The Circular Economy and Port Ecosystems

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1. Circularity and the Circular Economy

Production systems and the related supply chains tend to be organized **linearly** through a sequence involving the extraction of resources and materials, their transformation, manufacturing, and distribution. At every step, particularly after final consumption or the end of product lifecycles, wastes are generated and need to be discarded. However, in conventional supply chains, a rather small fraction of wastes are reused or recycled, mostly because production systems may not be designed to reuse some materials or because new materials may be easier and cheaper to procure. As environmental concerns emerged in the 1980s, greater pressures were placed on developing recycling capabilities with the emergence of concepts such as closed-loop production systems and "cradle to cradle" designs. The goal was to shift as much as possible from linear processes oriented along the "extract-manufacture-consume-dispose" paradigm toward circular processes such as "reduce-reuse-recycle".

Conventional economic systems were mainly built around linear principles where resources were extracted, transformed, distributed, and eventually disposed of. This principle can be mitigated with recycling mechanisms where discarded resources can reinputted into the manufacturing process. Most economic systems have recycling mechanisms, particularly when it is cost-effective.

The emergence of circular economic principles aims at a more comprehensive closed-loop system with several feedback mechanisms. It requires an adaptation of linear and recycling principles with a focus on:

1. **Product design**. Products can be designed with a long life cycle in mind, with options to be repaired, upgraded, or remanufactured.
2. **Product use**. A product can go through multiple life cycles, switching consumers through sharing, reselling, or refurbishing.
3. **Recycle**. A conventional approach where, at the end of a product life cycle, its materials will be recovered for other uses.

The goal is to try to minimize the importance of procurement and disposal by ensuring that materials are circulated within the economic system.

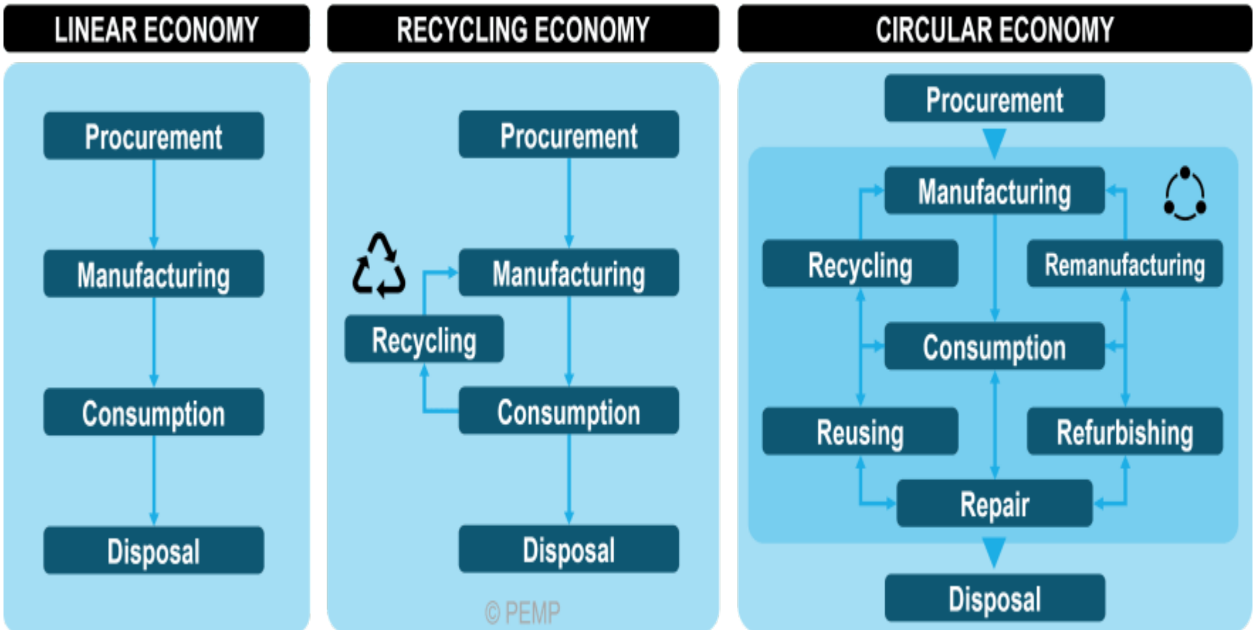


Figure 1. From Linear to Circular Economic Principles

This **circularity** was eventually conceptualized in a wider context and became known as the circular economy (CE).

> *The* ***circular economy*** *is a feedback system that tries to minimize the inputs of resources as well as the generation of wastes leaking into the environment.*

The circular economy emphasizes reducing waste and promoting resource efficiency through recycling, reusing, and remanufacturing. It applies well to products and assets with longevity and is less suitable for products with a short life cycle. For instance, assets such as vehicles and appliances can be better designed with CE principles than products such as clothing and even mobile phones. From a supply chain perspective, circularity is expanding **reverse logistics** principles into a more comprehensive framework, including two subsystems: one related to biological goods (e.g., food) and the other to technical goods (products).

Most environmental processes, such as the water and carbon cycles, are based on large-scale circular principles since materials flow from one state to another. However, true circular principles are impossible from an entropic perspective since environmental processes require an important external input, which is energy (solar), to function. The circular economy tries to imply some of these principles on a smaller scale, such as within definable supply chains. Similar to environmental processes, a circular economy cannot function without large and low-cost energy inputs.

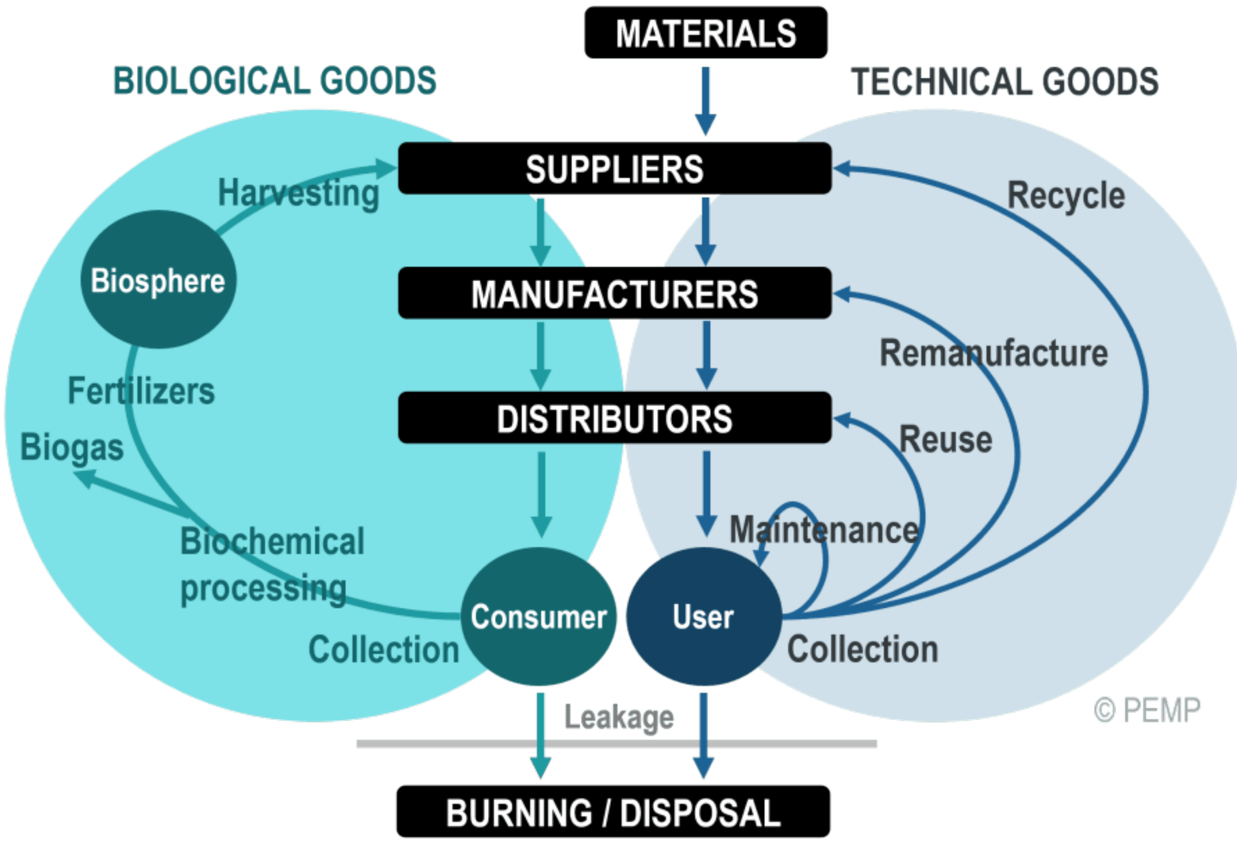


Figure 2. The Circular Economy and Supply Chains

Four fundamental principles help define circularity:

- **Maintenance**. A product can be regularly serviced and upgraded to expand its life cycle before becoming obsolete or unusable.
- **Reuse**. A product can be transferred from one user to another by using a form of leasing or sharing involving collection, maintenance, storage, and delivery.
- **Remanufacture**. The manufacturing of a new product from similar products once it has ceased to function because of damage or wear and tear. The manufacturer refurbishes major parts and adds new components for the parts that cannot be repaired if necessary. Then, the product is reintroduced into the supply chain.
- **Recycle**. Once consumption occurs, discarded products can be collected and used as inputs in manufacturing other products.

Implementing these principles requires two fundamental changes within supply chains:

- **Product design**. Conventionally, products are designed to be single-use and discardable. The goal is to design products that can be modular, upgradable, and of longer duration. At the end of their life cycle, it should be possible for the product to be disassembled, reused, and recycled. A challenge concerns that technological developments incite the design of products with short life cycles.

- **Feedback loops.** Capabilities to incorporate feedback loops need to be developed so that circular supply chains become operational. Through feedback loops and their collection mechanisms, goods can be shared, reused, remanufactured, or recycled. A challenge concerns that feedback loops can be complex and costly to implement.

The CE brings forward the concept of extended producer responsibility, imposing on manufacturers and distributors a higher degree of responsibility for the environmental externalities of the goods they produce. This involves increasing involvement, even covering some of the related costs, over three main cycles: production and distribution, consumption and recycling. Improving the **production and distribution cycle**, mostly through improved product design, is expected. Further, the **consumption cycle** allows for extended longevity of the product, namely a capacity to reuse, and once a product is discarded, mechanisms should be in place to ensure that it enters the **recycling cycle**. During the latter, goods are collected, sorted, and reprocessed, eventually transformed as manufacturing inputs, thus reentering the production cycle. The concept of extended producer responsibility also involves a form of legal and economic responsibility. However, this raises ethical and legal issues as the burden is placed on the producers and distributors over environmental externalities that are complex and controversial to assess and, particularly, to measure. At the same time, users may face less accountability for their consuming behavior.

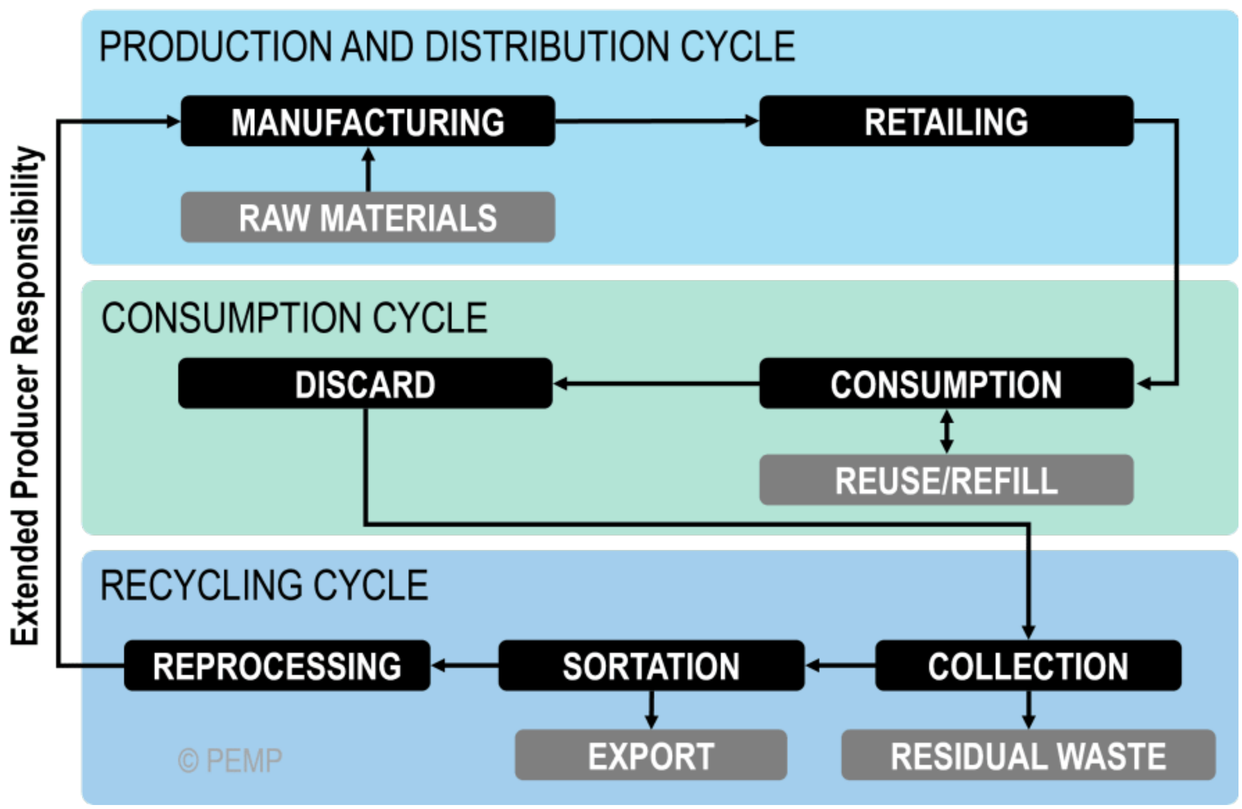


Figure 3. The Concept of Extended Producer Responsibility

2. The Circular Maritime Economy

The crucial role seaports play in global trade and economic development is well documented[1]. As sustainability concerns gained traction, the circular economy emerged as a **parallel concept** that redefines conventional linear supply chain practices by adding **feedback mechanisms.** Its principles, namely reduce, reuse, recycle, and remanufacture, align with stated goals by the port industry to minimize its environmental impact, conserve resources, minimize its footprint, and optimize operations. These principles promote a closed-loop system, encouraging seaports to envision their practices and rethink their role in global and local supply chains. The application of circular economy principles is not only about more efficiency in the existing economic system but also about notable changes in supply chains.

The circular economy presents a paradigm shift for seaports, transforming them into **actors more actively involved** in implementing sustainable principles and promoting resource efficiency. By addressing challenges and seizing opportunities, seaports can contribute to a circular global economy with the expectation of improved resilience and environmental impacts. An alignment between governments, businesses, and stakeholders can facilitate the process, but the nature and extent of such an alignment have **not been well defined**. Ports and governments are paying attention to the energy transition, or even parts of it, such as hydrogen (flows, infrastructure). Circular challenges are somewhat overshadowed, and the interactions between energy and CE transitions are not fully recognized.

A comprehensive overview of the circular economy, as it applies to maritime container shipping and ports, underlines the main linear and feedback mechanisms particular to the industry. It underlines that there are two separate and interdependent circular systems:

- **Maritime shipping** ship maintenance, ship sales and charters (reuse), ship conversion (remanufacture), and ship scrapping (recycle) are elements of CE mechanisms. Responsible ship recycling and circular ship design are key fields of action in this area.
- **Ports** have CE mechanisms, including port maintenance, concessions (reuse), port upgrading (remanufacturing), and port conversion (recycling).

