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« Maritime ports and the energy transition challenge »

The International Maritime Organization (IMO) committed to reducing the global fleet's total greenhouse gas (GHG) emissions by 50% by 2050, while cutting ships' carbon intensity by 40% by 2030 and 70% by 2050. Concurrently, in 2020, the European Commission adopted a strategic proposal aiming to slash GHG emissions by at least 55% by 2030, setting the EU on a strict trajectory toward absolute climate neutrality by 2050. Achieving this milestone mandates a 90% reduction in transport sector emissions. Every single transport mode, including maritime shipping, must actively contribute to these mitigation efforts. The objective also targets reinforcing the resilience of the Union's energy architecture—currently over-dependent on Russian fossil fuels—and fostering the rapid scaling up of sustainable alternative fuels. While these targets are commendable, they demand concrete implementation measures. Ports, as the ultimate nerve centers of our globalized economy, concentrate the supply chains of manufactured goods, food commodities, and energy. Tomorrow, they must or will become "green flow integrators." Within the French landscape, ports have for decades relied on a commercial model where 50% of traffic depends on hydrocarbon flows; furthermore, they must cope with rising operating costs, notably fiscal charges. The economic model of French Major Sea Ports (GPM — *Grands Ports Maritimes*) is therefore structurally fragile and highly exposed to these emerging challenges. One can then legitimately ask: Are the imperatives of the ecological transition synonymous with brand-new commercial opportunities for ports, or do they risk destabilizing port economic architectures even further?

Context and operating environment

Decarbonization within port boundaries encompasses several overlapping strategic and operational domains: the electrification of port handling equipment, Onshore Power Supply (OPS) for vessels at berth, clean fuel bunkering infrastructures, renewable energy production on port-owned land, and the deployment of more complex handling, storage, and energy conversion technologies. It also involves industrial ecology mechanisms and, more recently, geo-engineering solutions such as Carbon Capture and Storage (CCS), alongside supporting the decarbonization of industrial clusters embedded within these industrial-port zones (ZIP — *Zones Industrielles-Portuaires*).

Operational trade-offs must be executed between these alternative solutions depending on the port's specific profile, its geographical location, its industrial-port ecosystem, its customer base, its available resource reserves, its potential commercial outlets, its legacy infrastructure, and its hinterland connectivity—but also the local context surrounding the social acceptability of such infrastructure developments.

To each of these strategic items are applied specific criteria in terms of infrastructure development, identification of the most strategically attractive investments, spatial planning adjustments, innovative commercial business models, supply chain connectivity, and potentially brand-new administrative responsibilities and technical expertise. Compounding this equation is the acute technological and ecological uncertainty surrounding certain alternative solutions, backed by economic business models that are not yet proven or profitable, which inherently demand upfront public financial support. The societal acceptability of these greenfield industrial activities, particularly when urban zones border the port, can also be severely hindered by the famous NIMBY ("Not In My Back Yard") phenomenon within this future energy mix. Financial support across local, regional, national, and European tiers must irrigate infrastructure requirements, storage capacities, and alternative fuel production while assisting the green retrofit of the existing merchant fleet and the construction of future, more complex, and therefore more capital-intensive vessels.

It must be recalled that ports in France have historically stood as the "poor relations" of transport infrastructure funding. The French Transport Infrastructure Financing Agency (AFIT France) is tasked

with financing transport and mobility infrastructure projects on behalf of the State. In its 2021 annual report, AFIT outlines the structural breakdown of its expenditures: out of a total budget of €3 billion, ports were allocated only €64 million, representing a mere 2.1% of the total budget. The Agency is furthermore embedded in implementing the transport component of the "France Relance" national economic stimulus plan. Out of the €100 billion allocated to this macro-plan, the transport component received €2.66 billion; yet, over the 2020–2021 financial exercise, only 6.4% of this transport budget was attributed to maritime ports.

A fraction of this "France Relance" envelope helped co-finance diversified projects, such as the quayside electrification for cruise ships calling at Le Havre (€2.5 million), improving the water quality of the Seine (€4.6 million), the thermal renovation of a building within the HAROPA Rouen port layout, and the *HyFret* project (focusing on hydrogen production and the deployment of hydrogen-powered switch locomotives for port rail freight operations) at the GPM of La Rochelle. These capital investments are colossal and lock ports into strictly long-term strategies. We will now review three core pathways through which ports are actively working to green the maritime sector: industrial-port ecology, Onshore Power Supply, and the distribution of alternative marine fuels.

