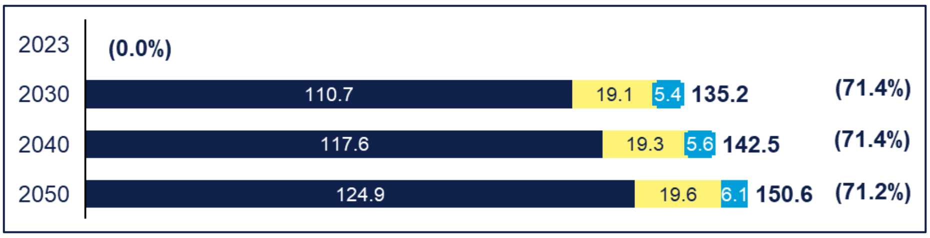

Figure E- 15: Evolution of electricity supplied for shore power to vessels > 400 Gton in Valencia port, in GWh

3. **Evolution of CO_2 emission reduction due to use of OPS by vessels >400 Gton:**

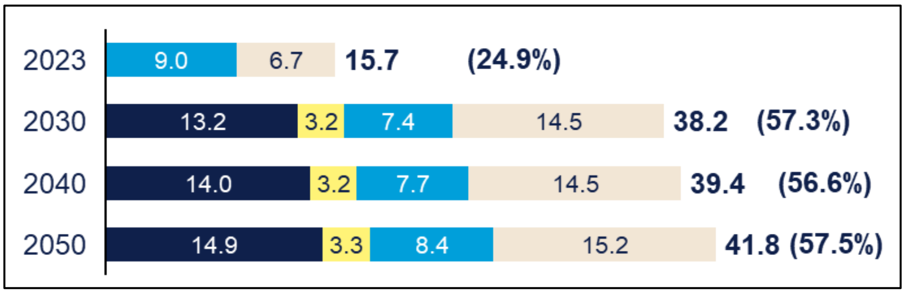

Figure E- 16: Evolution of CO2 emission reduction from use of OPS by vessels >400 Gton in Gothenburg, in kton

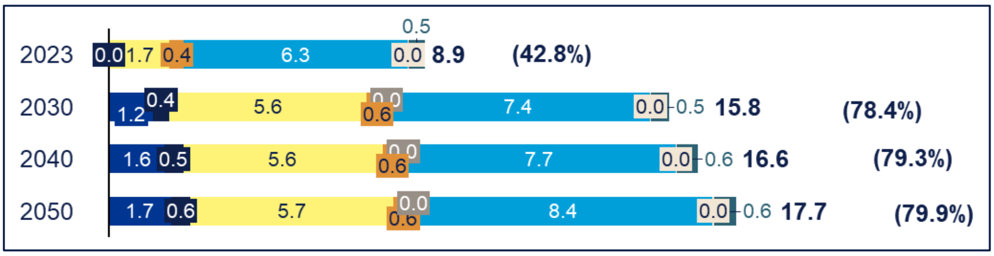

Figure E- 17: Evolution of CO2 emission reduction from use of OPS by vessels >400 Gton in Kristiansand port, in kton

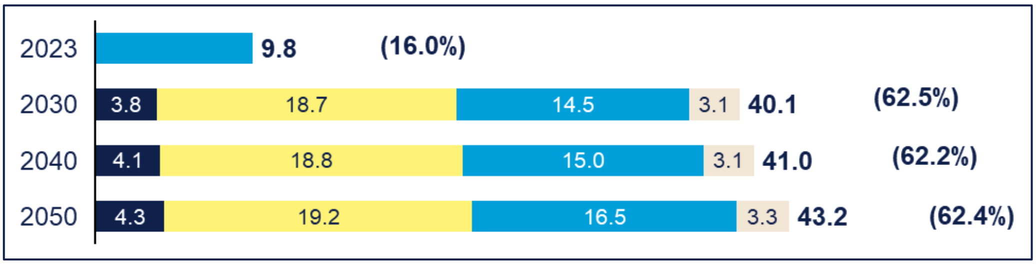

Figure E- 18: Evolution of CO2 emission reduction from use of OPS by vessels >400 Gton in Marseille port, in kton