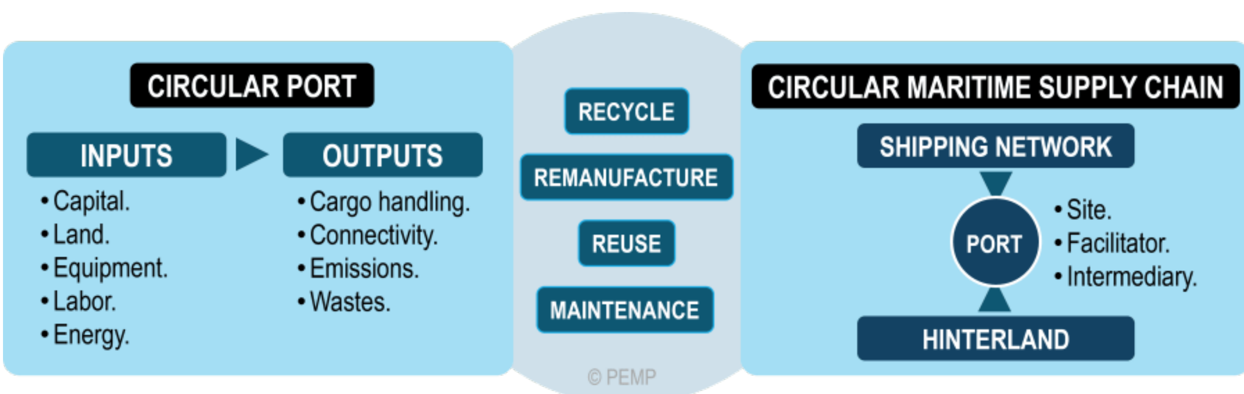


Figure 4. Circular Ports and Circular Maritime Supply Chains

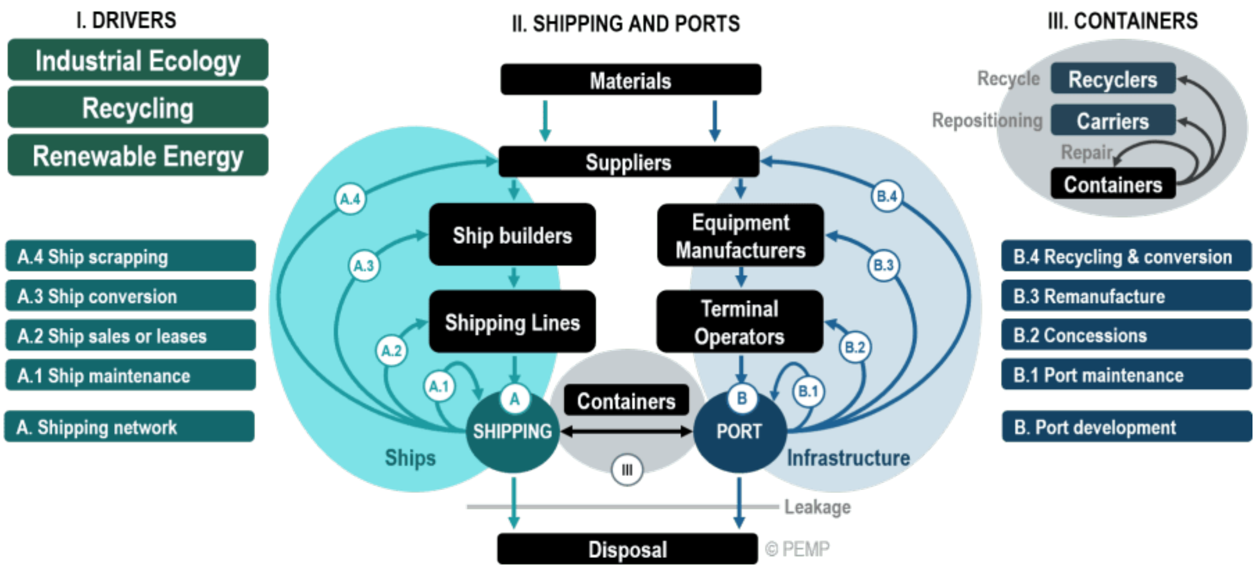


Figure 5. The Circular Economy in Ports and Maritime Shipping

The port and maritime shipping industry have **unique forms of circularity**. Both shipping lines and terminal operators rely on their linear supply/procurement chains, with the outcomes being the setting up of shipping networks (A) and investments in port infrastructure (B). Four principles common to the circular economy can be integrated into the port and shipping sectors:

- **Maintenance**. This basic form of circularity ensures that the product can be recurrently used and has its life cycle extended. To maintain acceptable operational conditions, both ships (A.1) and ports (B.1) require recurring maintenance. For capital-intensive assets, maintenance is a common aspect of extending their life cycle, in opposition to several consumer goods not designed to be repaired. Therefore, the port and shipping industry are based on substantial repair and maintenance practices where cost-effectiveness and predictability are at the forefront of their commercial viability. Maintenance is a particularly challenging issue for port terminals as operations have to continue while maintenance is taking place.

- **Reuse**. There is an extensive market for ship sales or leases (A.2), allowing shipping assets to be shared and remain optimally used. For instance, several of the largest shipping lines can lease more than half of their ship assets. At the end of the lease, the ship can return to the leasing market and be “reused”. Another circular characteristic concerns the cascading of ships from deepsea to regional feeder services when new and larger ships are introduced. Since ports are fixed assets, concessions (B.2) can be perceived as circularity mechanisms where port authorities offer terminal assets to be leased. Once the concession is over, the terminal asset can be leased by another terminal operator. Terminal equipment can also be leased to cover periods of high activity or to remove excess capacity.

- **Remanufacture**. Ships can be converted to new uses and new propulsion technologies (A.3). For instance, the first containerships were converted bulk and break-bulk ships, and the first cruise ships were converted liners. Low sulfur bunker fuel requirements implemented in 2020 are inciting many shipping lines to reconvert their ship engines with technologies such as scrubbers. In the port sector, changing the function or operational characteristics of a port terminal by upgrading the existing equipment (B.3) is a form of circularity. For instance, cranes and yard equipment can be upgraded for automation.

- **Recycle**. There is an extensive industry that scraps ships and recycles their components, particularly metals (A.4). India and Bangladesh are the most significant locations where ships are scrapped. Once at the end of its life cycle, terminal equipment can be discarded and recycled (B.4). A more complex issue concerns the land footprint of a terminal that can be converted for other uses, such as residential. For instance, if the nautical profile of the terminal is no longer suitable for port operations (lack of depth), the site can be "recycled" into urban redevelopments.

Containers represent a **specialized form of circularity** as container shipping is designed as a recycling system. A container is a reusable unit constantly being repositioned by carriers who own or lease container fleets. Another segment involves container leasing companies allocating their assets to maximize returns. Thus, the container is an interchangeable transport unit, with its carrying capacity being traded on transport markets. To remain a suitable asset for carriers, containers need to be cleaned, maintained, and repaired. At the end of their useful life (about 15 years), containers can be discarded and recycled for their components or other uses (e.g. storage, office space).

Box 1: Ship Recycling, Demolition or Scrapping

Figure 6. Ship Recycling, Demolition or Scrapping[2]

The ***average ship demolition/scrapping/recycling age*** *ranges between 20 and 32 years, depending on the vessel type, the freight market conditions, and the demand from scrapyards. When freight and charter rates are high, average demolition ages are typically high. Regulatory requirements (for example, phasing out of single-hull tankers) and technical conditions (new Panama Canal locks introduced in 2016) can also impact the average ship age for scrapping.*

According to UNCTAD data, the top three ship vessel scraping countries in terms of tonnage are Bangladesh, India, and Pakistan. There are four types of ship recycling/shipbreaking setups:

- ***Dry Docking****: The ship is sailed into a dock, and the water is pumped out. Subsequently, workers dismantle the vessel, and upon termination, the dock is cleaned and flooded again. As building and maintaining a dock is relatively costly, this method is hardly used for ship recycling purposes only (examples: some places in Europe).*
- ***Pier breaking/alongside****: The ship is secured along a wharf or quay in calm waters, where a crane removes the pieces of the ship until the vessel is lifted or sent to a dry dock for final cutting. (examples: some places in China, Europe, and the US).*

- ***Landing/slipway***: *The vessel is sailed against the shore or a concrete slipway that extends into the sea at sites with little or no tides. The ship is subsequently dismantled using a mobile crane located onshore or on barges. Additionally, temporary quays or jetties are used on-site to use heavy lifting or cutting equipment (for example, quite common in Turkey).*
- ***Beaching***: *Sailing a lightened vessel full steam onto a tidal beach so that workers have access to the ship in order to cut off the ship's pieces (examples: Bangladesh, India, and Pakistan).*

Unserviceable vessels are sold *based on the Lightweight Tonnage (LDT) of the vessel. The light weight of a vessel is the weight of the hull, including machinery and equipment. The length, breadth, depth, and displacement are also very important factors for buying and selling an unserviceable ship. Generally, 95% of a ship's body is made of mild steel (M.S.), 2% of stainless steel, and 3% of miscellaneous metals, such as brass, aluminum, copper, gunmetal, and other alloys, which are important factors of ship breaking. Ships also contain stores and other materials ranging from foodstuff to clothing, from electrical to electronics, machinery of most types, life-saving equipment, drugs, communication equipment, etc. In fixing the price of a ship to be scrapped, consideration is given to the factor of whether it is a dead ship or a running one.*

*In recent years, several countries have tightened regulations pertaining to ship demolition to anticipate the entry into force of the I**MO Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships** of 2009, as well as an EU Ship Recycling Regulation in force since 31 December 2018. The Hong Kong Convention overhauls how shipowners can dispose of tonnage. It gives responsibility to owners to keep a tally of what is on a ship so that recycling facilities can reduce the health risks to workers as well as make owners and re-sellers use only approved facilities that meet specific standards. Ship recycling facilities are required to provide a 'Ship Recycling Plan', specifying how each vessel will be recycled based on its particular characteristics and its inventory of hazardous materials. Voluntary initiatives by industry associations and other domestic policy priorities also induce changes in the sector to make it safer and cleaner. In 2018, China imposed a ban on the entry of all foreign ships to China for recycling.*

Box 2: Key Components of Circular Ship Design

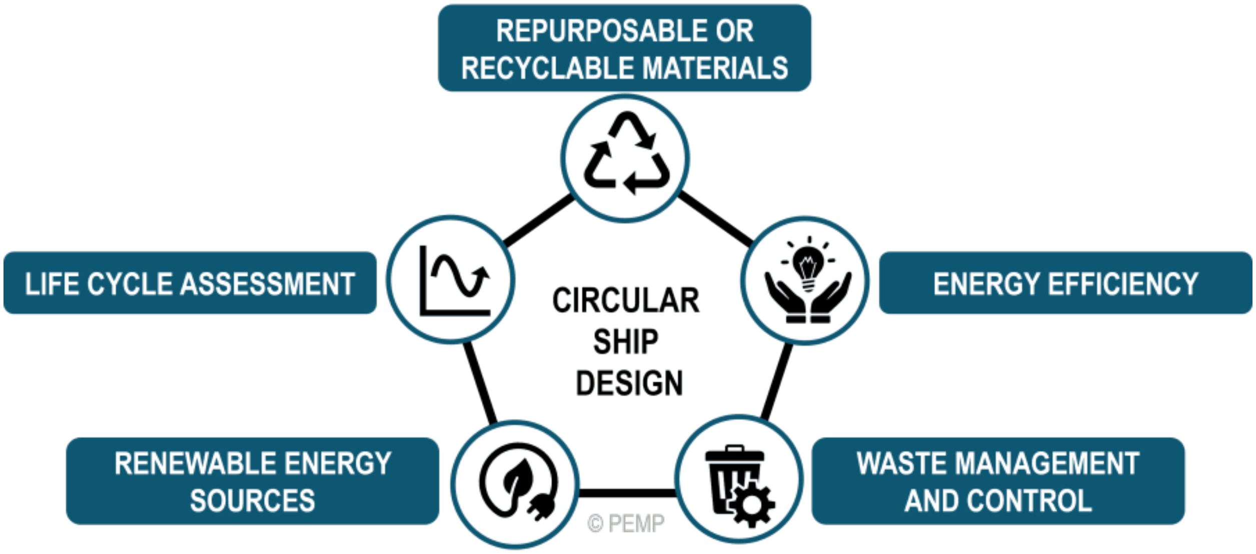


Figure 7. Key Components of Circular Ship Design

*In recent years, increasing attention has been geared towards **circular ship design**. Bringing circularity into ship design typically refers to incorporating principles of sustainability, environmental responsibility, and resource efficiency in the design and operation of ships. This is part of a broader effort to create a more sustainable and environmentally responsible maritime industry. The main areas of advancements in this field relate to:*

- *The use of **environmentally friendly and recyclable materials** in ship construction, such as reusable composites, aluminum, or advanced polymers, that have lower environmental impacts. This includes considerations on how materials can be repurposed or recycled rather than scrapped.*
- *Implementing more **advanced methods for life cycle assessment of the ship design** to evaluate the environmental, energy, and circularity impacts during construction, operation, maintenance, and eventual disposal. **Steel corrosion prevention and treatment are essential parts** of maintenance strategies to extend the lifecycle of a vessel. Another key area relates to the use of eco-friendly and **anti-fouling coatings**. **Smart technologies and data analytics** can be used to monitor and optimize ship performance and for preventive maintenance purposes. A ship design focused on easily disassembling, repairing, and upgrading the vessel or parts thereof can extend the vessel's lifespan and reduce the need for new ship production.*
- *The optimization of the ship design for **energy efficiency** using advanced propulsion systems and energy-saving technologies like waste heat recovery and improved hull design.*
- *The integration of **renewable energy sources**, such as wind propulsion technology. Wind-assisted ship propulsion solutions cover a wide array of technologies, such as large rigid sails (wingsails) or soft sails; hull sails; suction wings that create an upward lifting force similar to the wings on airplanes; small rigid sails on deck which can utilize both*

wind and solar energy; towing sky sails or kites; wind turbines installed on deck; or the installation of rotors which are vertical spinning cylinders utilizing the Magnus Effect for ship propulsion.

- *The **minimization of waste generation** during the ship's construction and operation.*

While maritime shipping involves specific CE mechanisms, a focus on ports underlines that they play a **dual role** in the circular economy:

- **Circular ports**. Identifying the existing or potential circular processes within a port considering their inputs and outputs. Fundamental inputs to port operations include capital, land, equipment, labor, and energy, all of which can be subject to circular processes. At the minimum, circularity should result in similar output levels even if several inputs are reduced. A core strategy is to establish linkages between existing port users to find commonalities.

- **Circular maritime supply chains**. Identifying the existing or potential options where a port can develop and expand circular processes within the supply chains it supports. The port can be a site, a facilitator, and an intermediary for circular processes.

The setting of circular economy principles in ports is incited by drivers such as the goal to **attract new added value activities** in the port area, **new technologies** allowing for new circular mechanisms, the provision of **incentives** such as subsidies and tax abatements or inducing **compliance** to circular principles with rules and regulations about environmental externalities. However, several barriers can hinder the development of a circular economy at ports, such as an **organizational structure** having a lack of leadership, **stakeholders** seeing limited benefits from CE activities, acute **capital requirements** with limited demonstrable returns, **land availability** issues, and the need for **infrastructure** supporting circular economy activities such as electric power generation and recycling facilities.

