Circular Economy in Port Environments

Case examples for Circular Ports

This review of case examples is a part of the forthcoming 'Methodological Handbook on Circular Economy Assessment in Port Environments'.

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Best practices examples of Circular Ports

Ports that have advanced furthest in implementing circular economy (CE) practices in waste and resource management treat waste streams as valuable inputs for new value chains and use the port-industrial cluster as a platform for industrial symbiosis. The following case studies from the Ports of Rotterdam, Antwerp-Bruges and Amsterdam illustrate how different waste flows (composites, metals, mineral waste, industrial wastewater, plastics) can be integrated into circular loops.

Port of Rotterdam - composite waste and wind turbine blades

In the Port of Rotterdam, Circular Recycling Company (CRC) has developed a supply chain for end-of-life fibre-reinforced thermoset composites, including wind turbine blades, countertops and other composite products that historically were landfilled or incinerated (https://circularcitiesdeclaration.eu/cities/rotterdam).

Schematic of the recycling process for thermoset composites at Circular Recycling Company (CRC) – from composite waste to new materials and products presented in Figure 1.

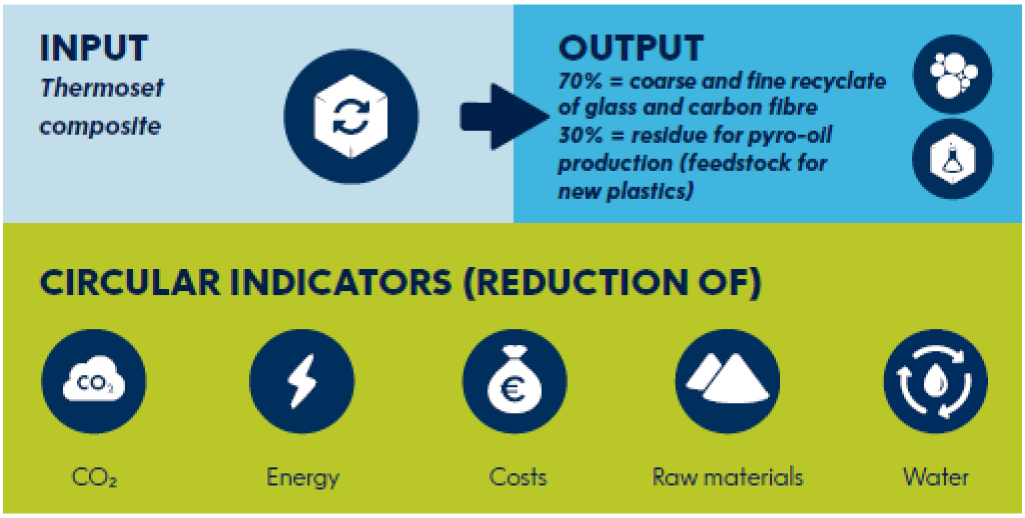
Figure 1. Schematic of the recycling process for thermoset composites at Circular Recycling Company (CRC) – from composite waste to new materials and products.

Source: https://www.portofrotterdam.com/sites/default/files/2023-02/case-study-wind-turbine-blades.pdf , (accessed 30 December 2025).

CRC collaborates with regional partners (wind farm operators, dismantling companies, logistics operators, recyclers) to collect, sort and process these composite products into recyclate used in construction and infrastructure applications, and to test blends with thermoplastics for potential use in the automotive industry.

Technically, CRC reduces the composite waste into different output fractions: approximately 70% becomes coarse and fine recyclate of glass and carbon fibres, while around 30% becomes a residue used for pyro-oil production as feedstock for new plastics. This chain approach provides a lower-cost and more sustainable solution than conventional waste management, creates new recycling streams for previously non-recyclable composites and leads to CO_2 savings when recycled composites substitute virgin materials in new products (Figure 2).

Figure 2. Input–output balance and reduction of environmental and resource indicators in the CRC recycling process.



Source: https://www.portofrotterdam.com/sites/default/files/2023-02/case-study-wind-turbine-blades.pdf , (accessed 30 December 2025).

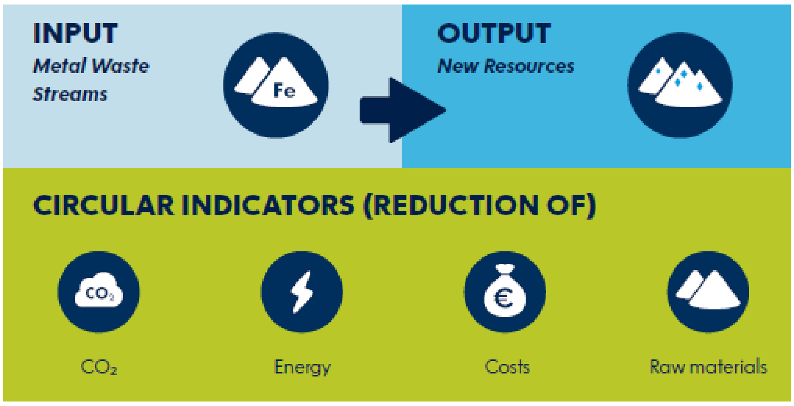
From a circular port development perspective, this example demonstrates a high level of maturity by connecting multiple value-chain actors around a clearly defined waste stream and treating composite waste as a managed resource rather than a disposal challenge. The initiative goes beyond conventional recycling by applying higher-order circular strategies such as rethinking product end-of-life pathways, enabling material reuse and supporting remanufacturing applications. As such, it provides a transferable reference model for ports that are increasingly confronted with growing volumes of end-of-life wind turbine blades and other composite structures.