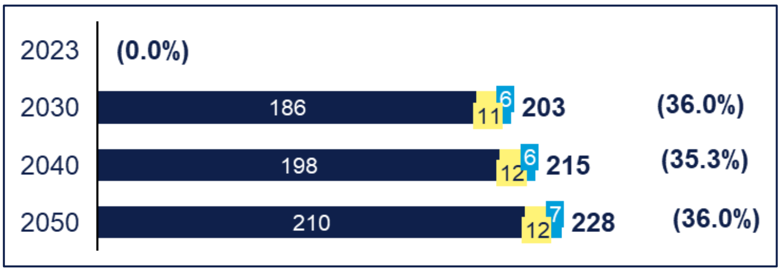

Figure E- 19: Evolution of CO2 reduction from use of OPS by vessels >400 Gton in Rotterdam, in kton

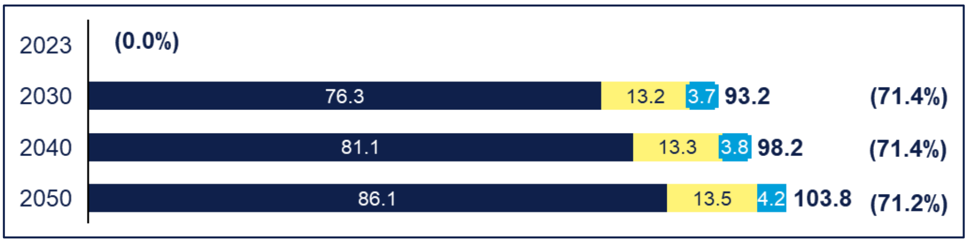

Figure E- 20: Evolution of CO2 emission reduction from use of OPS by vessels >400 Gton in Valencia port, in kton

Assumptions

The assumptions and shore power demand results presented in this study serve as a high-level estimation of the ports' shore power demand. The estimation is solely based on external data sources, and not on port data. Results cannot be used as a basis for, e.g., grid design.

Only seagoing vessels carrying an IMO number with an Automatic Identification System (AIS) transponder and with a time at berth longer than 2 hours are considered in the analysis. 1 hour of time is deducted from time at berth for connecting/disconnecting the vessels to OPS.

The OPS demand calculation is based on the number of port calls and time at berth from ship position data (AIS) for each ship type.

The energy demand at berth by ship type (MWh) is estimated based on auxiliary engine utilisation at berth, see table to the right, and the auxiliary engine setup installed (in case of cruise ships, the main engine setup installed is used as a basis (source: IHS Fairplay) because most cruise ships have a diesel-electric engine setup, so that the total installed power serves as a basis for shore power estimation; Sources: DNV project experience, IMO MEPC63 minimum power required. See **Error! Reference source not found.**.

Table E- 1: Utilisation at berth

Vessel type	% share of total aux power installed used at berth
Bulk Carrier	37%
Chemical Tanker	35%
Containership	31%
Cruise	24%
Gas Tanker	29%
Offshore	40%
Oil Tanker	33%
Other Cargo	40%
Passenger Ferry	33%
Ro-Ro	34%
Service Vessel	39%
Vehicle Carrier	31%

Fuel consumption at berth is calculated based on energy demand in MWh (see above) and a specific fuel oil consumption of 0.215 t VLSFO/MGO / MWh.

CO_2 emissions at berth are calculated based on an emission factor of 3.206 tCO_2/tVLSFO/MGO (Source: ANNEXES to the Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC)[)]. It can be assumed that 100% green electricity is available in all ports selected. Gothenburg and Marseille confirmed the use of green electricity. No information is available for Kristiansand; however, as the Norwegian electricity mix is dominated by renewable sources[3)], the assumption the green electricity for Kristiansand seems valid.

Growth of energy demand, OPS, CO_2 emissions, etc. until 2050 are based on global fleet growth. Source: Clarksons/DNV forecast.

APPENDIX F: METHODOLOGY MODELS FOR TWO AVERAGE PORTS

In this Section we describe how the scaling factors are defined for the representation of the average model ports.

a. Scaling factor Industrial Port

Considering that 1 million tonnes is considered the lower limit for significant European ports, we will identify ports that handle more than 1 million tonnes per year. According to Eurostat dataset mar_go_aa approximately 384 such ports exist. The average tonnage handled of those 384 ports is about 13 million tonnes (Figure F- 1). The average tonnage handled of those 384 ports is about 13 million tonnes (Figure F- 1).