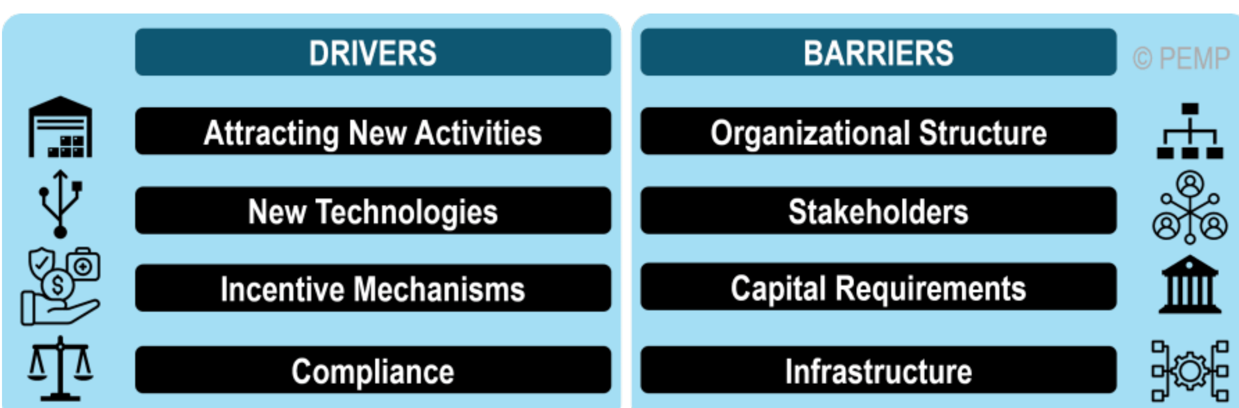


Figure 8. Ship Recycling, Demolition or Scrapping

Several **drivers** favor the implementation of circular economy mechanisms:

- **Attracting new activities**. New added value activities related to the circular economy can be located within a port complex, which supports a mission statement related to generating economic activities and their benefits for a regional economy.
- **New technologies**. Technological advances allow for new opportunities related to the circular economy, including digital technologies tracking assets for reuse and recycling; production technologies allowing for better designs and processes; energy technologies allowing the switch to alternative sources.
- **Incentive mechanisms**. Public actors offer incentives such as subsidies and tax abatements if circular economy practices are implemented in specific sectors.
- **Compliance.** Rules and regulations concerning carbon emissions, energy mixes, or recycling can comply ports to undertake circular economy initiatives.

Still, barriers can prevent or hinder the implementation of circular economy mechanisms:

- **Organizational structure**. There could be an unwillingness or a lack of leadership. On occasion, a port authority may not perceive circular strategies to be an element of its mission statement or jurisdiction.
- **Stakeholders**. Port customers and users may not be in sectors that could derive opportunities from the circular economy, including the generation of higher costs undermining their competitiveness.
- **Capital requirements**. Circular economy initiatives can be capital-intensive and have a lack of demonstrated economic benefits.
- **Infrastructure**. Port and ancillary infrastructure need to be present to support circular projects. In particular, low or no-emission electricity generation capabilities are required, as well as infrastructure for the collection and storage of recycling materials.

Containerization illustrates a specialized form of circularity since a container can be reused as long as it remains in good condition, requiring regular inspections and maintenance. Empty containers need to be repositioned between locations having a positive inbound trade balance and those with a positive outbound trade balance. At the end of their life cycle of about 15 years, containers can be recycled for their components or remanufactured for other uses, such as for storage sheds and real estate (housing, offices, retail).

American containerized trade with China in the 2010s can be considered an **early form of circular maritime supply chains**. Incentivized by imbalanced trade and the associated lower container freight rates for China-bound cargo, waste paper and recycled goods such as metals were collected on the US West Coast and loaded into empty containers, preferably 20-footers. Then, containers were carried to China, and the cargo was used as manufacturing inputs. Thus, the contents of many American retail imports from China, including the packaging, were recycled goods. This circular process emerged without any form of planning and was the **outcome of market considerations**, which should be the most desirable option in implementing circular processes.

Box 3: American Foreign Trade by Maritime Containers, 2017

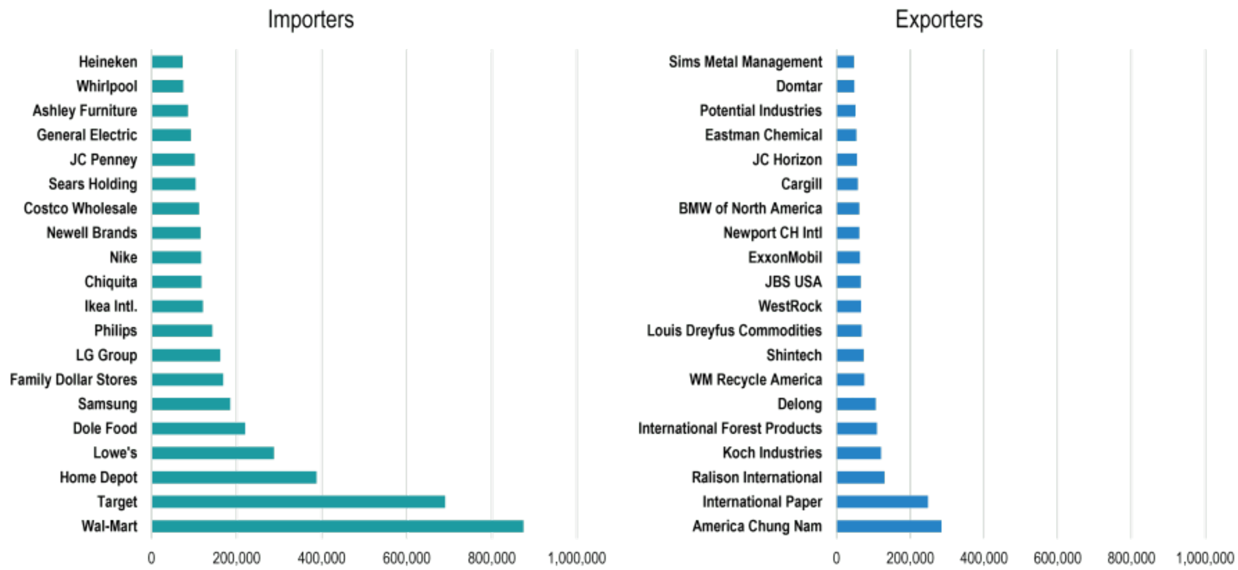


Figure 9. American Foreign Trade by Maritime Containers 2017 in TEUs[3]

American containerized trade is characterized by an asymmetry between the nature of its imports and exports. North American retailers account for a substantial share of containerized imports, mostly involving finished consumption goods bound to major inland freight distribution centers. The largest importers, such as Wal-Mart, Home Depot, Target, Costco, Ikea, and Lowe's, are all mass (Big Box) retailers relying on high volume and low margin goods, which are predominantly produced in China. It is worth mentioning that about 60% of all Chinese trade surplus with the United States is the outcome of American-owned firms operating in China and importing their output to the United States.

Exporters show a completely different profile. A major category of containerized export concerns recycled goods with exporters such as America Chung Nam, Ralison International, WM Recycle America, or Potential Industries. Other major exporters include diversified resource-based (Koch Industries) forest and paper products (e.g. International Paper, International Forest Products), agribusiness (e.g. Cargill, Archer Daniels Midland), or chemicals (e.g. Shintech, Dow, DuPont). Yet, a significant containerized trade imbalance remains.

The trade asymmetry being depicted is reflected in the relative value of imports and exports. While the average value of American imports is about $4.75 per kilogram, the value of exports stands at $2.50 per kilogram. This has also had significant impacts on North American logistics. The import-driven segment involves a series of stages to reach a multitude of outlets with a freight density correlated with population density. Since the retail trade is essentially unidirectional, many retail goods are transloaded at gateways into domestic containers while *the maritime (ISO) containers are re-exported empty. The export-driven segment relies on the massification of shipments at major gateways and inland ports.*

Since many resources (chemicals, forest products, food) are extracted inland at locations that rarely correspond to significant population centers, the reconciliation of containerized import and export logistics is a challenging task. While millions of TEUs will leave American ports empty, many inland locations are facing container shortages. This situation is exacerbated by the fact that China is increasingly regulating the imports of waste materials. In 2018, China started introducing bans on the import of solid waste such as paper, plastic, and steel, which accounted for the most important category of containerized exports from the United States to China.

3. Ports as Hubs for Material Sourcing

A. Recycling and beyond

The recycling economy differs from the circular economy in that most materials can only be recycled a few times before their quality declines and are no longer reusable. A circular economy aims to keep products and materials in use **without degrading their quality or downcycling into lower-valued products**. A wide array of **recycling, upcycling, and reuse processing techniques** are available for different types of materials, products, and waste streams:

- **Mechanical recycling** involves processing products or materials into secondary raw materials or products by mechanical processes such as sorting, washing, drying, grinding, re-granulating, and compounding. Mechanical recycling does not change the chemical structure of the material, which permits multiple reuse, creating a closed loop. Still, the quality of the component may degrade and can eventually no longer be recyclable.
- **Chemical recycling** involves processing products or materials by changing their chemical structure and turning them back into substances (even at the molecular level) that can be used as raw materials for manufacturing other products or materials. Chemical recycling technologies include, for example, pyrolysis, gasification, hydrocracking, and depolymerization. The challenge is that chemical recycling may consume large quantities of energy and may require expensive catalysts.

Each technique leads to different decomposition levels of the materials concerned, as exemplified by the available recycling technologies in the life cycle of plastics, the treatment of contaminated dredged material, ship recycling, or the recycling of wind turbines. The associated chemical processes (if any) need to be very precise and flexible, as the input materials can be very diverse. This requires detailed knowledge of the incoming materials and advanced methods to sort out different waste products. Next to recycling, waste material flows can be reduced by **simplifying materials and products** at the design phase and by designing **business models** and **product designs** to make more efficient use of materials.

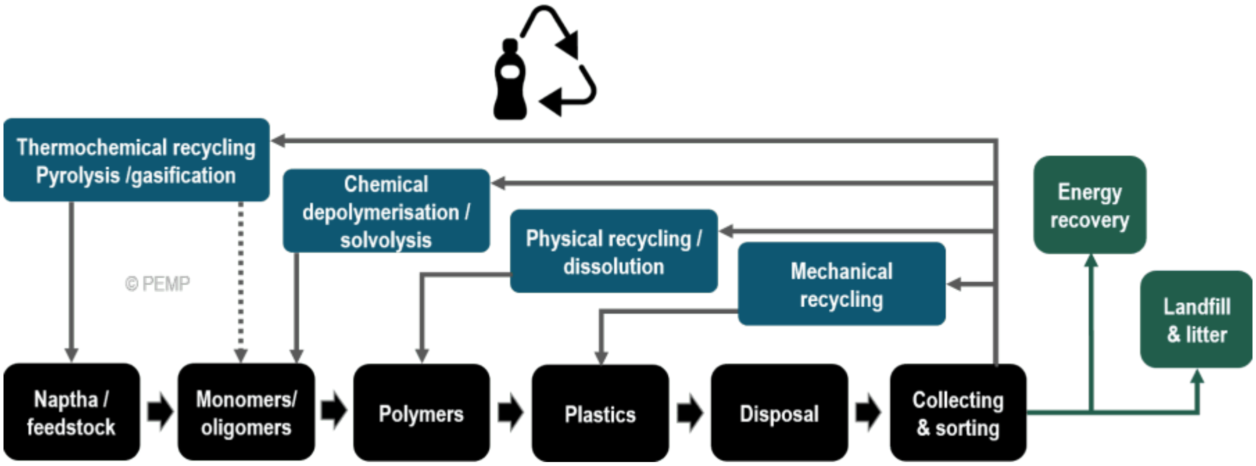


Figure 10. Recycling Technologies in the Life Cycle of Plastics[4]

Box 4: Treatment of Contaminated Dredged Material

Figure 11. Treatment of Contaminated Dredged Material[5]

Several technologies exist to treat polluted dredged material:

- ***In situ ("in place") remediation** refers to the clean-up of contaminated soils and groundwater without removing contaminated media from the subsurface, typically through the use of physical and/or chemical processes.*

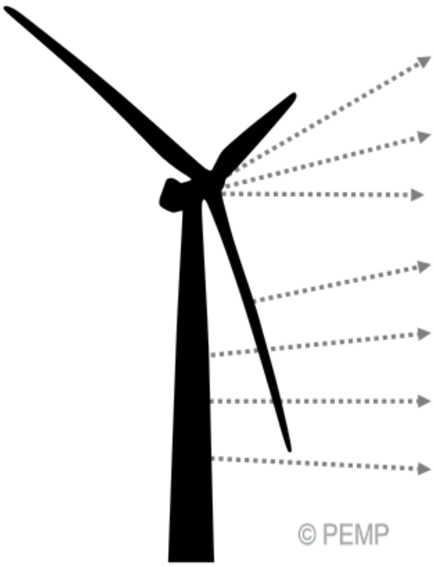
- ***Ex-situ remediation*** *involves the removal of contaminated media, either for off-site disposal or for on-site treatment, and subsequent return to the subsurface.*

The treatment mechanisms can range from physical/chemical, biological to thermal treatment technologies:

- ***Physical/Chemical treatment technologies*** *can potentially remove high levels of metal contaminants in situ. Many metal species can be simultaneously removed. Despite their effectiveness, they generally cost a lot, due to the specialized devices, machinery, and chemicals. This category of treatment includes soil vapor extraction, solidification/stabilization, chemical oxidation, soil flushing, and electrokinetic separation.*
- ***Biological treatment technologies*** *use a process whereby contaminants in soil, sediments, sludge, or groundwater are transformed or degraded into* ***innocuous substances,*** *such as carbon dioxide, water, fatty acids, and biomass, through the* ***action of microbial metabolism****. This technology is commercially available for treating fuel contamination. This category of treatment includes bioventing and phytoremediation.*
- ***Thermal treatment technologies*** *raise the temperature of the contaminated soil to approximately 260 °C for a specified period of time by exposing it to hot gases (i.e. heated air), volatilizing the contaminants, and destroying them in an afterburner. The techniques available include electrical resistance heating, steam injection, and extraction, conductive heating, radio-frequency heating, and vitrification.*

An example of ex-situ treatment of dredged material is the ***Amoras project,*** *which became operational in 2011 in the port of Antwerp, Belgium. Water is removed from the soil by chamber filter presses, after which the filter cake can be disposed of in a controlled manner. This joint project by the Flemish government and Antwerp Port Authority offers a sustainable solution for the processing and disposal of dredged soil from the port. In parallel with Amoras, the Vamoras project looks at ways of recycling the filter cake in e.g. bricks, lightweight aggregate, or concrete for foundations.*

Box 5: Wind Turbine Parts, Materials and Potential Disposal Methods



Turbine Part	Materials	Disposal Method
Hub	Iron	Recycling (foundry)
Canopy	Glass fiber/epoxy or steel	Recycling, incineration or landfill
Nacelle	Steel, permanent magnets, PCB, batteries	Recycling (as filler), incineration or landfill
Blades	Glass fiber, epoxy, composites & balsa wood	Recycling (as filler), incineration or landfill
Platforms & ladders	Aluminum	Recycling (foundry)
Cables & busbars	Plastic, copper, aluminum	Recycling (foundry)
Tower	Steel	Recycling (foundry)
Miscellaneous	Lubricants, grease, paint, rubber, plastic	Recycling, incineration or landfill

Figure 12. Wind Turbine Parts, Materials and Potential Disposal Methods[6]

*As a result of the rise of wind energy as part of the energy transition mix, wind blade equipment is estimated to constitute roughly 20% of **ocean-borne multi-purpose heavy lift cargo**. These cargos require specialized port terminals and specialized vessels due to their dimensions and the specific know-how required to handle the large sections constituting a wind turbine. Compared to the blades, some of the turbines and the other structures, such as the towers, can get quite heavy.*

*As the first generation of wind turbines was introduced decades ago, the **replacement and recycling** of these turbines have become a growing issue and concern in recent years. At the end of their 20-to-30-year lifespan, wind turbines have to be removed and recycled. Recycling wind turbines poses several challenges due to the complex nature of their components and the variety of materials used in their construction. However, efforts have been made to develop techniques for the recycling of wind turbines to address environmental concerns. **Wind turbines consist of various materials**, including steel, copper, aluminum, fiberglass, and composites. Efficient material separation is crucial for recycling. Technologies such as shredding, sorting, and magnetic separation are used to separate different materials. **Specific technologies are available or being developed** for the recycling of specific components of wind turbines:*

- ***Blade recycling**: Wind turbine blades are often made from fiberglass and other composite materials, which, combined with the durability of these materials, complicates the recycling process. Some techniques involve grinding the blades into small particles, while others explore chemical processes to break down the composite materials. Still, quite a few windblades still end up in landfills as the alternatives often remain costly.*