Port of Rotterdam - End-of-Waste certification for metals (EMR Netherlands)

EMR Netherlands, located in the Port of Rotterdam, is currently the only metal recycling company in the Netherlands holding an End-of-Waste (EoW) certificate, which allows it to market recycled metals (iron, steel, aluminium) as pure raw materials rather than as waste.

This certification provides assurance to buyers and sellers that EMR processes and supplies metals in a sustainable and responsible way, aligning with its mission to be a global leader in sustainable materials and contributing to a circular economy with a zero-emission ambition (Figure 3).

Figure 3. Input–output flows and circular indicators of the EMR metal recycling process.



Source: https://www.portofrotterdam.com/sites/default/files/2023-02/end-of-waste-certificate-recycling.pdf , (accessed 30 December 2025).

EMR's process starts with the purchase and delivery of heterogeneous scrap metal, often containing non-metallic components such as plastics, wood, glass and asphalt, followed by rigorous inspection, contamination assessment, stock management, and advanced sorting and processing. Through careful separation and removal of non-metal impurities, the company currently achieves product purity of at least 98%, with a target of 99.5% by 2030, and aims to maximize the volume of new raw materials extracted from each tonne of metal waste (Figure 4).

Figure 4. EMR metal recycling process from scrap acquisition to trading of secondary raw materials.

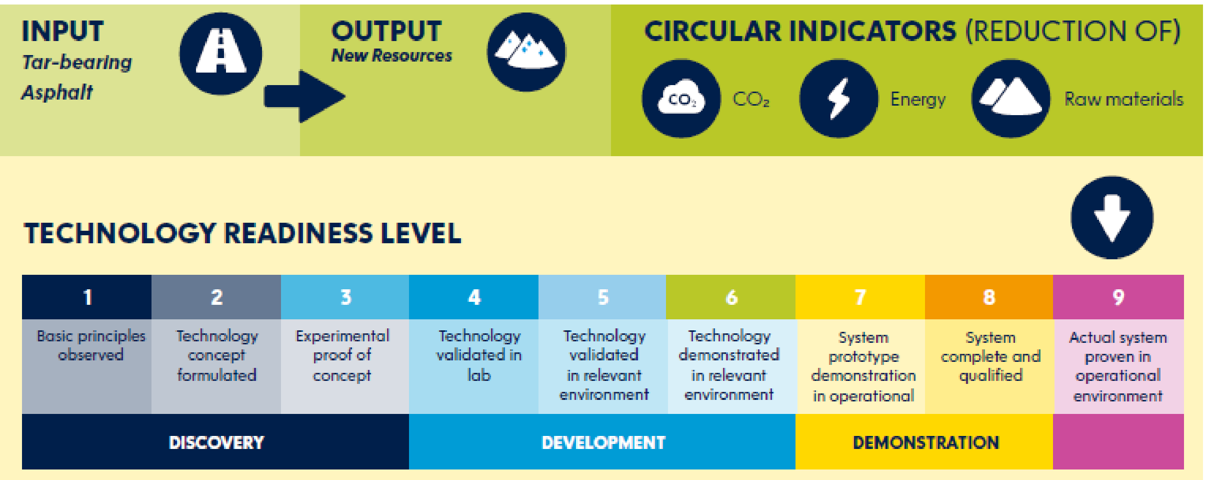
Source: https://www.portofrotterdam.com/sites/default/files/2023-02/end-of-waste-certificate-recycling.pdf, (accessed 30 December 2025).

This case shows how robust quality control and traceability enable the transformation of waste flows into certified products. The lessons learned - including the need for stringent inspection of all deliveries, qualified staff and continuous innovation - highlight the importance of data quality, process control and stakeholder confidence for achieving higher CE maturity levels in port-related recycling activities.

Port of Rotterdam - thermal cleaning of tar-bearing asphalt (REKO)

REKO Recycling Kombinatie operates a thermal cleaning plant in the Port of Rotterdam that converts tar-bearing asphalt, produced in large quantities in Europe and no longer allowed to be directly reused or landfilled, into new raw materials for the construction industry (Figure 5).

Figure 5. Input–output flows, circular indicators, and technology readiness level of the REKO thermal asphalt recycling process.

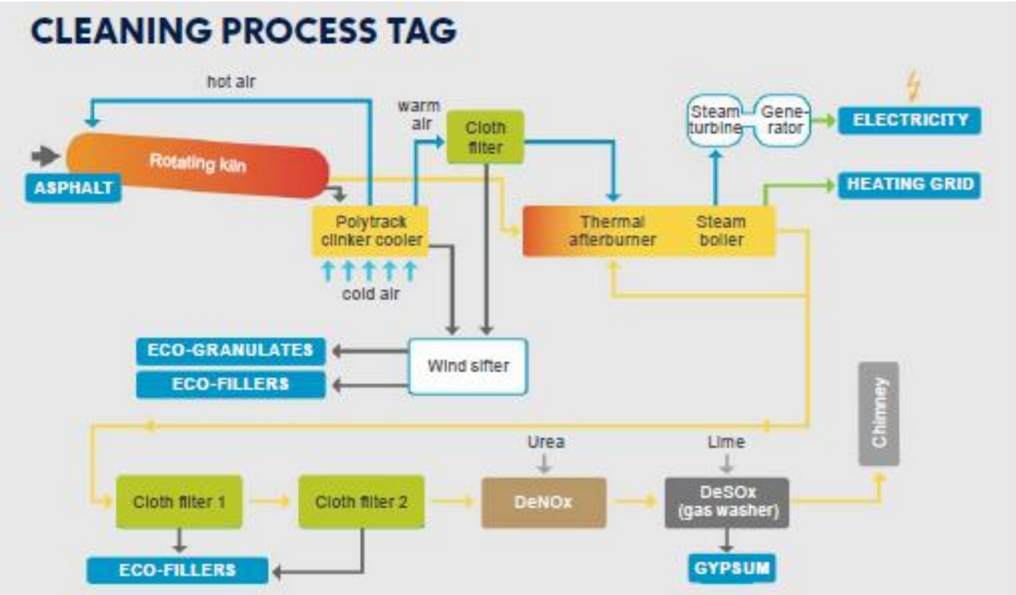


Source: https://www.portofrotterdam.com/sites/default/files/2024-05/thermal-cleaning-of-tar-bearing-asphalt.pdf , (accessed 30 December 2025).