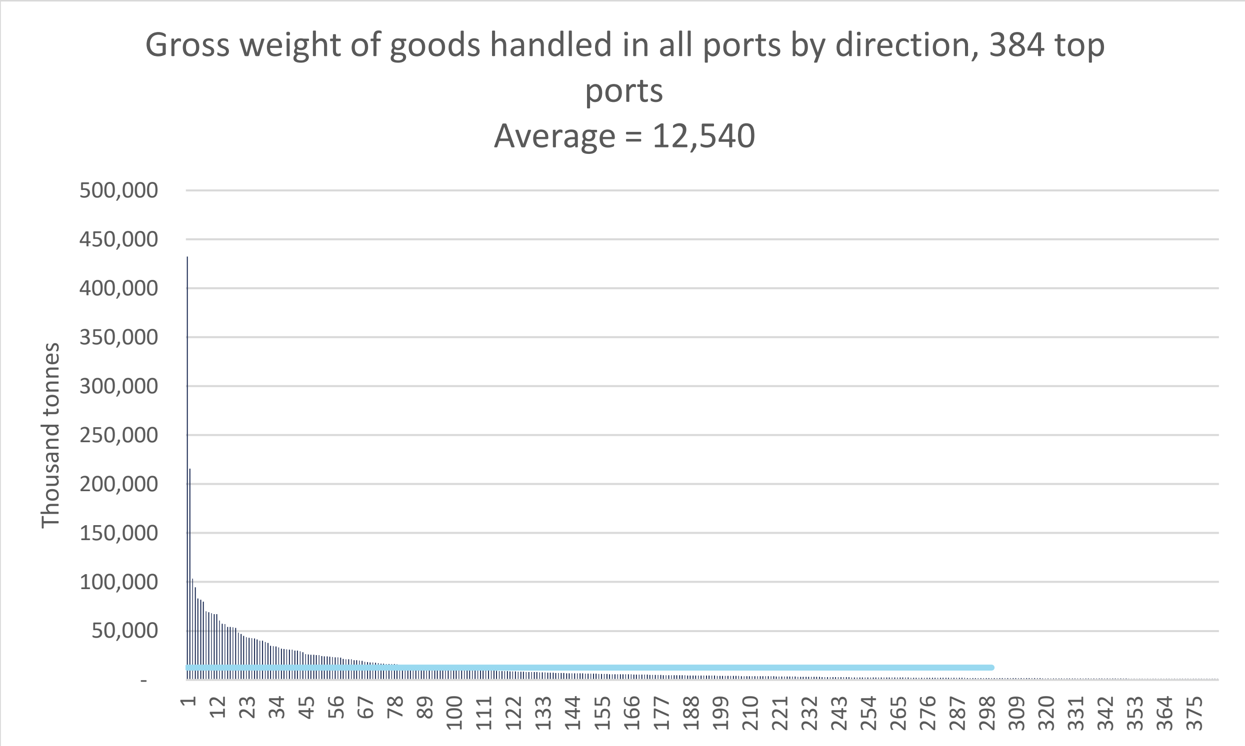

Figure F- 1: Gross weight of goods handled in all ports by direction, based on Eurostat data mar_go_aa

The scaling factor for the industrial port will be based on cargo tonnage.

$$SF_I = \frac{average\ of\ 384\ ports}{cargo\ tonnage\ Rotterdam} = \frac{12{,}540}{432{,}580} = 2.9\%$$

b. Scaling factor Transport Port

Considering that 215 ports have reported on their TEU throughput in the EU, the average annual TEU throughput is 502 thousand TEU (Figure F- 2). Considering that 215 ports have reported on their TEU throughput in the EU, the average annual TEU throughput is 502 thousand TEU (Figure F- 2)