- ***Steel recycling***: *The tower and structural components of wind turbines are typically made of steel. Recycling steel involves melting it down and reforming it into new products. This process is well-established in the recycling industry.*
- ***Recycling of other materials***: *Copper and aluminum are widely used in various electrical components of wind turbines, such as generators and wiring. Recycling these metals involves melting them down and reusing them to produce new components. Permanent magnets in wind turbine generators often contain rare earth elements. Efforts are being made to develop processes for the efficient recovery of these valuable materials while recycling wind turbines.*
- ***Reconditioning and reuse of specific components***: *Some components, such as gearboxes and generators, may be reconditioned and reused in other applications. This can extend the lifespan of certain parts and reduce the overall demand for new materials.*

*The **field of wind turbine recycling is evolving rapidly**, and new technologies and approaches emerge on a regular basis. It is also important to note that **regulations and best practices** for wind turbine recycling may vary by region. For example, some regions implemented Extended Producer Responsibility programs, requiring wind turbine manufacturers to take responsibility for the end-of-life disposal and recycling of their products. This can incentivize manufacturers to design products with recycling in mind.*

***Seaports** are not only important locations in the supply chains for installing new wind parks. Given their proximity to many offshore and onshore wind farms, they can also function as **favorable hub locations for establishing large-scale wind turbine recycling activities**. The generated recycled material can provide an additional source for recycling streams within the broader port cluster, making the port more attractive as a material-sourcing location.*

B. Action fields for material sourcing hub creation

Seaports can transform into hubs for circular materials by adopting comprehensive strategies. They can act as **hubs for material recovery and reuse** by implementing reverse logistics and encouraging sustainable product design. By salvaging materials from end-of-life products and returning them to value chains, seaports can contribute to a more resource-efficient economy. In this way, seaport ecosystems can manifest as sources of materials and even individual molecules that can form the building blocks for new materials and industry procurement sources. By integrating these aspects and fostering a circular materials ecosystem, seaports can advance circularity, reduce waste, and promote sustainable practices within their operations and the wider community. Several key areas of action can be identified:

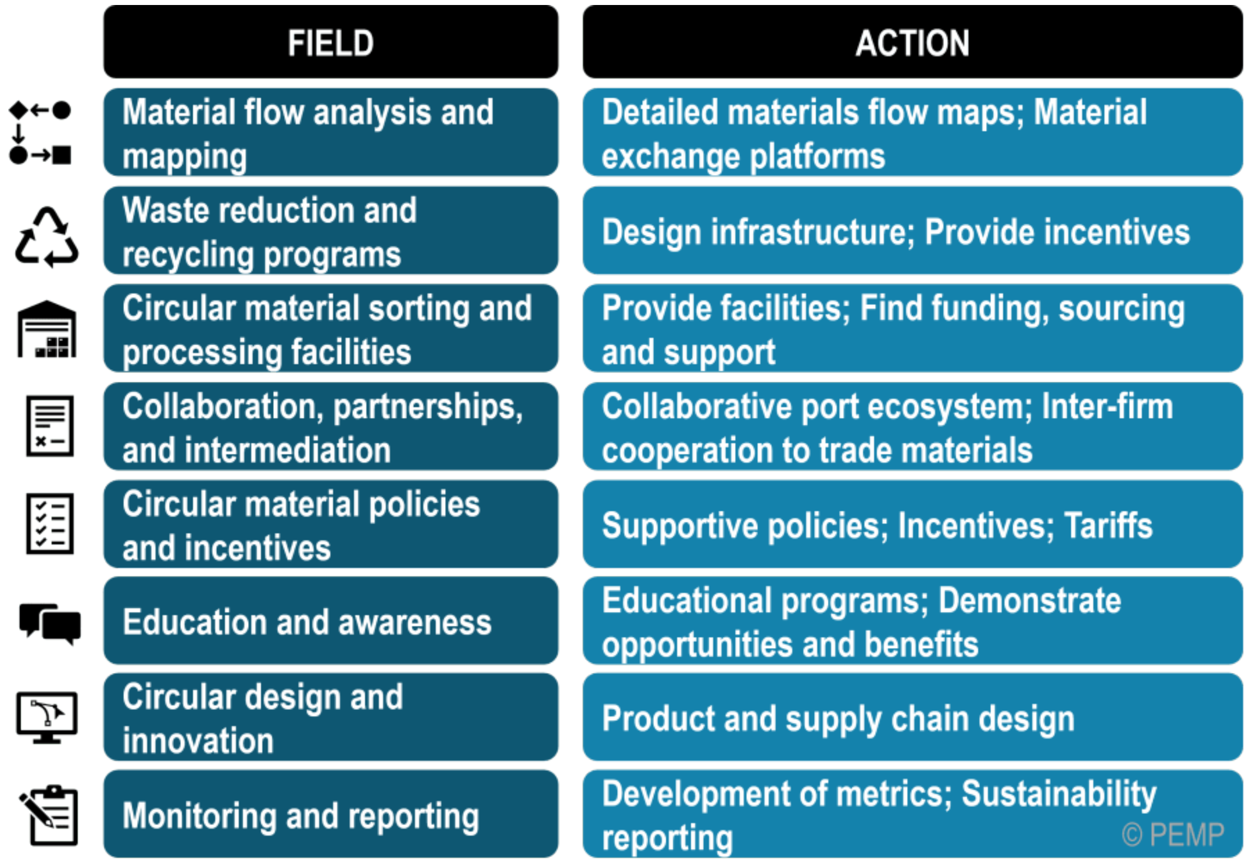


Figure 13. Action Fields for Material Sourcing Hub Creation in Ports

- **Material flow analysis and mapping.** Detailed insights on recycling and reuse flows for a broad array of supply chains (batteries, precious metals, plastics, etc.) and waste products (waste heat, wastewater, etc.) are needed. This requires thoroughly analyzing material flows within and outside the port to understand the types and quantities of imported, exported, and processed materials. Such an exercise should enable the creation of **detailed materials flow maps** to identify potential circular material opportunities. Some of these circular flows can be organized locally (including the port-city interface), while a more regional and even global flow system needs to be developed for others. Material exchange platforms are essential to material flow analysis and mapping and typically include four components: a material passport, a digital twin, material valuation, and matchmaking. Ports are challenged to develop digital platforms that connect businesses and industries within and around the port to facilitate the exchange and reuse of materials. Some industries may be unaware of material sourcing opportunities. Digital matching platforms ideally allow finding high-value reuse options for materials or (waste) products and unlock the potential of these streams by matching them to their highest-value uses.

- **Circular material sorting and processing facilities.** Port ecosystems that want to promote a hub function in material sourcing need to establish dedicated facilities within the port area for sorting, processing, and repurposing various materials. This also involves implementing technologies that enable efficient sorting and processing of materials to extract maximum value from waste streams. Ports can be instrumental in developing circular flows by supporting **small-scale demonstration or showcase projects** in the port area. Such projects enable testing the technical and economic feasibility of a broad array of material recycling and upcycling techniques. At the same time, such projects are needed to strengthen stakeholder support for circular activities and to gain access to capital to fund a later transition from proof of concept (typically start-ups) to projects of a viable economic scale (scale-up).

- **Collaboration, partnerships, and intermediation.** To become material-sourcing hubs, ports need to foster a collaborative port ecosystem focused on circularity. Port actors need local businesses, research institutions, government agencies, and non-profit organizations to drive research, innovation, and knowledge sharing in the field of circular materials. At the same time, port authorities, industry associations, and other relevant stakeholders can cooperate to facilitate industries to trade surplus materials, by-products, or waste streams that can be repurposed by others. Inter-firm cooperation through **industrial symbiosis** is a form of mediation to bring companies together in an innovative collaboration and find ways to use the waste of one as a raw material for the other.

- **Circular material policies and incentives.** For ports to become effective material-sourcing hubs, the wider port ecosystem should advocate for and implement policies that incentivize businesses to adopt circular practices, such as tax incentives for recycling and material reuse, reduced tariffs for reusing materials, or subsidies for circular technology adoption.

- **Education and awareness.** Relevant port actors should facilitate and implement awareness campaigns and educational programs to inform stakeholders, including businesses, employees, and the general public, about the benefits of and specific demands related to creating material sourcing hubs as part of a circular economy in a port context. The information provided should be evidence-based to avoid a public backlash if projects are hyped and do not yield according to inflated expectations.

- **Circular design and innovation.** The port ecosystem should promote and create awareness of product and packaging designs, prioritizing recyclability, reusability, and durability to ensure easier material recovery and reintegration into the economy. This also includes circular supply chain design by supporting businesses that prioritize sourcing materials from recycled content or utilizing reusable materials and by facilitating efficient transportation and logistics to minimize waste and optimize material use.

- **Monitoring and reporting.** The port ecosystem should be responsible for establishing monitoring mechanisms to track the progress of circular material initiatives, including relevant metrics related to material reuse, recycling rates, land use implications, and environmental impact. Regularly reporting progress to stakeholders enhances awareness and creates transparency. Such an exercise can be part of broader sustainability reporting or be developed separately.

- A core challenge remains that few, if any, of these practices have been demonstrated. The value proposition of port circular principles is still to be assessed.

Box 6. Building Blocks of Material Exchange Platforms

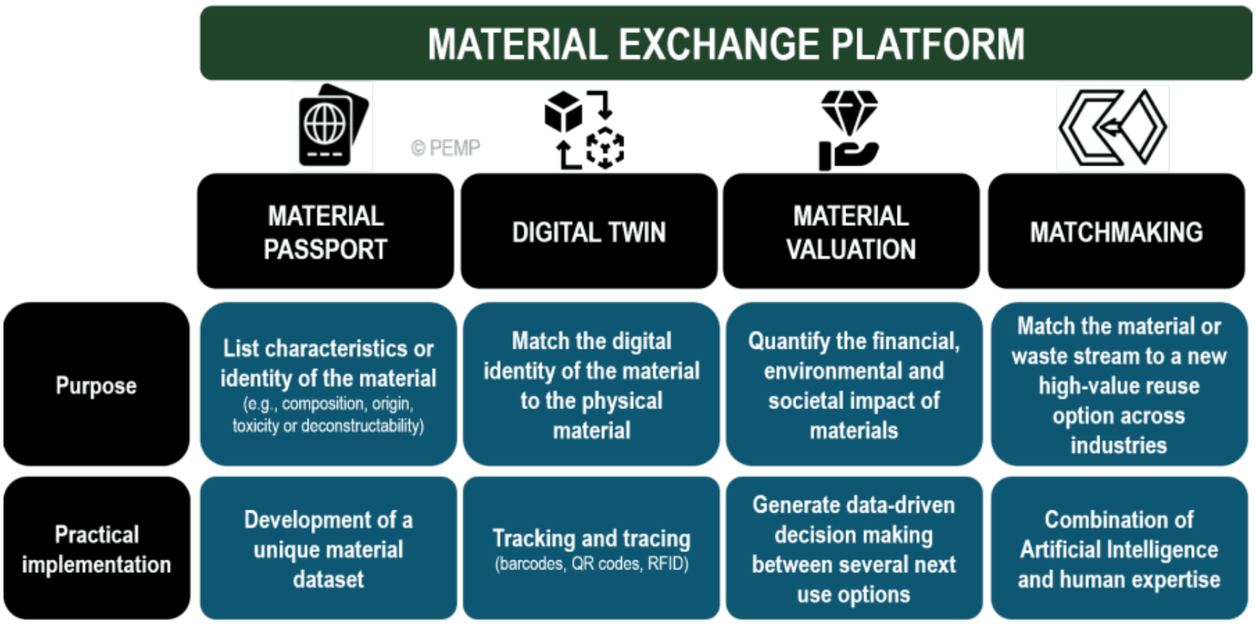


Figure 14. Building blocks of material exchange platforms

Material exchange platforms typically include four components:

- *A **material passport** includes the characteristics or identity of the material, such as its composition, origin, toxicity or deconstructability.*
- *A **digital twin** approach to match the digital identity of the material to the physical material (via tracking and tracing systems) in order to follow it throughout its life cycle.*
- *The **valuation** of the financial, environmental, and societal impact of materials, products, and waste streams, enables data-driven decision-making between several next-use options.*
- ***Matchmaking** of the material, product, or waste stream to a new high-value reuse option across industries, using a combination of Artificial Intelligence and human expertise.*

Material exchange platforms thus aim to link the input and output of collectors and processors in order to map entire material chains, including international recycling chains. Such platforms not only help to comply with reporting obligations (such as in the European Union) but also allow to determine how much of the selectively collected waste is effectively recycled, to assess how much is recycled, and how much secondary raw materials ultimately end up in new products and where.

- **Waste reduction and recycling programs**. Relevant stakeholders should implement waste reduction and recycling programs within the port and surrounding areas to minimize landfill waste. At the same time, appropriate infrastructure and incentives should be provided to allow the responsible disposal of materials. For the transition to a circular economy, ports are challenged to close material cycles so that residual flows are given a second life and reused or recycled.

Box 7. Sustainability Reporting by Port Authorities (Port of Antwerp)

The practice of sustainability reporting, beyond mere environmental reporting, started in the late 1990s. More recently, the port industry is adopting this reporting to conceptualize sustainability and as an essential basis for the license to operate. Mainly larger port authorities have started producing sustainability reports or integrated reporting on a voluntary basis in the past decade (e.g. Antwerp, Hamburg, Rotterdam). In contrast, others have been obliged to adopt the practice due to enforced legislation by governments when it comes to example-setting by state-owned enterprises (e.g. Swedish ports).

*Ports increasingly follow **global guidelines and standards for sustainability reporting** (such as the Global Reporting Initiative – GRI). In 2016, the first **Sustainability Report at the level of the European Port Industry** was presented in the context of the EC PORTOPIA project (PORTOPIA, 2016). The report is set up along six dimensions (Market Trends and Structure* *indicators – Socio-Economic indicators – Environmental and Occupational Health, Safety and Security indicators – Logistics Chain and Operational Performance indicators – Governance indicators – User Perceptions on Port Quality indicators). It uses datasets present within the European Seaports Organisation (ESPO) and the ECOPORTS project.*

Many unsolved conceptual issues and differences in approach among ports remain when it comes to sustainability reporting: (1) the scope and the boundaries of the reporting i.e. organizational, functional, or geographical boundaries; (2) the perspectives of performance and the calculation/definition of indicators, and; (3) the integration of stakeholder perspectives.[7]

4. Port Land Management

The circular economy in seaports impacts **land management and spatial planning by** promoting efficient resource use, waste reduction, and sustainable practices. This can lead to optimized land allocation, improved waste management systems, and the integration of recycling and reuse facilities within port areas. Additionally, the circular economy encourages the development of eco-friendly transportation and storage solutions, influencing the layout and design of port infrastructure.

A. Land availability and demand for CE

Land has become a scarce and complex resource for ports to manage. Therefore, it is over the issue of land and its footprint that ports are challenged to address the circular economy as this particular resource is difficult to improve. Land is required for CE activities to develop in ports, but how much space varies on the types of CE activities and future economic scenarios relevant to the port. Some studies in this area indicate that, depending on the scenario, the circular economy as a whole could require up to 40% more space in 2050 than the current linear fossil economy.

> *The circular economy as a whole could require up to 40% more space in the 2050s than the linear fossil economy of the 2020s.*

For CE to be implemented in a seaport context, it is important to create the **right conditions in spatial planning policy** by paying attention to circular strategies when developing, transforming, and restructuring areas in the port area and its region. This requires **coordination and cooperation** between relevant stakeholders such as various government departments, managing bodies of ports, and port land users or concessionaries. In many regions, it is considered a challenge to find the necessary space between existing land claims in seaport areas but also in the vicinity of the port (such as in relation to housing, nature, agriculture, and mobility).

Irreversible decisions on land allocation can further complicate the transition to a circular economy. For example, when an industrial estate with a high nuisance level or high environmental impact is given another destination, this decision can jeopardize the reuse of the site for industrial CE activities. Also, the development of an industrial estate of the highest environmental category takes decades due to permitting and licensing processes. Therefore, it is important to **reserve the space required for circular activities** with a more industrial character in a timely manner and to be careful with repurposing existing industrial estates and brownfields in seaport areas.