Using a proprietary thermal recycling process, REKO transforms tar-bearing asphalt into eco-granulates, eco-fillers and binding agents that can be directly used in new concrete and asphalt production, while simultaneously generating heat that is converted into high-pressure steam for adjacent companies or into electricity.

The first thermal cleaning plant was commissioned in 2006 as a unique facility capable of producing new products from asphalt and converting generated energy into electricity; a second plant (REKO II), under development since 2021, is six times more energy-efficient due to experience gained and technological optimisation. By providing a solution for millions of tonnes of tar-bearing asphalt expected to arise from road maintenance over the coming decades, the process reduces the need for permanent landfills and lowers demand for virgin sand, gravel and binders from stone quarries (Figure 6).

Figure 6. Process flow diagram of the REKO thermal cleaning technology for tar-bearing asphalt.



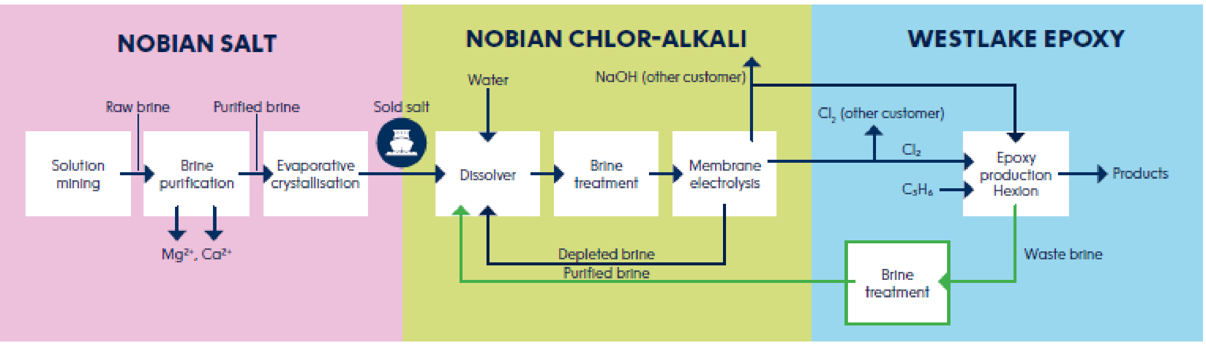
Source: https://www.portofrotterdam.com/sites/default/files/2024-05/thermal-cleaning-of-tar-bearing-asphalt.pdf , (accessed 30 December 2025).

This case demonstrates a combined material and energy circularity through the valorisation of waste heat. It also underlines typical implementation challenges for innovative CE technologies in ports, such as convincing financial partners of technological feasibility and competing with entrenched quality standards for virgin products.

Port of Rotterdam - circular industrial wastewater and brine (Water Mining project)

In the Rotterdam industrial area (Pernis), a demonstration project under the EU Horizon 2020 Water Mining programme showcases circular management of industrial wastewater and brine between Westlake Epoxy and Nobian's chlor-alkali plant. Waste brine from Westlake Epoxy is treated to produce high-purity brine that can partially replace mined salt and freshwater in the chlor-alkali process at Nobian, establishing a closed loop where the chlorine produced is again used by Westlake Epoxy for epoxy resin production (Figure 7).

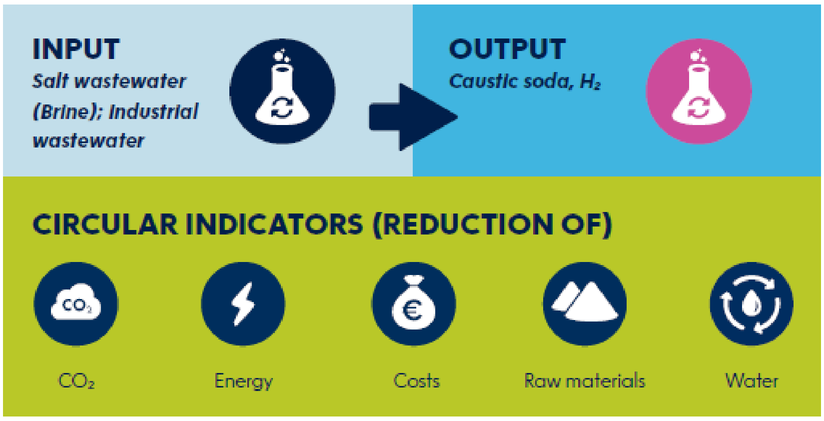
Figure 7. Circular brine and water management between Westlake Epoxy and Nobian's chlor-alkali process.



Source: https://www.portofrotterdam.com/sites/default/files/2022-10/Case-study-Wastewater.pdf , (accessed 30 December 2025).

At full scale, the purified brine is expected to reduce water consumption in the chlor-alkali process by around one third, and to save approximately 25 MWh of thermal energy and 6 kilotonnes of CO_2 emissions per year, while treating a waste stream as a resource. The project goes beyond technical feasibility by applying a co-design approach and creating a Community of Practice, engaging industrial partners, researchers and other stakeholders to address regulatory, market and risk issues related to using external brine in sensitive electrolysis processes (Figure 8).