Industrial-port ecology

Industrial and Territorial Ecology (ITE / *EIT*) aims to establish a collaborative framework between corporations, industries, and municipalities to create a long-term commitment centered on shared energy and resource exchanges.

The small Danish port town of Kalundborg stands as a global pioneer in industrial ecology, with its operational experience dating back to 1961. Long-term contracts signed between the municipality and local corporations regarding material flows enabled the creation of a closed-loop circular economy system, where waste rejected by one entity systematically becomes a raw material or an energy source for another. Through the deployment of various operational synergies, this cooperation allows the involved companies to optimize their operating costs while reducing their environmental footprint. The geographical proximity of stakeholders, the localized territorial context, and robust governance play a vital role. Furthermore, ITE frameworks actively strengthen the economic attractiveness of these territories by highlighting complementarities between industrial activities, thereby attracting greenfield investments.

While Kalundborg served as Europe's primary benchmark for decades, France—via ADEME—has for several years been backing the development of domestic ITE frameworks. The agency works toward defining a common methodology and metrics, notably the *ELIPSE* benchmark managed by the *Orée* association, while deploying software tools (such as *Act'IF*) to collect and map out industrial flows to identify potential regional synergies. ADEME also launches regional and national calls for proposals and structures the *Synapse* network, which federates industrial ecology stakeholders across France.

The French national carbon neutrality strategy is embedded within the "France 2030" macro-investment plan. A budget of €5.6 billion is dedicated to industrial decarbonization and climate commitment compliance, including €610 million earmarked to finance technological innovation and the deployment of low-carbon industrial solutions. One of the flagship calls for proposals launched in September 2022 aims to foster the development of "Low-Carbon Industrial Zones" (ZIBaC — *Zones Industrielles Bas Carbone*). The major sea ports of Dunkirk, Nantes Saint-Nazaire, and Marseille respond directly to this tender. The Port of Marseille already operates a dedicated industrial innovation hub in Fos spanning 130 hectares under the PICTTO platform framework (established in 2015). Concurrently, Dunkirk leverages a long-standing expertise in industrial ecology through the *Ecopal* initiative, active since 1999. This port-bound industrial ecology dynamic encompasses around twenty structures across metropolitan and overseas France, ranging from initial design phases to concrete project materialization (the animation and implementation of synergies). These frameworks remain deeply grounded upon operational execution and concrete project rollouts: steam networks, energy transition demonstrators, industrial co-product recycling loops, and the pooling of requirements through purchasing cartels, material flows, and energy exchanges.

Onshore Power Supply (OPS)

The onshore electrical connection of vessels at berth allows ships to shut down their auxiliary diesel engines while meeting their onboard energy requirements through the shoreside terrestrial electrical grid. This operational architecture completely eliminates ship-source emissions of sulfur oxides

(SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2), and fine particulate matter (PM_{10}), while eradicating localized noise nuisances.

Onshore Power Supply (OPS / *courant de quai*)

) demands massive capital expenditures, typically hovering around €3 million per equipped berth. The European Commission's proposal for an Alternative Fuels Infrastructure Regulation, known as the AFIR Regulation, mandates the provision of onshore electricity for container ships, passenger vessels, and Ro-Pax ferries across all core and comprehensive ports of the TEN-T network by 2030 (Article 9)¹.

This binding mandate will apply to all gateway ports exceeding a minimum threshold of annual port calls made by vessels over 5,000 gross tonnage (GT) within each respective shipping segment: namely, 40 ferry calls, 25 cruise ship calls, and 50 container ship calls per calendar year. Vessels remaining at berth for short durations (under two hours), ships deploying specified alternative zero-emission technologies on board, and unscheduled port calls executed strictly for emergency safety reasons are excluded from the scope of application. It should be recalled that ships' emissions at berth account for only 6% to 7% of the maritime transport sector's total GHG footprint².

The European Sea Ports Organisation (ESPO) would have preferred the Commission to adopt an approach based on traffic volumes per terminal rather than per port. The organization cautions against a systematic, blanket deployment of Onshore Power Supply (OPS), which could prove counterproductive if its utilization rate remains marginal and unsuited to the profile of calling vessels. The deployment of onshore power is fundamentally suited for ports receiving vessels on a regular, predictable basis, at the exact same berths, and with long turnaround times at dock. A systematic development unaligned with actual operational needs risks resulting in a waste of public funds through infrastructure under-utilization, while draining the budgets allocated to alternative shoreside decarbonization investments. Providing electrical power to a single mega-container ship is roughly equivalent to supplying 1,000 households. The terrestrial electrical grid must therefore be structurally resized to cope with these sharp consumption peaks, demanding rigorous grid stability studies to prevent any catastrophic blackout scenarios. Furthermore, heavy capital investments in frequency conversion infrastructures are required: European grids operate at 50 Hz, like a large portion of networks worldwide, whereas the standard operating frequency in the United States runs on 60 Hz.