To prepare for and accommodate the transition to a circular economy, managing bodies of ports, and local, regional, and national public authorities are challenged to consider the following:

1. Develop a **systematic approach** to secure the required space for CE developments: Decentralized authorities and managing bodies of ports must develop a regional spatial vision of the circular economy and raw materials, linked to a concrete implementation strategy at the regional level. In line with this, higher government levels must work with other parties at the country or supranational level on a spatial strategy or pathway for a circular economy.
2. Estimate the **space required** in and around seaport systems under different CE scenarios.
3. **Reserve strategic locations** in planning terms to avoid irreversible choices that hinder the CE transition. A physical environment that is attractive for circular behavior can contribute to the transition to a circular economy.
4. **Plan and develop infrastructure** for the circular economy: Circular economy requires timely adjustments in transport and energy network infrastructure and the space required to transport materials, goods, and the required (renewable) energy.

B. The (re)development and (re)use of port sites

From a port (re)development perspective, **port sites** can be labeled with several different field names, depending on the location and current use, including greenfield, brownfield, blackfield, greyfield and bluefield.

The designation of these terms can carry both regulatory and financial implications in the context of land redevelopment or regeneration.

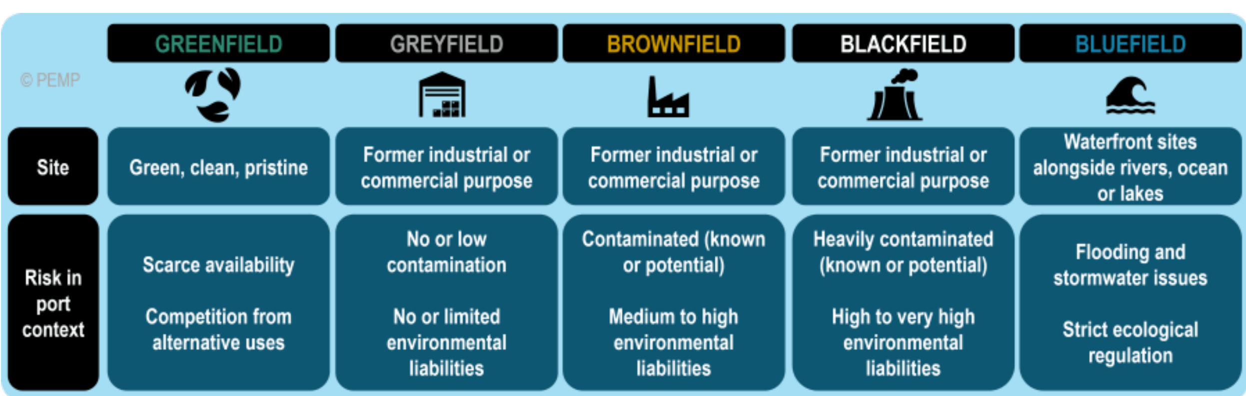


Figure 15. Greenfields, Brownfields and Related Terms

Land available for port development can fall into five main categories:

- A **greenfield** is a pristine land that has never been developed, such as woodland, wetland, and farmland. However, farmland might not be considered greenfields if pesticides and herbicides have been used intensively for a longer period of time.
- A **brownfield** is a property of which the expansion, redevelopment, or reuse may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant. Thus, a brownfield is a set of neglected and underused land that was used in the past for industrial or commercial purposes and has, therefore, been damaged or contaminated to such an extent that it can only be (re)used by means of structural measures.
- **Blackfields** are also underused areas where redevelopment is needed, but unlike brownfields, the soil is so heavily contaminated that project developers and investors no longer see the possibility of a profitable project. In these cases, it is, therefore, up to the government to take the initiative. Otherwise, no redevelopment or regeneration of these lands will occur. Thus, the difference between blackfields and brownfields can be seen in the question of who can carry out the remediation. In the case of blackfields, the contamination is so severe that a private party will never invest because the remediation costs are too high.
- **Greyfields** are areas that have been developed and then abandoned. The difference between a greyfield and a brownfield is that environmental liabilities are likely not a concern.
- **Bluefields** are waterfront sites alongside rivers, oceans, or lakes, with high flooding risks and subjected to extensive ecological laws. As bluefield areas are subjected to flooding and stormwater issues, reviving or reusing these sites may face issues such as soil instability, continued flooding, or property reuse restrictions.

Considering the above, three main approaches can be followed in view of the remediation of a contaminated port site: (a) the government or public agency solves the problem, such as in the case of blackfields; (b) the problem is solved through cooperation between public and private partners; (c) the contamination is solved entirely using private means.

Greenfield port development in uncontaminated areas is increasingly under pressure due to a lack of greenfield space, competition by potential alternative uses (nature, agriculture, urban), and the availability of other sites that could be reused. Therefore, ports are challenged to consider the **redevelopment, regeneration and reuse of existing port sites**. However, these sites are often contaminated. In the past, landfill sites in ports were very common, functioning as buffers or storage areas for waste. While these practices have been replaced by specialized chemical waste treatment facilities, reminders of the old practices can be found in the form of contamination at many port sites.

Non-greenfield land might face major challenges in attracting project developers and investors because of **(historical) environmental contamination**, even if these lands do (or could) have enormous potential in terms of space for port renewal or the implantation of new companies. Environmental contamination can involve soil penetration of chemicals, asbestos-containing materials, lead-based paints, and hazardous wastes. These locations can be frightening for most developers and business owners due to the fear of **expensive environmental liability, high remediation costs, and unsafe conditions for workers**.

Still, the **redevelopment of port brownfields** produces numerous environmental, social, and economic benefits. Today, many of these original port locations have been replaced by newer technology, or have moved to more strategic locations (the so-called port migration). In many cases, seaports have grown away from their original locations (see the 'Anyport' model[8]), many times leaving behind abandoned sites, buildings, and equipment. By cleaning up and returning these lands to use, communities can remove dangerous structures and stop or stabilize contamination near waterways. Most seaports were initially developed in or close to an urban core. Port redevelopment presents valuable opportunities for urban regeneration in the form of waterfront redevelopment[9], and it may catalyze revitalization in the broader community.

Box 8. Drivers of Port Terminal Migration and Relocation

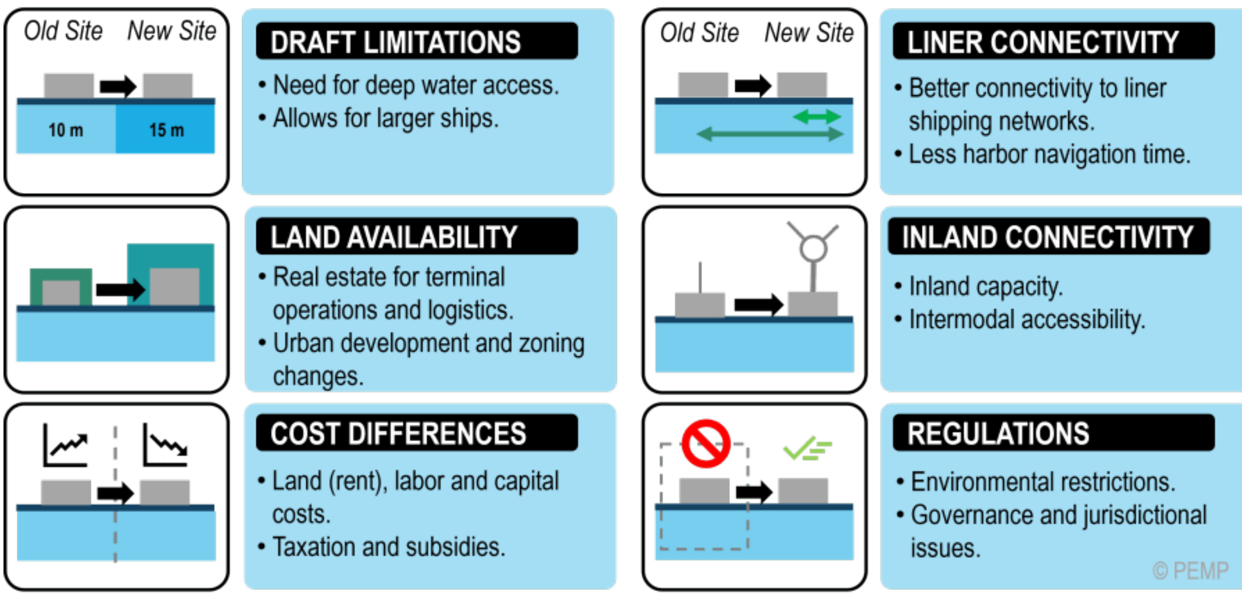


Figure 16. Drivers of Port Terminal Migration and Relocation[10]

There are multiple possible drivers for port terminal migration and relocation, including: (a) more stringent technical requirements, such as the need for deep water access to accommodate ever larger vessels; (b) the need for locations that offer better connectivity to liner shipping networks; (c) diseconomies of scale and land availability issues at existing port terminal areas; (d) additional real estate for terminal operations and supporting logistical activities in light of traffic growth; (e) better accessibility to regional transportation such as highways, rail or barge; (f) urban/city development dynamics; (g) cost differentials between existing and new locations in terms production factors capital, labor and or land; (h) environmental restrictions at established ports terminals; (i) competition between incumbent and entrant terminal operators; and (j) political and administrative issues in existing jurisdictions.

Brownfield redevelopment frees space for various uses and creates more available property for sale or lease, providing ports with additional sources of revenue. Besides, redevelopment of previously used sites can help alleviate pressure on undeveloped wetlands and coastal areas, thus protecting important coastal habitats.

Quite a few countries have worked out specific regulatory frameworks in order to facilitate the **redevelopment or regeneration of brownfield sites**. An example is the so-called **brownfield covenants or agreements** signed between a public authority on the one hand and the actors of a brownfield project on the other hand, in which the necessary agreements are made about temporal demands and expectations and procedural requirements and expectations. The brownfield covenant makes it possible to work on the concrete redevelopment of the port site or area over a longer period of time within the agreed framework. The responsible government or public agency might also provide a number of financial benefits when concluding a brownfield agreement, such as:

- A specific procedure for **expropriating essential land** to realize the project.
- An exemption from the normally mandatory provision of financial security on the **transfer of contaminated land**.
- An exemption from **registration duties** when purchasing real estate in the context of a brownfield project.
- Public authorities might offer **competitive grants** to provide funding for environmental assessments, remediation, public education, and economic assistance.
- **Financial assistance** to fund the necessary cleanup efforts can provide developers with the necessary liability assurance to invest in redeveloping these areas.

Brownfields can also play a role in **energy transition in ports**.

Energy generation from renewable sources is not affected by contaminated soil, groundwater, or air. When a property with environmental contamination is in various stages of remediation, the land can be used to house solar panels (**brightfields**) and wind farms (**windfields**). Thus, brownfields can be reused for renewable energy generation.

Next to greenfield and brownfield port development projects, port sites can also accommodate **retrofit projects** whereby the equipment, installations, and buildings on an existing site are upgraded to meet contemporary market or sustainability standards. Typical examples include:

- The transition from a conventional container terminal to a fully or semi-automated terminal by replacing manned yard equipment with automated stacking cranes (ASC) and automated guided vehicles (AGV) for horizontal transport.
- The **retrofitting of industrial installations** to allow a transition from fossil fuels to renewables; to change the feedstock used as input for the production process; or to enable the reuse of waste heat or other byproducts of the production process.

- Existing **warehouses and distribution facilities** in the port are upgraded by adding additional insulation, changing lighting to LED lights, installing solar panels on the roofs, and replacing diesel-powered equipment such as forklifts with electric equipment.

C. Lifecycle management of port infrastructure

An essential principle of the circular economy involves a commitment to keeping products in use and providing value to the process. Life cycle thinking involves the consideration of the economic and social values of circularity and thinking about design, development, and, crucially, what happens once a structure reaches the end of its life cycle. In this realm, ports are infrastructure-intensive facilities that should develop **infrastructures with an extended life cycle** that can be repaired, refurbished, and reused.

Lifecycle management of port infrastructure is an important aspect of circular principles.

Embedding circular principles within the design phase of port infrastructure considers **flexible port infrastructure design**, which allows for upgrades, extensions, and alternative uses when needed. Integrating flexibility concerns in the design of quaywalls and locks is not easy,[11] given that the initial construction and any changes made afterward are typically very expensive. Building infrastructure creates strong path dependency mechanisms since it sets standards and capacity for long periods. Therefore, **designing for flexibility** in practice might result in building more capacity than the current market (or projections) might anticipate to avoid expensive retrofitting or reconstruction afterward. For instance, designing a sealock larger than the current capacity would justify anticipating the potential future scale increases in vessel sizes. Still, new technologies such as **additive manufacturing** allow for new opportunities for the construction and maintenance of port terminal facilities, particularly if the materials are sourced from construction recycling materials.

The lifecycle management of port infrastructure also involves **sustainable maintenance strategies** aimed at reducing the environmental impacts of port operations, enhancing the resilience and performance of port assets, and extending the economic life of the infrastructure. There are different approaches and methods to develop such strategies, depending on the type and condition of the infrastructure, the port's vision and goals, available data and tools, and stakeholder involvement. Some key considerations for port infrastructure include:

- **Port infrastructure maintenance strategies** with a focus on minimizing the life cycle cost and greenhouse gas emissions while maximizing the reliability of the infrastructure.
- **Evaluate, compare, and improve maintenance strategies** by taking into account technical, environmental, and economic aspects. A **proactive and preventive maintenance approach** considers the uncertainties and complexities of port infrastructure.

- **Decision-making and maintenance planning system** by integrating data on the technical details of the condition of port infrastructure, a risk-based evaluation of infrastructure performance, and a cost-benefit analysis of risk treatment solutions.

Decisions and strategies concerning the **circularity of port infrastructure** are among the most costly and risk-prone. If they are successful, the benefits can be substantial, but if not, the sunk costs can create serious financial difficulties for infrastructure managers. When port infrastructure has reached the **end of its life cycle** for economic or technical reasons, it should be stripped for parts and components, and anything left should be recycled and reused. The challenge remains the cost of recovery and reuse of heavy physical infrastructures.

D. Land concessions

Land for port development is a scarce and valuable resource, making the concessioning of port sites to private companies[12] a primary task for landlord port authorities. A well-designed concession policy allows port authorities to retain some control over the organization and structure of the supply side of the port market while optimizing the use of scarce resources such as land.

Therefore, landlord port authorities[13] can consider the explicit inclusion of **circular economy factors when awarding land concessions to private operators**:

- When deciding which site to award, port authorities could more explicitly look at the **CE quality of the port site.** Brownfields might be more expensive to redevelop but often lead to higher spatial quality and site regeneration. Port authorities could also include more stringent guidelines on the circular design of port infrastructure and superstructure, making the concessionaire bear some responsibility for repurposing the site they used near the end of the concession.

- In the awarding or selection phase[14], the **CE quality** of the candidate's bid can constitute a new element in the qualification phase of a port site awarding process. By doing so, possible candidates are rewarded for their current proposals and previous initiatives in other ports or locations in circular activities and operations. There is scope to more explicitly integrate **circularity-inspired performance measures** in the selection process next to more traditional criteria such as throughput expectations, financial performance, the price bid, and socio-economic impacts in terms of value-added created and employment effects.

- Port authorities should also consider including CE elements in the post-bidding phase, such as by including circularity-inspired clauses that go beyond simply stipulating that the concessionaire will have to make efforts to comply with local, national, and supranational legislation related to CE. Such clauses could, for example, refer to the compulsory use of circularity management reporting or monitoring systems.

5. Energy Management

Circular economy strategies encourage the use of renewable energy sources and the adoption of energy-efficient technologies, which directly impact seaport operations. Energy is crucial in optimizing resource use, material recycling, and minimizing waste. Additionally, energy efficiency measures contribute to the overall sustainability of circular practices by lowering resource consumption during manufacturing and transportation processes in seaport areas.

Ports have a significant role in the needed convergence of energy and materials transitions. It concerns a twin transition or the transition to a circular and low-carbon society over the various components of the port ecosystem, such as waterways, quays, yards, and hinterland transportation. Renewable energy integration and energy-saving measures can enhance the overall sustainability of seaport activities. However, abundant and low-cost energy sources are fundamental to economic prosperity, particularly in developing economies. There is a high risk that circular principles applied to the maritime sector could increase the cost of energy and, consequently, the cost of transportation.