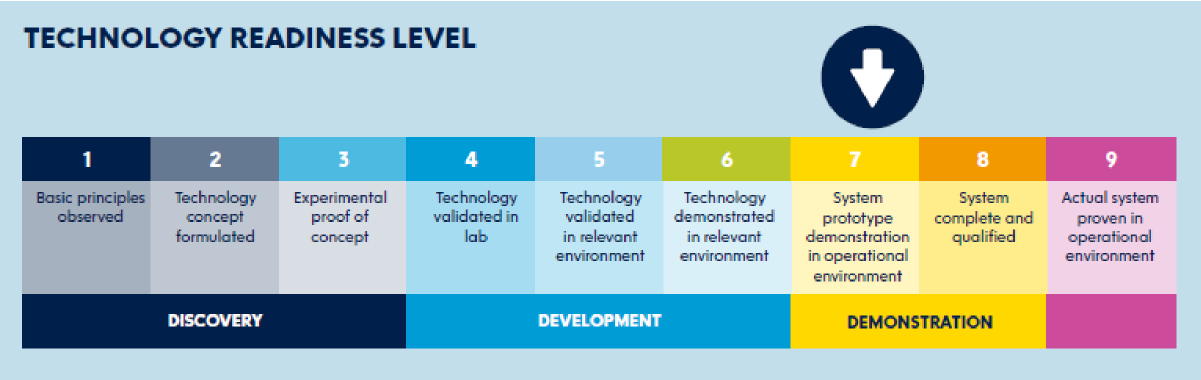
Figure 8. Industrial brine reuse: inputs, outputs and circular indicators.



Source: https://www.portofrotterdam.com/sites/default/files/2022-10/Case-study-Wastewater.pdf , (accessed 30 December 2025).

This case demonstrates an advanced approach to integrating water management with industrial symbiosis, in which water and brine are transformed into circular resource flows within the port cluster. It also highlights the importance of enabling policy frameworks, such as targeted support for circular investments, carbon or raw material pricing mechanisms, and appropriate regulatory conditions, particularly when addressing the reuse of low-value resources like water and salt, which may not be economically viable under current market conditions alone (Figure 9).

Figure 9. Technology Readiness Level (TRL) of the industrial water and brine symbiosis case.



Source: https://www.portofrotterdam.com/sites/default/files/2022-10/Case-study-Wastewater.pdf, (accessed 30 December 2025).

Port of Antwerp-Bruges: circular clusters and plastics recycling

The Port of Antwerp-Bruges strategically leverages its existing industrial clusters and robust infrastructure to facilitate circular activities, positioning itself as a critical node in Europe's transition towards a circular economy (*Port Strategy for Sustainable Development*, 2021). This involves the port moving beyond a traditional landlord role to actively orchestrate circular value chains, supporting both resource and energy transitions (Roberts et al., 2021). The port's proactive engagement in circularity aligns with broader trends in maritime industrial ports across Europe, which are increasingly seen as pivotal drivers for sustainable development by integrating circular practices into their operations (Barona et al., 2023). Furthermore, the port actively promotes industrial symbiosis, where waste or by-products from one industry become raw materials for another, significantly reducing waste and optimizing resource utilization within the port complex (*Key Factors for Successful Development of Offshore Wind in Emerging Markets*, 2021). This strategic shift enables the Port of Antwerp-Bruges to contribute to the European Union's ambitious climate neutrality goals and the broader circular economy action plan (Barona et al., 2023). This comprehensive approach positions the Port of Antwerp-Bruges as a forerunner in developing sustainable port-city territories, addressing global urgencies such as climate change and the energy transition (Martino, 2022).

The Port of Antwerp-Bruges positions itself as a global circular economy hub, building on Europe's largest integrated chemical cluster and a strategic climate and energy transition strategy aiming for climate neutrality by 2050. Circularity is embedded in this strategy through the development of dedicated circular zones (e.g. NextGen District) for companies engaged in recycling, upcycling and reuse of materials, and through targeted attraction of large-scale circular investments in plastics and other waste streams.

One prominent example is the SynPet project, a €300 million plant being built in the port that will process around 250,000 tonnes of mixed plastic waste per year into circular naphtha and renewable gas, enabling feedstock recycling of streams that are currently difficult to recycle. Such facilities are embedded in the existing petrochemical complex and supported by port-led clustering and infrastructure provision, making the port authority an orchestrator of circular value chains rather than only a landlord for traditional industrial activities (https://synpet.com/synpet-brings-emerging-technology-in-plastics-recycling-to-the-port-of-antwerp-bruges/).

SynPet has developed a patented Thermal Conversion Process (TCP®) that enables the recycling of all carbon-containing waste streams, including plastics that cannot be processed using conventional mechanical or chemical methods. The technology combines the use of water under elevated pressure and temperature with a multi-stage thermal cracking process, resulting in lower energy consumption and economic viability at an industrial scale. Following a successful demonstration phase, the TCP® technology is ready for commercial deployment.

The main output of the process is a circular naphtha substitute (CNS®) - a premium-grade feedstock that can be directly blended with conventional naphtha used in steam cracking installations. CNS® features a final boiling point of 360 °C, fully compliant with the requirements of European steam crackers, and, unlike standard pyrolysis oils, does not require any additional purification or hydro-processing.

The facility will be developed in the Port of Antwerp-Bruges, on a site with direct access to both waterborne and land-based infrastructure, in cooperation with the terminal operator Euroports. The plant is scheduled to become fully operational in the second half of 2028 and will serve both as a commercial production facility and as a research and development hub supporting the further advancement of circular technologies.

Port of Amsterdam as urban circular hub and alternative fuels

Compared to Rotterdam and Antwerp-Bruges, the Port of Amsterdam focuses more strongly on linking port activities with urban waste streams and alternative fuels, positioning itself as an "urban circular hub". This involves attracting companies that convert municipal and regional waste, biomass and other residues into biofuels and sustainable aviation fuels (SAF), as well as firms engaged in recycling metals, plastics and construction waste, leveraging the port's logistics network and proximity to the Amsterdam metropolitan area.