Beyond this technical complexity, OPS represents a major public policy challenge. These infrastructure investments are predominantly financed by public authorities. By way of illustration, the port complex of HAROPA will allocate €20 million by 2025 for the deployment of quayside electrification at the Le Havre Cruise Terminal, enabling three cruise ships to plug in simultaneously³. Prior to the Covid crisis, the Port of Le Havre received up to 140 cruise ship calls per calendar year.

In Marseille, since 2017, Ro-Pax ferries operating on Corsican trade lanes have been actively experimenting with onshore power connections. The GPMM (*Grand Port Maritime de Marseille*) aims to establish three brand-new installations for another passenger terminal by 2023. This capital investment is estimated at €14 million, though the financing round is not yet completely finalized. The most environmentally compliant shipowners will benefit from a 20% reduction in port dues. Beyond ferries, cruise ships are the primary segment exacerbating local tensions between coastal residents, port professionals, and the tourism industry. Prior to the Covid-19 pandemic, Marseille could accommodate up to 500 cruise ship calls per year. The OPS project for cruise liners is slated for delivery in 2025, with the municipality contributing up to €10 million to the funding pool. However, due to grid power limitations, only two vessels will be capable of plugging in simultaneously.

Shipowners must also retrofit their vessels to enable onshore connectivity, representing a capital investment of €500,000 to €1 million per ship. Crucially, the operational running cost for the shipowner remains two to three times higher than generating electricity on board via auxiliary engines, because they must purchase grid electricity and convert it, while facing the structural problem of the tax-exemption traditionally granted to marine bunker fuels—a historical loophole that stands in stark

¹ The Trans-European Transport Network (TEN-T) is an infrastructure development program within the transport sector of the European Union. It aims to facilitate the connection between road, rail, and inland waterway networks, as well as the ports and airports of Member States.

² Commission staff working document, Full-length report Accompanying the document Report from the Commission 2020 Annual Report on CO₂ Emissions from Maritime Transport

³ The cost of onshore power supply varies depending on the number of required connection points, the cable management system, and the distance to the electrical substation.

contradiction with global policies targeting climate change mitigation. In Hamburg, where onshore power has been available since 2017 for cruise ships, only 19% of total port calls actually resulted in a quayside connection. While the European Commission aims to make the use of OPS mandatory, strategic reflections could also expand to govern vessels' waiting times at anchorage. Port congestion is not a greenfield phenomenon; it was severely exacerbated during the pandemic and remains highly topical due to a persistent lack of traffic normalization.

Alternative marine fuels

There is no turnkey, ready-made fuel alternative capable of directly substituting heavy fuel oil (HFO). Multiple operational options coexist, spanning LNG, methanol, ammonia, synthetic fuels, and hydrogen—though for several of these, the actual lifecycle environmental benefit remains to be verified. Regardless of the alternative energy pathway selected, the price delta between conventional petroleum-derived marine fuels and renewable or low-carbon fuels remains exceptionally high. Methanol and LNG are predominantly derived from fossil energy sources, much like 95% of current global hydrogen production. Furthermore, the taxonomy and classification of green energies by regional governance bodies, such as the European Union, remain a subject of intense debate and occasionally raise sharp, structural contradictions.

European Taxonomy

Eurodeputies recently approved the 'green' label granted by the European Commission to gas and nuclear energy, two energy sources recognized as necessary to combat climate change. Previously, only renewable energies benefited from the 'green' label. The objective is to decommission coal-fired power plants and phase out fossil fuels as quickly as possible. This triggered the anger of selected environmental organizations that denounce a 'greenwashing' operation. The European executive estimates that renewable energies alone will not be able to meet the growing demand for electricity due to their intermittent production. Hence the requirement, on a transitional basis, to also foster investment in stable and dispatchable power sources such as gas and nuclear energy.

The choice of fuel or technology varies depending on the vessel segment, its itinerary, fuel availability, pricing, associated operational constraints, and potential regulatory shifts. Some vessels could combine alternative fuels and propulsion technologies. This versatility makes it highly complex for ports to adopt a clear, long-term strategic vision and execute the associated infrastructure investments.