PORT	WIDER PORT AREA	ECONOMY AND COMMUNITY
Decarbonizing operations in / near ports	**Industrial clusters, port-city links and offshore**	**Green supply chains and business models**
A1. Energy saving A2. Decarbonization of port equipment A3. Onshore power supply A4. Clean fuel bunkering A5. On-site renewable power	B1. Energy and chemical waste B2. Offshore energy B3. Offshore industry B4. Industry decarbonization B5. Sustainable urban energy B6. Energy conversion B7. Energy storage hubs B8. Carbon capture use/storage	C1. Zero/low carbon fuel supply chains C2. Zero/low carbon electron supply chains C3. Decarbonization of transport © PEMP

Figure 17. Ports and the New Energy Landscape[15]

	Maritime Transport	Waterways	Quays	Terminals	Storage	Port Area Networks	Hinterland transportation
Decarbonizing operations in / near ports							
A1. Energy saving			☑	☑			
A2. Decarbonization of port equipment			☑	☑		☑	
A3. Onshore power supply	☑	☑	☑			☑	
A4. Clean fuel bunkering	☑	☑	☑		☑	☑	
A5. On-site renewable power				☑		☑	
Industrial clusters, port-city links and offshore							
B1. Energy and chemical waste	☑	☑	☑	☑	☑		☑
B2. Offshore energy			☑	☑		☑	
B3. Offshore industry	☑	☑	☑	☑	☑	☑	☑
B4. Industry decarbonization	☑	☑			☑	☑	☑
B5. Sustainable urban energy						☑	
B6. Energy conversion						☑	☑
B7. Energy storage hubs		☑	☑	☑	☑	☑	☑
B8. Carbon capture use/storage				☑	☑	☑	☑
Green supply chains and business models							
C1. Zero/low carbon fuel supply chains	☑	☑	☑	☑	☑	☑	☑
C2. Zero/low carbon electron supply chains					☑	☑	☑
C3. Decarbonization of transport						☑	☑

Figure 18. Implications of Energy Transition for Ports[16]

In the context of seaports, energy management contributes to circularity in several ways, such as:

- **Renewable energy integration**. Seaports can adopt renewable energy sources such as solar, wind, or tidal power to generate electricity. Integrating these sources into the port's energy mix reduces reliance on non-renewable energy and lowers the environmental impact.
- **Energy efficiency measures**. Ports can implement energy-efficient technologies and practices in port operations to help reduce overall energy consumption.
- **Waste-to-energy systems**. Port ecosystems can explore waste-to-energy systems where waste generated within the port is converted into energy. This supports waste management and contributes to the circular use of resources by extracting value from materials that would otherwise be discarded.
- **Digitalization**. Deploying digital/data infrastructure and technologies, such as energy management systems and IoT devices, allows ports to monitor and control energy consumption in real-time. Digital solutions allow for more informed decision-making and the identification of opportunities for energy optimization.
- **Electrification of port equipment**. Transitioning from traditional fossil fuel-powered equipment to electric or hybrid alternatives reduces the carbon footprint of port operations. This electrification can extend to various activities, including cranes, trucks, and other machinery used for cargo handling.
- **Energy storage solutions**. Incorporating energy storage systems, such as using batteries or the transition of green electricity (wind/solar/hydro) to green hydrogen, allows seaports to store excess energy generated during periods of low demand and use it during peak times. This helps balance the energy supply and demand and ensures a more stable and efficient energy use.

- **Lifecycle Assessment**. A lifecycle assessment of the port's energy infrastructure is crucial for identifying areas where improvements in terms of energy use can be made.

Energy management also plays a crucial role in **recycling and upcycling activities in seaports**. The **collection and transportation of recyclable materials** by seagoing vessels, inland barges, rail, or trucks often involve energy-intensive processes. By optimizing routes, improving fuel efficiency, and transitioning to alternative energy sources, the overall energy footprint associated with the logistics of recyclables can be reduced. A vast amount of energy is required in the **sorting and processing stages of recycling facilities**. Advanced sorting systems and machinery, and the use of zero- or low-carbon energy sources help to minimize the energy and emission impact of these activities. In some cases, recyclable materials are used as **feedstock for waste-to-energy systems**, where they are converted into energy through processes like incineration. For these activities, it is essential to maximize the energy yield while minimizing environmental impacts. Finally, **manufacturing products using recycled materials** also requires energy management throughout the production processes through the use of energy-efficient equipment and renewable energy sources. Regularly monitoring, analyzing, and implementing energy-efficient technologies and practices throughout the recycling supply chains contribute to continuous improvement in recycling operations.

6. Waste Management

Seaports generate significant waste through dredging, construction, industrial activity waste, and vessel-generated waste. Managing wastes at ports has been practiced for centuries with simple disposal practices such as nearby landfills or simply dropping wastes into the ocean. For instance, Monte Testaccio in Rome is an artificial mound almost entirely composed of discarded imported amphorae accumulated during the maritime trade of the Roman Empire over four centuries. Many amphorae could not be reused because there were limited outbound trade flows for the capital city. The current scale of waste-generating activities in port areas forbids such practices, and in the last decades, **complex waste management activities** have emerged. Adopting CE practices represents the latest evolution in this trend by implementing **waste reduction and reuse/recycling programs**, leading to decreased environmental emissions and better resource management. It is shifting the focus to closing material loops at the port system level, where waste can be used as a resource in other parts of the value chain.

Waste management in seaports is inked with several activities including treating contaminated dredge material, recovering and reusing industrial waste heat, waste-reception facilities for vessels, and treatment of waste generated during port operations by port authorities, terminal operators, and other service providers. The way that ports collect and manage waste generated by landside activities or ship calls can lead to high recycling rates and valuable materials finding their way back into the economy. Otherwise, an inefficient system where most waste (recyclable or not) ends up in the sea or landfills or is incinerated, with harmful environmental impacts and potentially significant economic losses.

One of the most significant sources of waste in ports results from dredging to allow the berthing of seagoing vessels of increased size and to keep shipping channels open. For many ports, hundreds of millions of cubic yards of material are dredged annually to maintain access for ships into harbors and waterways. However, of that dredged material, only clean (non-contaminated) material, accounting for less than half of all dredged material, can be used for land reclamation, construction fills, beach reconstruction, topsoil, and habitat creation or restoration. Contaminated dredged material must be stored in specific facilities where it can either be left to naturally be restored over decades (decomposition by bacteria) or be manually and chemically decontaminated.

Box 9. Cubic Yards Dredged by the US Army Corp of Engineers at Selected Port Districts

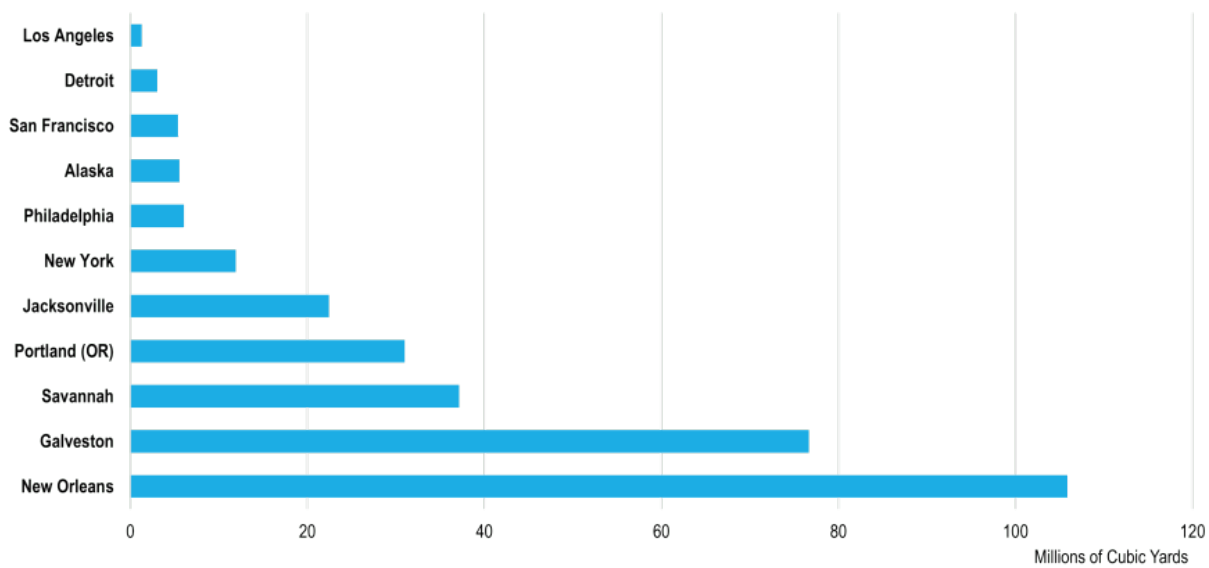


Figure 19. Cubic Yards Dredged by the US Army Corp of Engineers at Selected Port Districts 2014 2018[17]

The extent of capital and maintenance dredging work is related to the ***length of a port's access channel*** *and the* ***level of sedimentation****. The district of New Orleans accounts for the most extensive dredging efforts in the United States, with a navigation channel of around 400 km from the Mississippi Delta, including the ports of New Orleans and Baton Rouge. These efforts are justified by the importance of the Mississippi as a gateway to American grain and energy trades. The Galveston district includes the ports of Galveston and Houston, which are important cruise, container, and petrochemical ports. In particular, the Houston Ship Channel is an 83 km waterway granting access to the petrochemical and container terminals of Houston, Barbours Cut, and Bayport. Savannah, Portland, and Jacksonville are river ports requiring regular access channel maintenance. At the opposite end of the spectrum, the Los Angeles district, which includes the Los Angeles / Long Beach port complex, has limited dredging because of its direct maritime access and natural deep drafts.*

A challenge, as well as an opportunity, is the deposition of dredging materials. Commonly, materials are released at a defined offshore location, or they can be used for reclamation projects.

The development of effective port reception facilities **(PRF)** to collect ship wastes and the establishment of systems that provide incentives for ships to use these facilities are significant elements in a process toward reducing waste discharges and implementing circular principles related to waste management.

Figure 20. Recycling from Waste to Pure Raw Materials

Recycling from waste to pure raw material in a certified way allows for better environmental performance while helping people and companies become more sustainable. By carefully selecting and shorting materials, extracting the highest feasible volume of new row material for every tonne of waste is possible.

Certification allows for efforts towards a circular port economy to be acknowledged. Foremost, certification provides all parties with certainty and a level playing field to determine when a secondary raw material should no longer be considered as 'waste' but as 'end-of-waste'. One of the barriers faced by operators who want to use secondary raw materials is uncertainty about their quality. Given the absence of standards to ascertain impurity levels or suitability for recycling, certification increases trust in secondary raw and recycled materials, and helps support the market.

One such example exists in the Netherlands, where a metal recycling company transforms waste generated in the port of Rotterdam and provides an "End-of-Waste" (EoW) certificate. The certificate allows manufacturers to offer recycled materials such as iron, steel, and aluminum as pure raw materials. This recycled material can be used for the production process of new metals. Using recycled material instead of virgin materials not only solves energy but also reduces greenhouse gas emissions, including CO_2. Recycling metals also reduces other adverse environmental issues associated with extracting new raw materials from the earth. The certificate offers buyers and sellers of recycled materials the assurance that metal waste has been processed and offered sustainably and responsibly. Working this way favors the commitment to a sustainable and circular economy with the goal of zero emissions, as it lowers the use of raw materials, energy, and costs.

Waste treatment is critical to circularity in ports. Waste generation on seagoing vessels may be harmful when inadequately managed. The annual ship wastes and residues at sea are estimated to exceed 1,2 million cubic meters of oily waste, 1,4 million cubic meters of sewages, 450,000 tons of garbage, 24,000 cubic meters of sludge and 360,000 cubic meters of bleed-off from scrubbers. The amount and types of waste may vary from one ship category to another.

TYPE OF WASTE	GENERATION RATE	DRIVER
Oily bilge water	0.01-13 m^3 / day; larger ships generate larger quantities.	Condensation & leakages in engine room; size of ship
Oily residues (sludge)	0.01 to 0.03 m^3 of sludge / ton of HFO; 0 and 0.01 m3 / ton of MGO.	Type of fuel; fuel consumption
Tank washings (slops)	20 to hundreds of m^3	Number of tank cleanings; Size of loading capacity
Sewage	0.01 to 0.06 m^3 / person / day; Sometimes mixed with other wastewater; then total amount: 0.04 to 0.45 m^3 / person day	No of persons onboard; type of toilets; length of voyage
Plastics	0.001 to 0.008 m^3 of plastics per person per day	Number of person on-board
Food wastes	0.001 to 0.003 m^3 per person per day	Number of persons on-board; provisions
Domestic wastes	0.001 to 0.02 m^3 per day per person.	Number of persons on-board; type of products used
Cooking oil	0.01 to 0.08 liters per person per day.	Number of persons on-board; type of food prepared
Incinerator ashes	0.004 and 0.06 m3 per month. © PEMP	Use of incinerator; cost of using incinerator
Operational wastes	0.001 to 0.1 m^3 / person / day.	Size of the ship; type of cargo
Cargo residues	0.001–2 % of cargo load	Type of cargo.; ssize of ship

Figure 21. Estimations of Ship-Ggenerated Wastes per Type of Waste[18]

For almost every type of waste generated by seagoing vessels, there is a variety of waste flows depending on the size of the ship, the cargo carried, and the number of persons on board. Fuel is a primary source of oily waste, depending on the size of the ship, the type of fuel used, the amount consumed, and the condensation and leakages in the engine room. Some additional variables are important regarding the waste generated onboard passenger and cruise ships. These are the provisions for passengers and personnel on board, the types of products used, and the type of food prepared.

For example, **cruise ships** are among the highest waste generators. While they comprise only a small percentage of the global shipping industry, it is estimated that around 24% of all waste produced by shipping comes from this sector. At the same time, some geographic areas are more exposed to the accumulation of and impacts from sea-based waste due to their proximity to shipping routes. Two European cases, Malta and the North Sea, with heavy maritime traffic, are good examples of higher geographic exposure compared to other parts of the world, such as the Baltic Sea, the East Mediterranean, the Caribbean Sea or the North Persian Gulf. For ports, it is crucial to develop the essential PRFs and associated processes (i.e. segregation, recycling, etc.) for handling the waste that ships deliver.

Box 10. Cruise Ship Waste Streams for a One Week Itinerary

TYPE OF WASTE	CONTENT/TYPE	3,000 PAX SHIP	Per PAX
Sewage (black-water)	Waste water and solids from toilets.	210,000 gallons	70 gallons
Gray-water	Wastewater from sinks, showers, galleys, laundries (*Contains detergents, cleaners, oil and grease, metals, pesticides, and medical and dental wastes*)	1,000,000 gallons	333 gallons
Hazardous wastes	Dry-cleaning waste *(chlorinated solvents)*.	5 gallons	0.001 gallons
	Used paint.	10 gallons	0.003 gallons
	Expired chemicals, including pharmaceuticals.	5 gallons	0.001 gallons
	Other wastes (print shop wastes, used fluorescent and light bulbs, used batteries)	Unknown	
Solid waste	Plastic, paper, wood, cardboard, food, cans, glass	8 tons	5.8 pounds
Oily bilge water	Liquid collected in the vessel's lowest point when in static floating position.	25,000 gallons	8.3 gallons

© PEMP

Figure 22. Cruise Ship Waste Streams for a One Week Itinerary[19]

Depending on the ship size, the number of persons on board, the ship-operating route, the voyage duration, and the time spent in the respective areas, waste discharge might be restricted to time spent in port. The quantity and types of garbage to deliver by cruises into a port reception facility may vary a lot, making the port's waste services planning and provisions more challenging to manage in terms of demand, capacity, and adequacy.