These activities demonstrate how ports can integrate municipal waste management with industrial processing to create circular value chains that extend beyond the traditional port hinterland, supporting local climate targets and circular city strategies. For the Circular Ports methodology, Amsterdam provides a complementary example to heavy industrial ports, illustrating how CE in waste management can be anchored in urban-port cooperation and focused on energy-from-waste and recycling of urban waste flows.

This approach fosters resource efficiency, waste reduction, and material reuse, thus promoting innovation through new technologies and partnerships within the maritime industrial port context (Barona et al., 2023). Furthermore, this integration allows ports to transition from linear models of resource consumption to more sustainable circular models, aligning with global efforts to mitigate environmental impact and enhance economic resilience (Barona et al., 2023). This strategy positions ports as crucial nodes in the broader circular economy, bridging urban centers with industrial processes and facilitating the regional exchange of secondary resources (*Port Strategy for Sustainable Development*, 2021). This includes initiatives that focus on the exchange of materials and energy at a meso-level, often through eco-industrial networks, and extend to macro-level considerations of eco-cities (Sornn-Friese, 2024). This comprehensive approach not only diversifies revenue streams for port authorities but also contributes significantly to regional sustainability goals by minimizing waste sent to landfills and reducing reliance on virgin materials (Berghe et al., 2020; *Port Strategy for Sustainable Development*, 2021). The Port of Amsterdam's emphasis on urban-port symbiosis demonstrates a model where ports become integral to municipal resource management, transforming waste into valuable products such as bioenergy and new feedstocks. This strategic integration is further exemplified by the growth in revenues from circular activities, demonstrating the economic viability and rapid expansion of such initiatives within the port's overall operations (*Port Strategy for Sustainable Development*, 2021).

Municipal waste processing

The Port of Amsterdam plays a key role in the regional municipal waste management system. The vast majority of waste generated by households, the hospitality sector and businesses in the Amsterdam metropolitan area is directed to processing and recycling facilities located within the port area. This includes a wide range of waste fractions, from organic waste (GFT) and paper to plastics as well as construction and demolition waste. By concentrating waste processing infrastructure in one location, the port enables efficient logistics and environmentally sound material recovery, while reducing the need for long-distance transport (https://www.portofamsterdam.com/en/discover/sustainable-port/circular-economy).

Chemical industry and innovation ecosystem

The Port of Amsterdam hosts a broad range of chemical and energy companies, biofuel producers, chemical plants and power generation facilities. Circular economy development is driven by close cooperation between the port, the chemical industry, research institutions and the start-up and spin-off ecosystem. A key role is played by collaboration with Innovation Lab Chemistry, which facilitates knowledge transfer and the deployment of innovative technologies. An illustrative example is Chaincraft, a biotechnology company producing compounds for animal feed, which started in the Prodock innovation hub and has since established its own production facility within the port area (https://www.portofamsterdam.com/en/discover/sustainable-port/circular-economy).

Biofuels and bio-based resource loops

Organic waste represents a significant material stream entering the Port of Amsterdam from households, businesses and the hospitality sector across the region. This stream offers substantial potential for the development of the bioeconomy and the production of renewable energy carriers. Several companies located in the port convert organic waste into biofuels, including biogas and biomethane. A notable example is the green gas installation operated by Waterschap Amstel, Gooi & Vecht, where biomethane is produced from sludge remaining after wastewater treatment. In addition, through the Biopark initiative, the port is developing approximately 18 hectares of space dedicated to companies implementing circular solutions, enabling further scaling and integration with existing port infrastructure (https://www.portofamsterdam.com/en/discover/sustainable-port/circular-economy).

Plastics and material recycling

The Port of Amsterdam plays an important role in giving plastic waste a "second life." At Plastic Recycling Amsterdam, collected plastic waste is processed into high-quality secondary raw materials suitable for reuse in industrial applications. The use of Magnetic Density Separation technology allows for precise separation of different plastic types, significantly improving recycling efficiency. This system is complemented by GBN Artificial Grass Recycling, where used artificial grass mats from sports facilities are collected, dismantled and processed into plastic granules that are then used to manufacture new artificial turf. These examples demonstrate how the port supports closed-loop material cycles, including for specialized and complex waste streams (https://www.portofamsterdam.com/en/discover/sustainable-port/circular-economy).

Other relevant port initiatives

Beyond these leading ports, numerous other European ports contribute to circular waste management through specific projects and programmes documented in initiatives such as LOOP-Ports and Green Inland Ports.

Common practices include beneficial use of dredged materials, reuse and recycling of construction and demolition waste from port infrastructure, high recovery rates for port-generated operational waste, and development of eco-industrial parks where waste streams from one terminal serve as inputs for another.

Industrial-urban symbiosis models such as Kalundborg in Denmark, which combine port, industrial and municipal systems to exchange waste heat, water and by-products, are increasingly referenced at EU level as "Hubs4Circularity" and serve as reference concepts for ports aiming to scale up industrial symbiosis and circular waste management. These examples can inform Circular Ports partners in selecting, designing and assessing CE projects that move beyond isolated recycling initiatives towards integrated circular ecosystems, aligned with the indicators and maturity levels proposed in this Handbook.

Port of Gothenburg (Sweden)

The Port of Gothenburg is the largest port in Scandinavia and one of the leading actors in sustainable development in the Baltic Sea region. The circular economy is an integral part of the port's overall strategy and is implemented through concrete infrastructure projects, operational measures, and coordinated cooperation across the port logistics hub.