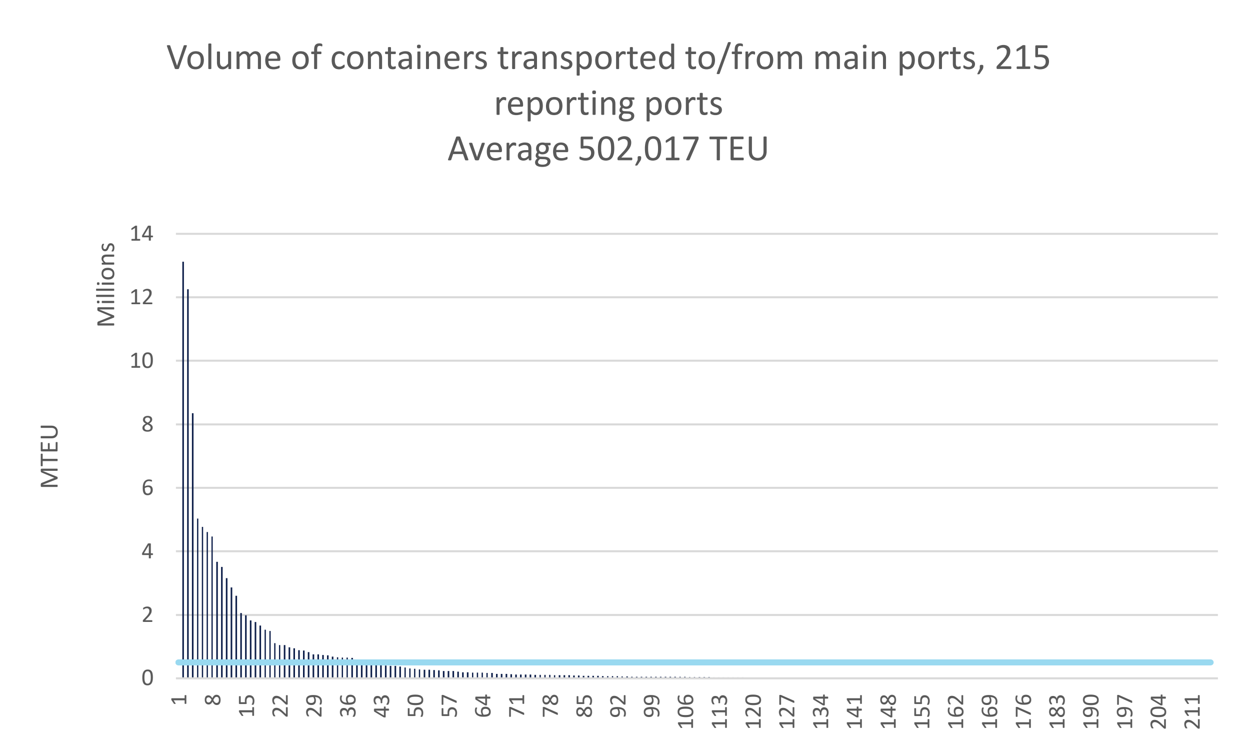

Figure F- 2: Volume of containers transported to/from main ports, based on Eurostat data mar_go_qm

The scaling factor for the transport port will be based on containers handled (TEU).

$$SF_T = \frac{Containers\_handled\_average}{Containers\_handled_T} = \frac{502{,}017}{5{,}029{,}620} = 10\%$$

c. Scaling factors applicable both for Industrial port and Transport port.

OPS scaling:

To scale the demand for OPS, we will assume the model ports will follow AFIR regulation: maritime ports that see at least 50 port calls by large passenger vessels, 100 port calls by container vessels or 25 port calls by cruise vessels must provide OPS by 2030. From January 2030, vessels staying for more than two hours in a port would have to connect to OPS. SFI will be used to scale the expected OPS connections due to AFIR regulation.

The OPS demand scaling factor (OPS_SF_P) for each port P will be calculated as follows:

$$OPS\_SF_p = OPS\ systems\ at\ model\ port * SF$$

E-RTG and H2 reach stacker scaling

The number of containers handled by each port can indicate the need for equipment such as cranes (RTGs) and reach stackers. The equipment scaling factor (Equip_SF_P) for each port P will be calculated as follows:

$$Equip\_SF_p = Equipment\ at\ model\ port * \frac{Containers\_handled\_average}{Containers\_handled_p}$$

The final scaled parameters for each port will be calculated by multiplying the applicable scaling factors.

Renewable energy

Renewable energy will be scaled according to the installed capacity solar PV and wind envisioned in the model port. For example, Valencia published their plans for to be installed renewable capacity up to 2030, after that, due to lack of data, it will follow the deployment of Rotterdam port. For Rotterdam, the maximum solar PV potential is expected to be reached by 2040, onshore wind capacity is kept constant based on higher restrictions on land usage. The scaled port will consider the same ratio, applying the scaling factor to scale it down.

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