Pollutants and waste from cruise ships include air emissions, ballast water, wastewater, hazardous waste, and solid waste. An average cruise ship generates a minimum of 1 kg of solid waste plus two bottles and cans per passenger per day and an average of 50 tons of sewage (black water) per day. A figure of 3.5 kg/passenger/day, with the estimated amount of generated waste (typical one-week voyage) including 25,000 gallons of oily bilge water; 210,000 gallons of sewage (or black water); 1 million gallons of non-sewage wastewater from showers, sinks, laundries, baths, and galleys (or grey water) and eight tons of solid waste (i.e. plastic, paper, wood, cardboard, food, cans, glass).

The average cruise ship of 3,000 passengers and crew generates about 50 tons of solid waste in a single week. A cruise ship with 3,000 passengers is considered of average size, with the largest ships exceeding 6,000 passengers. A typical cruise is seven days, and the ship stores are usually replenished at the turn port, so the cruise carries all the provisions for the full journey. For instance, about 24,000 water bottles are loaded on board at each cruise turn. The provisions on the following chart are all containers (plastic, aluminium, cardboard, or glass) that need to *be disposed of and compacted on the ship as international laws forbid their disposal at sea. This requires a recycling facility on board as well as a point of collection at the turn port. Further, it offers a large amount of materials to be used within the port community for circular economy processes. These vessels, or the ones with double capacity (i.e. the Royal Caribbean Oasis-class vessels that exceed capacities of 6.000 passengers), cruise with a capacity utilization that exceeds 90%, thus producing significant wastes and residues to be delivered at the cruise ports they visit.*

Figure 23. Some Goods Consumed On Board a 3,000 Pax Cruise Ship per Week[20]

Overall, a consid erable part of the solid waste generated by shipping comes from cruise ships. In the absence of recent data, it is worth noting that two decades ago, the share of comparatively lesser cruise activities was measured to stand at approximately 24% of the total waste produced. Under the IMO International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), ports are complied to provide adequate port waste reception facilities with no undue ship delay.

A cuircular economy approach also demands an emphasis on lowering the wastes generated by seagoing vessels discharged at sea. In the absence of available global data, the precise amount of the *waste gap,* that is, waste generated on board ships but not delivered at ports or treated onboard, is not known, i.e., wastes at sea might be the outcome of several sources, in Europe alone, and although garbage delivered in ports has increased since the introduction of regional rules for ports reception facilities, a significant delivery gap in waste remains, estimated between 60,000 and 300,000 tonnes, i.e., 7% to 34% of the total to be delivered annually.

With shipping accounting for substantial discharges of wastes and residues at sea, port activities targeting the reduction of discharges of ship-generated waste and cargo residues into the sea are closely linked with protecting the marine environment. Ports have a crucial role to play in achieving this goal. Avoiding dumping any food, domestic, and operational waste by a vessel or disposing of plastics in territorial waters is subject to ports providing the facilities for receiving ship-generated residues and waste. PRFs should meet the disposal needs of ships using the port without causing undue delays. Circularity is advanced by implementing a cost recovery system (e.g., a waste fee), incentivizing ships not to discharge ship-generated waste at sea. Still, addressing the existing "waste gap" goes beyond port responsibilities and demands investments and measures to combat a range of waste resources, thus requiring collective action by additional stakeholders.

The efforts of ports in selecting and managing the waste they collect are linked with the need to implement waste management and develop facilities, technologies, or services to allow continuity to a ship's waste disposal life cycle. This involves separate perceptions between how waste management from vessels is carried out and the systems and controls implemented in land-generated solid waste management. Since there are differences between land-based and maritime waste management, it is worth effectively segregating the types of waste generated onboard and ashore with the recycling facility. Yet, an **on-board and ashore integrated waste management system** is essential to avoid a ship-shore interface break. Developing and implementing comprehensive programs where all types of waste and the waste management process are jointly considered might best address the adverse impacts of waste management. This is because implementing the appropriate waste management schemes would enable avoiding abrupt breaks in the life cycle of waste streams sorted and collected on-board and their transfer ashore.

An integrated approach takes into account five over-arching **principles for waste management:**

- **Waste management hierarchy**. The aim is for waste materials to be reused, recycled, recovered, or used as an energy source rather than to prevent waste generation and reduce its harmfulness by safe disposal. The goal is to identify the most harmful or valuable wastes and prioritize the handling, disposal, and reuse accordingly.
- **Self-sufficiency in the community** along with establishing an integrated and adequate network of waste disposal facilities.
- **Implementing the best available techniques**. Costs associated with circularity are reduced as much as possible and in the most economically efficient way.
- **Proximity**. Wastes should be disposed of as close to the source as possible.
- **Extended Producer Responsibility**. Economic operators, particularly product manufacturers, must be involved in extending the life cycle of substances, components, and products from their production.

Regulatory initiatives at international and regional levels support a circular approach in handling the generated waste, as they provide specific long-term obligations for ports that establish the right conditions for receiving and treating the reception of wastes. The International Maritime Organization (IMO) Convention for the Prevention of Pollution from Ships (MARPOL 73/78) has addressed the delivery of ship-generated waste and cargo residues via initiatives promoting PRF availability and enhancing suitability. The requirements that limit the types of waste discharged into the marine environment have been adopted as part of Annex V of the convention, which sets restrictions on handling waste, including all food, domestic, and operational waste.

An example of the measures endorsed at a regional level concerns the European Union (EU), where institutions have adopted and regularly reform directives that aim to enhance the presence of effective PRF in European ports. This directive applies only to ship operations in EU ports, addressing in detail the legal, financial, and practical responsibilities of the different operators involved in delivering ship-generated waste and cargo residues.

3. Strategies for the Circular Economy in Ports

Implementing CE strategies requires the involvement and commitment of many stakeholders and **demonstrable benefits**. It also involves social and organizational changes supported by economic and legal tools.

A. Path creation toward circularity

The specific challenges brought by CE for ports in the fields of material sourcing, land management, energy management, and waste management were discussed in the previous sections. These challenges include knowing the contribution of a particular economic activity, such as a port service provision, to the environment, equipping the labor force with the relevant skills, raising awareness, and increasing the capacity of involved business entities, modifying linear economic systems, developing and investing in new business models, changing behavior and relationships between consumer and producer liability regimes, pricing goods and services to reflect full costs and set up policies that promote circular economy.

From a strategic perspective, it is important to acknowledge that **circularity in ports is to be perceived as a long-term transition with path dependency mechanisms**. This implies that a successful circular transition is a step-by-step process in which small-scale opportunities for closing material flow cycles are identified and seized (for example, two companies in the port area linking waste streams), opening up opportunities for new and larger projects or initiatives. It also underlines the risks of hyping the potential of circularity with inflated expectations. While port **authorities and other stakeholders might set large-scale, long-term ambitions regarding circularity** as part of strategic planning processes, practical implications often involve a **growth path from isolated circular initiatives involving only a few actors to more integrated port-wide plans and projects**.

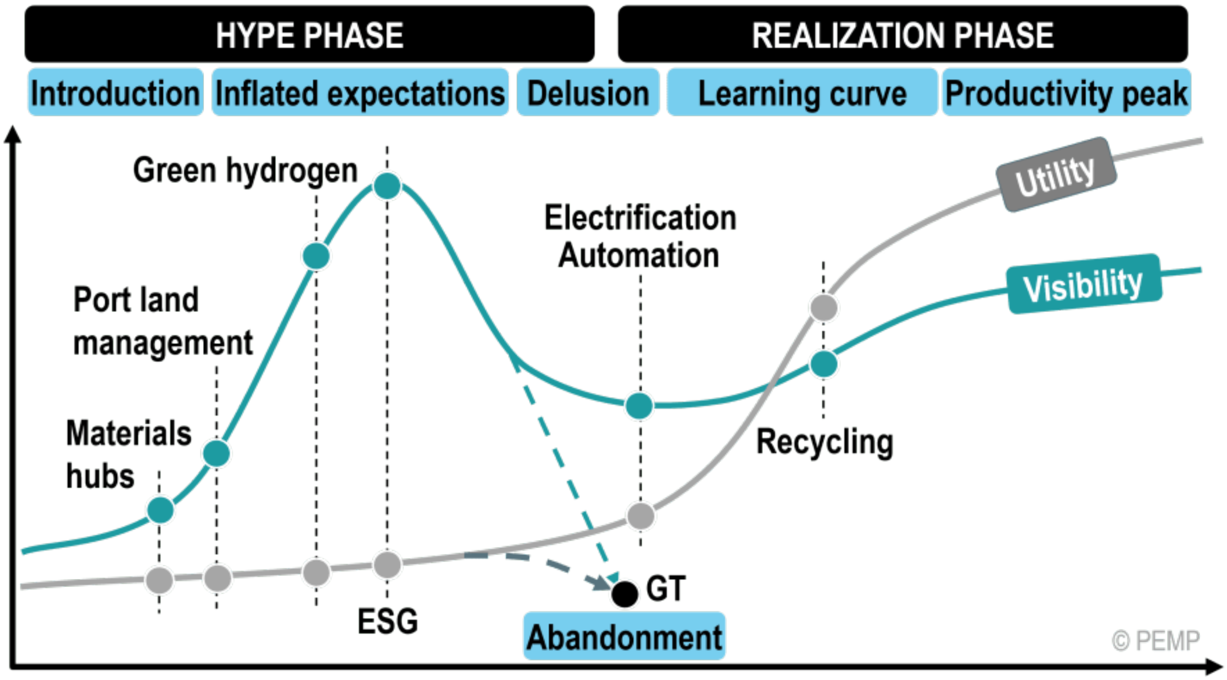


Figure 24. Technology Hype Cycle and the Port Circular Economy

Since port circular processes are a relatively recent endeavor relying on technologies and concepts that have not been fully formalized, they can be subject to hype cycles. There is a potential that some aspects of circularity can be exaggerated and may lead to **delusion** and even **abandonment**. This path dependency is not assured, but a realistic assessment of each port circular process needs to be considered to avoid a backlash from funders, policymakers, and the general public. Although each port may have a different potential for the realization of circularity, the following can be currently assumed:

- **Introduction**. Some circular processes are being introduced in some ports as test cases, most of the time with high levels of subsidies. For instance, material hubs have yet to demonstrate their supporting role fully. A more inventive process of port land management is underway, particularly in ports in transition, but the costs and risks of brownfield sites can lead to a reassessment.
- **Inflated expectations**. The issue of green hydrogen can be the subject of inflated expectations due to the difficulties and high cost of procuring fuel on a scale relevant to maritime shipping. ESG (Environmental Social Governance) financing has been more controversial, associated with massive capital misallocations on projects with limited or no returns or forcing corporations to comply with policies imposed by external actors with unproven benefits.
- **Realization**. Electrification and automation are well-proven technologies that have gradually been implemented into port terminals because of the measurable operational benefits. Still, these strategies are complex and capital-intensive, not necessarily available to smaller ports. Further, recycling has a long-standing implementation in the

maritime industry, particularly concerning dismantling ships and containers. Recycling is being expanded to include circular processes such as reuse and remanufacturing as well as better mechanical and chemical processes for recycling.

Most circular initiatives have not yet reached the productivity peak, when the principles are effectively implemented, leading to productive outcomes.

Circularity in ports can only materialize when acting in an entrepreneurial way. The existing technological, economic, and governance-related knowledge and know-how and the relationships and interactions between actors in the port community are the starting point. Such an entrepreneurial approach is expected to eventually generate multiple 'small wins' that have the potential to accumulate in a much more profound circular transition in the port. In that sense, a port will have to go through a transitional stage before growing into a truly circular port in the longer term.

	CONVENTIONAL PORT	TRANSITIONAL PORT	CIRCULAR PORT
INPUTS Land Capital Energy Equipment Labor	• Focus on greenfield projects. • Diesel-powered equipment. • Carbon-related electric generation. • RoR investments.	• Circular clauses in concessions. • Land reuse and redevelopment plans. • Electrification and automation projects. • Energy transition projects. • Environmental accounting.	• Circular port land management. • Complete electrification and automation. • Renewable energy generation and distribution. • ESG financing (?).
OUTPUTS Cargo handling Connectivity Emissions Wastes	• Supporting linear maritime supply chains. • Shipping corridors. • Most port-related wastes discarded.	• Implementation of circular projects. • Setting green corridors. • Port-related waste recycling projects. • Emissions measurement and control.	• Supporting maritime circular supply chains. • Green corridors connectivity. • Port as material sourcing hub. • Extensive recycling and reuse of port wastes. © PEMP

Figure 25. Circular Economy Transition Phases for Ports

A port can transition to a circular port through a series of phases and the related actions concerning its major inputs (land, capital, energy, equipment, labor) and outputs:

- **Conventional port**. Tend to focus on greenfield development projects and the port is challenged by the reconversion of existing sites that are underused or abandoned. Most of the equipment is powered by fossil fuels, and fossil fuels may also generate electricity. Financing for infrastructure, superstructures, and equipment is predominantly assessed on a rate-of-return (RoR) basis, with limited consideration of environmental accounting. The port acts as an intermediary location in supporting linear supply chains with the handling and transit of import and export cargoes. The port is connected to the shipping network through scheduled services with ships powered by bunker fuels. Wastes generated by port activities are partially recycled, but most end up in landfills.
- **Transitional port**. The land footprint of the port is more comprehensively managed with strategies aiming at reusing brownfield sites with new activities, but greenfield development projects are still common. Efforts are made to electrify the equipment with labor partially

substituted through automation and digitalization. Energy transition projects are implemented, including alternative energy sources and surplus heat distribution. Circular economy projects such as material exchange platforms begin to be implemented to identify opportunities. In particular, hubs for material recovery and reuse are being set. Most port emissions and waste generation are being identified and monitored. Further, green corridors, both at the foreland and hinterland, are set with a reliance on alternative fuels.

- **Circular port**. Land management is fully integrated with strategies to reuse all the brownfield sites under the port's jurisdiction, with greenfield developments uncommon. Most terminal activities have been automated and electrified. Several activities related to renewable energy generation and distribution are present, allowing port activities to be supplied with renewable heat and electricity. The financing and environmental reporting are mainly undertaken through ESG guidelines. Cargo handling has been integrated within circular supply chains, and connectivity is mainly achieved through green corridors. The port becomes an effective material sourcing hub with recycling and reuse processing techniques for different materials, products, and waste streams. Port-related wastes are close to being fully recycled and reused and made available to other activities.

The transition to circularity is related to a path dependency by type of terminal, implying that a series of decisions lead to outcomes locking in the facility. This is commonly the case when a commitment is made to a specific technology, such as yard equipment, locking the terminal into an operational business model.

Integrating circularity into seaport planning involves designing and operating seaports with sustainability and resource efficiency in mind. In general, CE activities need to develop at three different levels:

- **Micro-leve**l. Focus on improving the environmental performance of individual companies involved in port activities by reducing resource consumption and pollution discharges or designing more environmentally friendly services.
- **Meso-level**. Focus on networks that improve regional systems and environmental protection, energy cascading, exchanging by-products, recycling waste, and, when possible, sharing infrastructures.
- **Macro-level**. Focus on port-related communities (i.e., regions, cities, municipalities, or provinces) that might facilitate the development of a sustainable port services provision and use system.

Existing CE initiatives at ports already range from the **micro-level**, such as reusing waste streams within a single port or service provider, to the **meso-level**, such as industrial symbiosis between two or more companies at a port, to interregional port-industry networks for the exchange of secondary resources at the **macro-level** (e.g. the Bioport of Europe project of the Port of Rotterdam). The initiatives have varied from short-term demonstration projects (see, e.g. the Port of Antwerp Sustainability Strategy), to more innovation and optimization-focused medium-term initiatives (see e.g. the Biopark Terneuzen project of the Port of Zeeland), to long-term vision strategies.