One of the key areas of action is energy efficiency and the reduction of resource losses in port operations, exemplified by the extensive deployment of Onshore Power Supply (OPS). The Port of Gothenburg is a pioneer in OPS solutions for tankers, notably through the innovative Green Cable project, which enables safe shore power connections for vessels in explosion-risk environments. This solution allows CO_2 emissions to be reduced by more than 90% during a single port call, while significantly lowering fossil fuel consumption during berthing. In parallel, the port is expanding OPS infrastructure at Skandia Port, where EU funding was secured in 2024 to further develop shore power facilities for container and ro-ro vessels.

In the area of resource efficiency and circular infrastructure development, a flagship initiative is the Skandia Gateway project - the largest port expansion in over 40 years. The project includes deepening the fairway and reinforcing quay structures, while systematically applying circular economy principles in port construction. Recycled steel is used, and the cement content of concrete is reduced through the incorporation of granulated blast furnace slag, a by-product of the steel industry. This approach significantly lowers the carbon footprint of the investment and demonstrates the practical application of circular economy principles in large-scale port infrastructure projects.

The Port of Gothenburg has also implemented electrification of its own fleet and port operations, including the electrification of the inspection vessel M/S Hamnen. The vessel now operates more than 97% of the time in electric mode, substantially reducing fuel consumption and emissions while improving working conditions on board. This project illustrates how circular and low-emission solutions can be successfully applied to smaller auxiliary port vessels (https://www.ube.ac.uk/whats-happening/articles/gothenburg/).

Within the broader context of energy transition and alternative fuels, the port is developing its role as an Energy Port, positioning itself as a key hub for future energy carriers such as biofuels, methanol, hydrogen and ammonia. In 2024, the port commissioned a hydrogen refuelling station for heavy-duty vehicles, launched pilot projects involving hydrogen-powered port machinery, and invested in infrastructure for liquefied biogas (LBG). At the same time, the port participates in international initiatives such as Port Readiness Marine Fuel, which aim to assess and harmonise port preparedness for handling new marine fuels.

An essential component of the Port of Gothenburg's approach is transparency and systematic sustainability reporting, primarily through the annual Sustainable Port report. The port is actively implementing requirements related to the EU Taxonomy and Corporate Sustainability Reporting Directive (CSRD), including double materiality assessments and systematic mapping of environmental, economic and social impacts. This ensures that circular economy actions are measurable, comparable and subject to continuous improvement.

The case of the Port of Gothenburg demonstrates that a high level of circular economy maturity can be achieved through a coordinated set of operational, investment and organisational measures, even without the development of large, dedicated recycling facilities. This model provides a valuable reference for ports seeking to advance circular economy practices through optimisation of existing assets, infrastructure and stakeholder relationships (https://www.portofgothenburg.com/globalassets/dokument/port_of_gothenburg_sustainableport2024_eng.pdf).

Port of Barcelona (Spain)

The Port of Barcelona is actively advancing circular economy principles through a range of innovative projects and strategic initiatives that integrate material reuse, resource efficiency, energy recovery, and industrial symbiosis across its operations.

Industrial Circularity - Residual Cold Recovery

A flagship initiative in Barcelona's circular strategy is the residual industrial cooling project that repurposes energy normally lost during the liquefied natural gas (LNG) regasification process. Traditionally, the extreme cold associated with LNG regasification was simply dissipated into the environment. Through a pioneering system developed in collaboration with public and private partners, the port now captures this residual cold and distributes it as a sustainable energy source for industrial, tertiary, and residential applications.

This innovative infrastructure has the capacity to deliver approximately 131 GWh per year of thermal energy at negative temperatures (down to -20 °C), enough to meet the cooling needs of a city of roughly 80,000 inhabitants. By recovering cold that would otherwise be wasted, the system avoids an estimated 42,000 tonnes of CO_2 emissions annually, making it one of the world's first large-scale circular energy reuse applications connected directly with port operations.

The project was phased over many years, beginning with early network deployment and culminating in the connection of Barcelona's LNG regasification plant to a dedicated "cold pipeline" system. Ongoing plans include expanding the distribution network to serve other key urban and industrial partners, increasing flexibility and matching energy supply with demand more effectively (https://piernext.portdebarcelona.cat/en/technology/circular-economy-applied-to-industrial-cooling-the-pioneering-case-of-barcelona/).

Plastic Waste Transformation and Valorisation

To tackle plastic waste generated within the port community, Barcelona has launched the Plastic Waste Transformation and Revaluation Program, coordinated by BCN Port Innovation Foundation in collaboration with multiple port stakeholders. The program focuses on collecting, cleaning, and pelletizing plastic waste - including polyethylene (PE), polypropylene (PP), and PET - so that it can be reintroduced as usable feedstock within the port's operational cycles.

An important infrastructure component has been the refurbishment of an industrial building equipped with clean energy systems (including photovoltaic panels), positioning the project as an energy-efficient and scalable model for plastic recycling. Plans include installing advanced extrusion and pelletising technologies to support local reuse and create value-added products for the port environment.

Key objectives of the program include (https://bcnportinnovation.org/en/projects/circulars/):

- Reducing plastic waste volumes and limiting environmental impacts, including marine pollution;
- Valorising recycled plastics into functional products for use within or beyond the port;
- Improving energy efficiency by powering recycling processes with renewable sources;
- Promoting replicability of the model in other ports and industrial contexts;
- Strengthening collaboration among port community actors to enhance material reuse and reduce reliance on virgin resources.

Associated efforts, such as the recent plastic recycling centre commissioned by MB92 Group and Pinmar within the port area, underline this direction. This 200 m^2 facility uses water-free, non-chemical cleaning and infrared filtration to decontaminate plastic waste from superyacht maintenance and other maritime activities, enabling more than 100 tonnes of plastics to be processed annually into flake form for industrial reuse (https://bcnportinnovation.org/en/projects/plastic-waste-transformation-and-revaluation-program/).