The options are vast, and the constraints regarding storage and bunkering are equally challenging. Compared to conventional diesel, alternative fuels such as LNG, ammonia, and liquid hydrogen require two, three, and four times more storage space respectively. Safety protocols are significantly more demanding. Liquid hydrogen storage must be maintained under tight cryogenic conditions at -253°C. Ammonia demands specialized storage and fuel transfer infrastructures constructed entirely from stainless steel to prevent leak hazards and mitigate corrosion risks facing alternative alloys (such as plastic, copper, and nickel). It is a highly toxic and chemical product, necessitating supplementary safety equipment, including emergency ventilation and gas absorption systems.

This dynamic leads back to the classic chicken-and-egg dilemma: should ports or shipowners invest first? Some shipping lines have already taken firm positions: CMA CGM within the container sector, alongside Carnival and MSC inside the cruise industry, while Brittany Ferries, Baleària, and soon Corsica Linea are initially wagering heavily on LNG.

In a second phase, innovation will center on the deployment of alternative e-fuels manufactured directly within port boundaries. Among active projects, the partnership between CMA CGM and Engie stands out, targeting the production of biomethane in Le Havre to supply its LNG-fueled container ship fleet. Named Salamandre, the project will rely on pyrogasification utilizing dry biomass salvaged from local wood waste and solid recovered fuels (SRF). CMA CGM is also participating in the Jupiter 1000 project in Fos-sur-Mer, which aims to manufacture decarbonized e-methane to address the decarbonization challenges of the gas grid and mitigate the intermittency of selected renewable energies. Ports will also be directly impacted by green hydrogen production, even if its future end-use will not encompass large-format transoceanic maritime transport.

Maersk targets having its first carbon-neutral vessels operational as early as 2023, aiming for absolute carbon neutrality across its entire footprint by 2040. Numerous ocean carriers share this ambition,

pivoting toward green methanol, ammonia, and/or advanced biofuels. While ammonia is actively envisioned for long-haul transoceanic maritime shipping, hydrogen will undoubtedly be reserved for smaller coastal units and harbor crafts. Industrial-port zones (ZIP) will be directly integrated within the manufacturing loops of these alternative fuels. Beyond local production, the overarching question of supply chains remains paramount—a challenge directly addressed by the Clydebank Declaration and its framework concept of "green shipping corridors."

Green shipping corridors and the future of port architecture

On the fringes of COP26, the international climate summit, around twenty countries, including France, committed to making six maritime trade routes entirely carbon-free by 2025. These trade lanes are projected to be navigated by 200 zero-emission vessels by 2030. The establishment of "green shipping corridors," encompassing port authorities, terminal operators, shipping lines, shippers, and stevedores, aims to create a zero-emission transport loop between twin ports while simultaneously stimulating both the supply and demand for alternative marine fuels. Numerous ports are beginning to operate within this framework to promote and facilitate the introduction of zero-carbon bunkering.

However, does the emergence of these green corridors not risk concentrating maritime flows even further toward a handful of giant, multi-service port hubs equipped with the full spectrum of alternative energies, while secondary ports are left abandoned? In this scenario of ultra-localized and highly specialized maritime gateways, the risk of a counterproductive road modal shift to transport cargo toward the final consumer must be taken into internal accounting. This monopolistic concentration would carry severe social consequences, while undermining the sovereignty of sovereign States whose domestic ports would be relegated to "second-tier" status—effectively reducing them to landlocked States, thus more vulnerable to the strategic dictates of their maritime neighbors.

A rigorous operational simulation was executed across two primary global corridors: the iron ore trade lane between Australia and Japan, and the container shipping route linking Asia and Europe. According to industry stakeholders, three fundamental factors are required to unlock success:

- Securing an absolute consensus on fuel supply pathways.
- Deploying targeted political support to help bridge the cost gap for the most expensive zero-emission fuels.
- Fostering value-chain initiatives to consolidate and lock in cargo demand.

The spatial planning and port architecture of tomorrow are bound to become increasingly complex due to the integration of alternative energy strategies, operational trade-offs demanding brand-new infrastructures, and colossal capital expenditure requirements—all unfolding within a hyper-competitive landscape, potentially marked by global energy shortages or mandated sobriety. It is an entire ecosystem that must execute its structural transformation, and the equation is far from obvious given the prolonged lifecycle of maritime assets. It remains exceptionally difficult for port authorities to adopt fixed, long-term perspectives within a highly uncertain, technologically immature, and likely multi-fuel future. Will we genuinely possess the luxury of choice to completely phase out fossil energies? Ultimately, beyond the environmental footprint of the maritime transport sector alone, strategic reflections must integrate the comprehensive end-to-end supply chain.

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