B. A system thinking approach

> *Integrating circularity in seaport planning and operations **demands a systems thinking approach.***

Port authorities and port-related stakeholders should consider the **interconnectedness and interdependence of various elements within a system** when addressing challenges related to the path toward circular processes in ports. To consider the environmental, social, and economic aspects of circularity in ports holistically, system thinking also requires understanding the interactions and interdependence of various elements within the system, such as materials, energy, technology, land, governance, and human behavior. Changes in one part of the system can have ripple effects throughout the entire system over time. For circularity to gain traction in ports, all actors involved should gain an understanding of the dynamic nature of the system, thereby recognizing that it evolves and adapts over time and should be able to adapt to changing conditions and uncertainties, namely through resilience.[21]

Synchronism considerations are part of the system thinking approach. Not all elements within the system will develop at the same speed, leading to time lags and bottlenecks in the development of ports towards more circularity. For example, a lack of funding, scarcity of land, limited supply of material flows for recycling, non-optimal governance arrangements, or constraining regulatory frameworks are some of the reasons that can stall the development of a circular project in a port. By adopting a systems thinking approach in circularity, stakeholders can develop more effective strategies and interventions that address the complexity and interconnectedness inherent in sustainable and circular practices.

C. Self-assessment and monitoring

Port ecosystems should engage in **circular economy self-assessment**. Ports are challenged to assess the current operations of the seaport to identify areas where circularity principles can be applied. This may involve thoroughly analyzing the materials and resources flowing through the port, waste generation, and energy consumption. The setting up of a port-based material exchange platform (see Box 6) can help achieve this, but other initiatives to improve transparency on flows, projects, and plans in the CE context are welcomed.

Performance measurement **and monitoring** also play a key role in supporting the circular transition in ports. In view of assessing the circular port efficiency and port effectiveness, key performance indicators (KPIs) can be developed and implemented to measure and follow up on circular economy aspects in ports. Implementing performance metrics also helps track the progress of circularity initiatives within the seaport. Some port authorities (such as Copenhagen Malmo Port) have already developed monitoring practices in this field, while broader monitoring exercises have been designed recently, such as the Circular Port Monitor. This monitor provides a concrete framework of 12 indicators tracking the progress towards a circular port. It provides port authorities with a monitoring system of the progress of and performance towards circularity and allows the formulation of the next steps for the gradual advancement of circularity ambitions. Still monitoring progress towards **circular goals** is at an early stage of documentation, exploration, and implementation.

Box 11. Potential Indicators for Monitoring Port Circular Processes

INDICATOR	UNIT
Number of CE business activities located in the port area.	Absolute value
Number of CE projects in the port area	Absolute value
Share of CE start-ups in the port area which make use of incubation services	Percentage (%)
Share of tender specifications which include a circular procurement policy	Percentage (%)
Share of port companies which are members of a CE platform/s in the port cluster	Percentage (%)
Share of non-recyclable waste generated onboard ships	Percentage (%)
Share of cargo volume of end-of-life materials	Percentage (%)
Share of non-recyclable waste generated in the port area	Percentage (%)
Share of hectares of CE activities in port area	Percentage (%)
Share of direct employment from CE activities and projects in port area	Percentage (%)
Amount of end-of-life material processed in the port area	Tons, Litres, kilojoules
Share of secondary material consumption in the port area © PEMP	Percentage (%)

Figure 26. Circular ports monitor[22]

Monitoring progress toward circular goals is at an early stage of documentation, research and implementation. A concrete framework tracking the progress towards a circular port has been developed and tested in the context of the Circular Flanders activities.

This **Circular Ports monitoring framework** offers a set of 12 indicators that provide Port authorities with a monitoring system of the progress of and performance towards circularity and allow the formulation of the next steps for the gradual advancement of circularity ambitions.

The 12 selected indicators are:

1. **The number of CE business activities located in the port area.** The indicator directly relates to the number of CE business activities in the port area. A circular (business) activity is defined as an initiative that passed the minimum efficient scale or pilot phase, moving to a greater maturity level.
2. **The number of CE projects in the port area.** A circular project is defined here as a temporary circular initiative that has recently started. It has not yet passed a minimum efficient scale. The initiative is still in a pilot or test phase and is mostly financially supported by one or more organizations.

3. **Share of tender specifications that include a circular procurement policy.** This indicator relates to the circularity of port infrastructure and governance measures used by Port authorities. Circular requirements referred to in tender specifications could include, but are not limited to, building infrastructure modularly or requiring that a minimum percentage of the used materials be secondary.
4. **Share of CE start-ups in the port area which uses incubation services**. The indicator indicates the R&D and services that can be used to push circular initiatives to become economically more robust. Incubators can provide start-ups with services related to, amongst others, administration and applications for subsidies. The idea is that CE start-ups that use incubation services will grow faster and further than those that do not and, therefore, have a higher long-term potential. Embedded in this indicator is another value: the number of CE start-ups in the port area. This gives an idea of the CE innovation in the port area. Examples of incubation services include Prodock (Port of Amsterdam) and Circular Kickstart (Antwerp, Ghent, Bruges).
5. **Share of port companies which are members of a CE platform/s in the port cluster**. The indicator introduces the notion of a CE platform. This network of actors and players enhances collaboration, innovation, and/or knowledge transfer. The more members it holds, the greater its value resulting from synergies. This is particularly relevant in the context of the CE because it facilitates industrial symbiosis. For example, the production waste of one port company can be used as a valuable input in the production process of a different port company (An example of a CE platform is Smart Delta Resources (North Sea Port, Belgium/Netherlands).
6. **Share of non-recyclable waste generated onboard ships**. The indicator relates to waste generated onboard ships, particularly the non-recyclable waste. In this case, the recyclable waste deposited at the port reception facility is assumed to be recycled. The non-recyclable waste, however, is disposed of. Existing codes defined internationally (such as the "D-codes' developed by the European Union institutions) allow for distinguishing recyclable from non-recyclable waste.
7. **Share of cargo volume of end-of-life materials.** The indicator has two components, namely, (a) import and (b) export, and identifies the volume of the cargo streams that relate to the CE, i.e., how the CE transition is reflected in ports' cargo streams.
8. **Share of non-recyclable waste generated in the port area**. Analogous to indicator no 6, this indicator concerns waste generated in the port area- the assumption is made that recyclable waste collected by the waste collection system is indeed recycled.
9. **Share of hectares of CE activities in the port area**. This indicator relates to the land use within the port area and to what extent land is used for circular activities. The calculation is straightforward for concessionaires whose activities are fully circular, as the whole plot area can be included. However, for plots where circular activities are only a part of the total activities taking place, the feasibility of providing an accurate value is limited.
10. **Share of direct employment from CE activities and projects in the port area**. This indicator considers the issue of employment in the CE. Employment is an important factor for ports' social license to operate, which makes it worthwhile to know how the CE transition

may affect this. The feasibility of measuring this indicator depends on whether the circular activities comprise the total business activities.

11. **Amount of end-of-life material processed in the port area**. This indicator is made up of four components: (a) material (tons), (b) water (liters), (c) energy (kilojoules) and (d) CO_2 (tons). It relates to the processing of end-of-life material. Here, processing pertains to recycling and encompasses other R-levels, such as re-manufacturing, repair, and processing for internal and external reuse. Material, water, energy, and CO_2 are prepared to be used as a new input. These are the main types of resources given a second life in the port area.
12. **Share of secondary material consumption in the port area**. This indicator relates to the use of secondary material in the port area. Its four components are the same as those of the previous indicator: (a) material (tons), (b) water (liters), (c) energy (kilojoules) and (d) CO2 (tons). This indicator provides insight into using secondary materials instead of virgin materials by port companies.

While the exercise is admittedly a "work in progress", it provides a valuable instrument to **ports for developing competitive advantages in the circular economy and benchmarking themselves against their competitors**. A common set of relevant circular indicators that can potentially raise the circular ambitions of ports allows for baseline, follow-up, and benchmarking analysis. These circular indicators would also support the possibility of aggregating information across ports and show their collective efforts for society in this transition.

D. The governance of circularity in ports

Implementing circular principles in ports requires the consideration of a series of governance challenges:

- **Intermediaries for configuring, brokering, and facilitating circular transition efforts.** Intermediation helps to balance the many different objectives and efforts in the complex network of port-related actors and stakeholders. A wide array of public and public-private organizations can be instrumental in community building and leadership toward circular transition. A good example is Circular Flanders in Belgium.
- **The role of the port managing entity.** Port authorities play a central role as active community builders, engaging policymakers across different policy areas and levels of governance, as well as various stakeholders in the circular port transition. Port governance settings have to be aligned to make it possible to fully benefit from the port's managing entity's position between actors and networks so that the port authority engages as an intermediary in the port's circular transition and is a leader in building-related communities with the port ecosystem. Port authorities might advance processes reducing, incentivizing, and supporting waste reduction and high-quality separation of generated waste, enabling industrial symbiosis, facilitating the clustering of activities to prevent by-products from becoming wastes, advancing new business models, and encouraging wider and better consumer choices. While they aim to decarbonize their footprint in the energy transition process, port authorities can also stimulate emission reductions of the main

emitters. Within the wider port area and to benefit the wider economy and community, port authorities can be the facilitator, enabler, developer, and integrator of renewable energy streams and supply chains and stimulate energy transition initiatives in the port.

- **Community building and collaboration** enable the collaborative resolution of common issues, the development of case studies that can act as blueprints to accelerate the take-up of initiatives, the realization of the essential incremental phases, and any (de)regulatory needs and the required transitional phases. It can also bring CE-related projects to reality (i.e., not being overambitious) and, not least, increase investments in advancing circularity. As circular projects are not necessarily interconnected, and their contribution might not be entirely visible and understandable by all involved in the port ecosystem, the level of voluntary investments by individual entities might be otherwise low. As cluster and community managers, port authorities have a specific role in engaging and stimulating collaboration with local governments, environmental organizations, and businesses to exchange best practices, share resources, and align goals for CE in ports.[23] Through cluster governance of the circular port transition, the port authority might even assume leadership in aspects that conventionally were outside its jurisdiction, such as various strategies to monitor and improve circular performance, setting up material flow analysis tools, and facilitating relations with its surrounding urban areas on circular port issues. The leadership of the port authorities creates conditions for increased levels of investments in advancing port circularity.

Box 12. Benefits of the Leadership of Port Authorities in Promoting Circularity

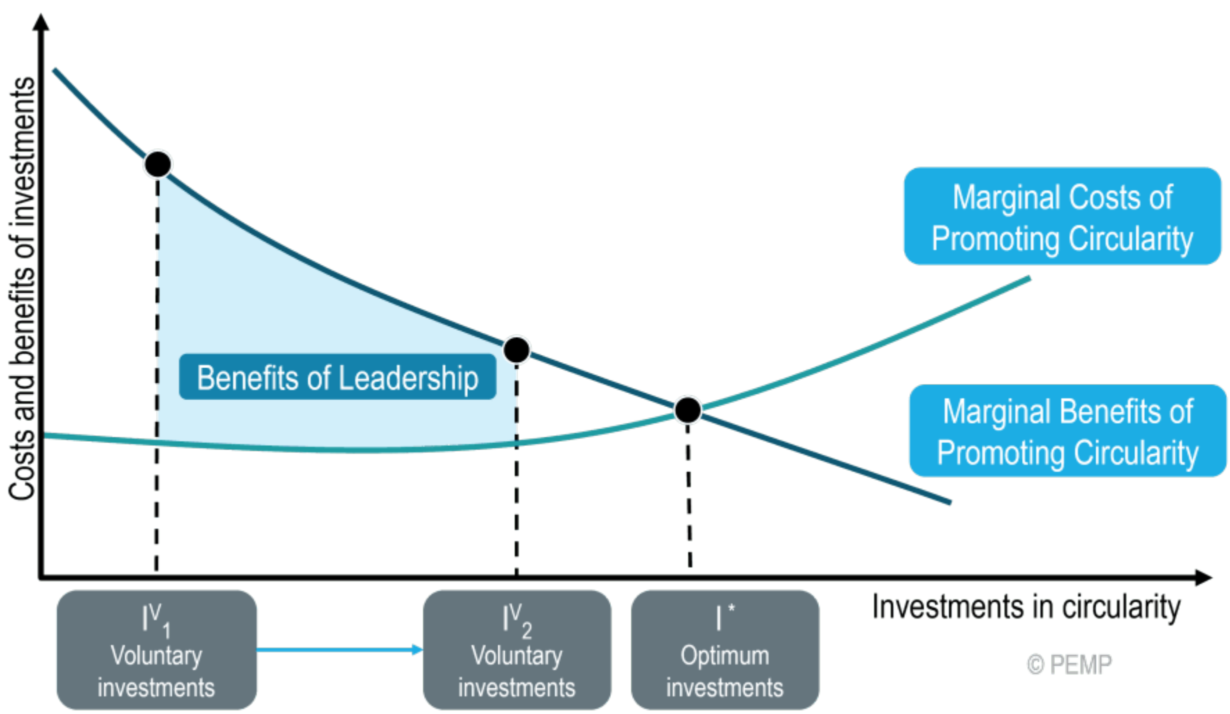


Figure 27. Benefits of the Leadership of Port Authorities in Promoting Circularity

The leadership of the port authorities creates conditions for increased investments in advancing port circularity. By assuming a leadership role, port authorities are the active community builders engaging policymakers across different policy areas and levels of governance, as well as various stakeholders, in the circular port transition.

Substantial investments condition circularity in any given port. However, ports are complex ecosystems with multiple service providers, users, and stakeholders who might not necessarily devote resources and invest alone in initiatives enhancing the circular transition. This is because the benefits of such initiatives might not be visible, individual entities might endorse different hierarchies, or simply because the impact of investments by a single actor alone might not be considerable. The level of voluntary investments is considerably lower than the optimum level (I).*

Port authorities might advance processes, incentivizing, supporting, and, thus, enabling the clustering of activities. They might also introduce new business models and encourage broader and better CE-related investments and choices. In addition, port authorities can be facilitators, enablers, developers, and integrators that stimulate circularity transition initiatives in the port.

Besides, as cluster and community managers, port authorities have a specific role in engaging and stimulating collaboration with local governments, environmental organizations, and businesses to exchange best practices, share resources, and align goals for CE in ports. Through cluster governance of the circular port transition, the port authority might even assume leadership in aspects that conventionally were outside its jurisdiction, such as various strategies to monitor and improve circular performance, setting up material flow analysis tools, and facilitating relations with its surrounding urban areas on circular port issues.

Port authorities can potentially be the crucial intermediaries in transitioning the many different sectors that intersect in ports. Intermediation helps to balance the many different objectives and efforts in the complex network of port-related actors and stakeholders.

E. Focus areas

Implementing port circular processes can particularly focus on the following approaches:

- **A focus on resource efficiency**. Port infrastructure and facilities need to be planned, designed, and operated to minimize resource consumption, such as energy, water, and raw materials. This includes, for example, energy-efficient lighting, renewable energy sources, and water recycling systems.
- **A focus on sustainable transportation**. This does not only involve using low-emission and energy-efficient transportation methods, such as electric or hybrid vehicles, for cargo handling and transport. It also assumes a sustainable modal split in the connection to the hinterland.
- **Digitalization and smart technologies.** Digital technologies and data analytics are not only important to optimize port operations. They can also help improve resource allocation,

reduce energy consumption, provide transparency in material flows, and enhance overall circular efficiency.
- **Circular business models**. Port authorities can encourage port-related businesses to adopt circular business models, where products and materials are designed for reuse, refurbishment, or recycling.
- **Research and innovation**. Port authorities can support research and innovation initiatives to find new circular solutions, technologies, and practices for seaports.
- **Public awareness and education**. Educating port stakeholders and the general public about the importance of circularity in seaports is key to making the transition feasible and fostering a sense of responsibility and sustainability within the community.
- **Regulatory compliance**. Port authorities should ensure the port complies with relevant environmental and sustainability regulations and standards. At the same time, the broader port community should provide input and feedback about the regulatory environment, such as when complex and inconsistent regulations complicate the CE transition in the port.
- **Financial considerations**. The circular transition involves significant needs for finance and investment. Port authorities, in cooperation with relevant stakeholders, should carefully estimate and assess the upfront investments needed for circular projects and the associated return on investment. Also, the link with sustainable finance is an important consideration when engaging in circular projects in a port context.

Other focus areas in the fields of material sourcing, land management, energy management, and waste management were discussed in the previous sections.

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