Innovation and Knowledge Sharing

The Port of Barcelona also promotes circularity through PierNext, a digital knowledge hub for spotlighting innovations in logistics, sustainability, and environmental technology. PierNext disseminates best practices, case studies, and forward-looking insights - including how ports can contribute to circular economy goals through energy recovery, waste valorisation, and collaborative innovation - positioning Barcelona as a thought leader in this space. The port supports wider community engagement in sustainability through participation in citizen science and marine conservation efforts, such as initiatives that monitor marine plastics and encourage waste collection by local fishers.

Port of Singapore (Singapore)

The Port of Singapore is one of the world's most technologically advanced ports and a leading example of implementing circular economy principles under conditions of severe spatial constraints. Sustainability and circularity are embedded in the strategic framework of PSA, the port operator, which positions the port as a Sustainable Smart Port integrating decarbonisation, resource efficiency and digital transformation.

A cornerstone project supporting circular economy implementation is Tuas Nexus, an integrated facility that combines a waste-to-energy plant with a water reclamation facility. By co-locating waste and wastewater treatment infrastructure, Tuas Nexus enables the recovery of energy, water and materials while significantly reducing land use, energy demand and operational inefficiencies. This integrated approach illustrates how circular solutions can be embedded into critical urban infrastructure in land-scarce port cities.

Beyond Tuas Nexus, the Port of Singapore has made full electrification of port operations a central element of its sustainability strategy. Tuas Port is being developed as a fully electrified facility, incorporating battery-powered automated guided vehicles (AGVs), electric container handling equipment and smart grid systems supported by Battery Energy Storage Systems (BESS). These measures are expected to reduce operational carbon emissions by approximately 50%, while simultaneously improving energy efficiency and operational reliability.

Circular economy principles are also applied in port construction and infrastructure development. Berths and yard areas at Tuas Port are built using environmentally friendly concrete incorporating Ground Granulated Blast-Furnace Slag (GGBS), a by-product of the steel industry. The use of GGBS reduces the carbon footprint of construction activities by up to 72%, demonstrating the port's commitment to circular material use in large-scale infrastructure projects. In addition, solar panels are installed across port rooftops to support on-site renewable energy generation. The Port of Singapore actively integrates circular economy principles into day-to-day operations and resource management. PSA has implemented comprehensive recycling programmes covering industrial waste, electronic waste and office waste, achieving a waste recycling rate of approximately 62%. Water conservation is another critical area, supported by rainwater harvesting systems and the use of reclaimed water (NEWater) at Tuas Port Maintenance Base, which alone saves over 37,000 m^3 of potable water annually (https://www.singaporepsa.com/wp-content/uploads/2022/10/PSA-Sustainability-Narrative.pdf).

Digitalisation plays a key role in improving resource efficiency across the supply chain. Platforms such as ACE (Advanced Container Exchange) optimise vessel utilisation and yard inventory management across shipping lines. PSA estimates that a 20% improvement in vessel utilisation can result in a 25% reduction in carbon footprint, highlighting the strong link between digital optimisation and circular resource use. Complementary digital tools such as CALISTA and SmartBooking further optimise cargo flows, reduce unnecessary movements and lower emissions across multimodal logistics chains.

In parallel, PSA promotes a strong green port culture, focusing on staff engagement, training, and community integration. Initiatives such as the *PSA SG in Bloom Programme*, urban greening projects, food gardens and participation in Singapore's *One Million Trees* movement contribute to enhancing biodiversity, social value and the integration of port activities with the surrounding urban environment.

Overall, the Port of Singapore demonstrates how circular economy principles can be implemented through a systemic combination of integrated infrastructure, electrification, digital optimisation, circular construction materials and operational resource management.

Port of Los Angeles (USA)

The Port of Los Angeles is implementing circular economy principles primarily through its ambitious Zero Waste Plan, regulatory initiatives, and a broad suite of sustainability programs embedded in its longer-term strategic planning. As part of the Los Angeles Harbor Department's sustainability framework, the Zero Waste Plan sets progressively ambitious targets to reduce waste to landfill - aiming for 90% diversion by 2025, 95% by 2035, and 100% by 2050.

The Port's approach to circularity is multi-faceted and deeply integrated into its operational and administrative functions.

Strategic frameworks. The Port has adopted the Sustainable City pLAn, aligning with the City of Los Angeles' broader sustainability agenda that emphasizes environment, economy, and equity. This plan guides the Port's environmental efforts from short-term actions to long-term targets across waste, energy, air quality, and infrastructure development (https://portoflosangeles.org/environment/sustainability/sustainability-reports).

The Zero Waste Plan extends beyond simple recycling, aiming to reduce waste generation at source, expand recycling programs, and integrate organics and industrial recycling streams. It includes:

- Reducing office and administrative waste through enhanced recycling of paper, plastics, metals, and electronic waste;
- Expanding organics recycling (e.g., food scraps, mulch, compost) to divert these materials from landfill;
- Maintaining high diversion rates for construction and demolition waste (90%+ since 2020);
- Implementing responsible disposal and recycling programs for hazardous materials, including batteries and used oil.

Operational standards and enforcement Circular economy goals at the Port are realized through operational standards imposed on terminal operators and tenants, including updated permitting language and waste management requirements intended to drive participation and compliance across all Port users.

Comparative overview of Circular Economy best practices in selected ports

The table below provides a comparative overview of circular economy best practices implemented in selected leading ports. It highlights strategic focus areas, key circular projects, dominant resource loops and the role of port authorities, illustrating different pathways toward circular port development. The comparison supports benchmarking of circular economy maturity and facilitates the transfer of proven solutions across port contexts.

Table 1. Circular economy best practices in selected ports.

Port	Strategic CE focus	Key circular projects & initiatives	Main circular resource loops	Role of port authority
Port of Rotterdam	Industrial symbiosis and high-volume waste valorisation	• Composite recycling (CRC - wind turbine blades) • End-of-Waste certification for metals (EMR) • Thermal cleaning of tar-bearing asphalt (REKO) • Circular industrial wastewater and brine (Water Mining)	Composites → construction materials; metals → certified secondary raw materials; asphalt → aggregates & energy; wastewater → industrial brine	Orchestrator of circular value chains; facilitator of cross-industry cooperation
Port of Antwerp-Bruges	Circular clusters embedded in chemical and energy transition	• NextGen District circular zone • SynPet feedstock recycling (TCP®, CNS®) • Large-scale plastics recycling investments	Mixed plastics → circular naphtha & renewable gas; by-products reused within chemical cluster	Active orchestrator and cluster developer, beyond landlord role
Port of Amsterdam	Urban-port circular hub linking municipal waste and fuels	• Municipal waste processing hub • Biofuels & biomethane from organic waste • Plastic Recycling Amsterdam & artificial grass recycling • Innovation ecosystem (Prodock, Chaincraft)	Urban waste → biofuels, SAF, secondary materials	Connector between city and industry; enabler of urban-port symbiosis

Port of Gothenburg	Operational efficiency and circular infrastructure	• Onshore Power Supply (Green Cable, Skandia Port) • Circular construction (Skandia Gateway, recycled steel, GGBS concrete) • Electrification of port fleet (M/S Hamnen) • Energy Port (LBG, hydrogen, methanol readiness)	Energy efficiency; construction materials reuse; electrification	Implementer and standard-setter; strong monitoring and reporting
Port of Barcelona	Energy and material circularity through innovation	• LNG residual cold recovery network • Plastic Waste Transformation & Revaluation Program • Port-based plastic recycling centres • PierNext innovation hub	Waste cold → industrial & urban cooling; plastics → pellets & products	Innovation facilitator and pilot project incubator
Port of Singapore	Integrated circular infrastructure under land constraints	• Tuas Nexus (waste-to-energy + water reclamation) • Fully electrified Tuas Port (AGVs, BESS) • Circular construction materials (GGBS concrete) • Digital optimisation (ACE™, CALISTA™)	Waste → energy & water; electricity & data → efficiency gains	System integrator of urban-port infrastructure
Port of Los Angeles	Regulatory-driven circularity and zero waste	• Zero Waste Plan (90-100% diversion targets) • Organics & construction waste recycling • Green Shipping Corridors • Technology Advancement Program (TAP)	Waste diversion; reduced material loss; clean technology adoption	Regulator and enforcer via permits and standards

Source: own elaboration.

Overall Conclusions: Circular Economy in Leading Global Ports

The analysis of leading international ports demonstrates that ports are evolving from traditional logistics and transport hubs into key platforms for circular economy implementation. By leveraging their concentration of material flows, industrial activities, energy infrastructure and governance capacity, ports are increasingly acting as Hubs for Circularity, enabling systemic resource efficiency, industrial symbiosis and closed-loop value chains.

The reviewed case studies show that there is no single universal model of a “circular port”. Instead, circular economy strategies are shaped by local conditions such as industrial structure, urban proximity, land availability, regulatory frameworks and strategic priorities. Nevertheless, several common success factors can be identified across all ports.

Ports such as Port of Antwerp-Bruges and Port of Rotterdam demonstrate how large industrial ports can act as orchestrators of circular value chains, embedding advanced recycling, feedstock substitution and industrial symbiosis directly into existing petrochemical and manufacturing clusters. Their role goes beyond land management, positioning port authorities as active coordinators of circular investments and infrastructure.

In contrast, Port of Amsterdam illustrates an urban-port circular hub model, where municipal waste streams, bio-based resources and alternative fuels are integrated into port-based industrial processing. This approach highlights the potential for ports to support circular city strategies and regional waste management systems while creating new industrial value chains.

The Port of Gothenburg shows that a high level of circular economy maturity can be achieved through operational optimisation, energy efficiency, circular construction practices and transparent sustainability governance, even without large, dedicated recycling facilities. Its experience demonstrates the importance of standardisation, stakeholder cooperation and continuous performance monitoring.

The case of the Port of Barcelona highlights the potential of energy and material circularity, particularly through the recovery of residual cold from LNG regasification and the structured valorisation of plastic waste within the port community. These projects illustrate how ports can integrate industrial symbiosis with urban energy systems and innovation ecosystems.

The Port of Singapore provides a leading example of circular economy implementation under conditions of severe spatial constraints. Through integrated infrastructure such as Tuas Nexus, full electrification of port operations, circular construction materials, advanced digital optimisation and water reuse, Singapore demonstrates how circularity can be embedded into critical urban and port infrastructure at system level.

Finally, the Port of Los Angeles illustrates a regulatory and governance-driven approach to circular economy implementation. Through its Zero Waste Plan, operational standards, monitoring systems and international partnerships, the port shows how public policy instruments and enforcement mechanisms can effectively drive waste reduction, resource efficiency and behavioural change across a complex port ecosystem.

Overall, the analysed ports confirm that circular economy implementation in ports is most effective when it combines:

- long-term strategic vision and leadership,
- integration of circularity into core port planning and infrastructure,
- industrial and urban symbiosis,
- operational standards and stakeholder engagement,
- transparent reporting and performance measurement.

Together, these elements enable ports to move beyond isolated recycling initiatives towards integrated circular ecosystems, supporting climate neutrality, resource security and long-term economic resilience at local, regional and global scales.

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