

Supplementary File

In this Supplementary File, we first introduce the coding framework used in Section 3 of the main manuscript. Then, in Section S1, we provide a summary of port-specific documented decarbonisation initiatives and data sources. In Section S2, we include evidence-based evaluation of documented decarbonisation implementation across 16 UK ports and 17 analytical cases.

In the coding framework, the numerical values are ordered category labels for documented implementation maturity. They are not interval-scale measurements, and equal differences between adjacent values are not assumed. The revised analysis therefore uses category frequencies and distributions rather than arithmetic sums or means. Observable anchors are specified by dimension in Table S1.

- 0 = No public evidence identified within the stated documentary search. This code does not confirm non-implementation.
- 0.2 = Publicly announced feasibility study, plan, procurement activity or time-limited trial.
- 0.4 = Limited operational implementation in one asset, site, route, process or formal programme.
- 0.7 = Established partial implementation across several assets, sites, routes or organisational functions.
- 1.0 = Extensive or dominant operational implementation across the relevant port activity or organisational scope.

Where a meaningful denominator is available, the original thresholds of below 10%, 10-50% and above 50% support the distinction between 0.4, 0.7 and 1.0. For policy, operational and partnership indicators, the dimension-specific documentary anchors in Table S1 are used. Ambiguous evidence is assigned to the lower category. A value of 0 remains a documentation code and is not interpreted as evidence of poor actual performance.

Table S1. Dimension-specific manual for documented implementation maturity coding.

Dimension	Code	Observable documentary anchor
Energy supply and management	0	No public evidence identified.
	0.2	Feasibility, announced project, planning or trial.
	0.4	Operational at one site or asset, or below 10% where a denominator is reported.
	0.7	Established across several sites or assets, or 10-50% where a denominator is reported.
	1.0	Extensive or dominant supply across the port, or above 50% where a denominator is reported.
Infrastructure and equipment	0	No public evidence identified.
	0.2	Design, procurement, readiness study or single pilot asset.
	0.4	Limited operational deployment in one facility or below 10% of the relevant fleet.

Dimension	Code	Observable documentary anchor
	0.7	Established partial deployment across several facilities or 10-50% of the relevant fleet.
	1.0	Extensive deployment across the relevant asset base or above 50% of the fleet.
Operational efficiency	0	No public evidence identified.
	0.2	Proposed system, proof of concept or time-limited operational trial.
	0.4	System operating in one process, terminal or functional area.
	0.7	System embedded across several linked processes or terminals.
	1.0	Port-wide or dominant operational use with routine integration.
Transport connectivity	0	No public evidence identified.
	0.2	Feasibility study, proposed corridor or trial service.
	0.4	Limited operational routes, services, or facilities.
	0.7	Regular partial network coverage across several routes or services.
	1.0	Extensive or dominant network integration across the relevant hinterland or maritime links.
Policy and Regulations	0	No public evidence identified.
	0.2	Public commitment, draft plan or baseline compliance statement.
	0.4	Formal policy, target or procedure with documented application.
	0.7	Policy embedded across several functions with regular monitoring or reporting.
	1.0	Comprehensive port-wide governance, monitoring and public reporting.
Stakeholder partnerships	0	No public evidence identified.
	0.2	Announced relationship or participation in a single exploratory project.

Dimension	Code	Observable documentary anchor
	0.4	Active collaboration with a documented project or recurring activity.
	0.7	Multi-project programme or established cross-organisational partnership.
	1.0	Institutionalised port-wide partnership structure with sustained delivery across several initiatives.

File S1. Summary of Port-Specific Documented Decarbonisation Initiatives and Data Sources

This Supplementary File Section S1 provides supplementary evidence for the comparative analysis in the main manuscript. It compiles the operational characteristics, documented sustainability initiatives and cited sources for 16 UK ports. Southampton is represented by two distinct analytical cases, Southampton (DP World Container Terminal) and Southampton (ABP Estate). The study therefore contains 17 analytical cases.

The five subsections correspond to the port categories analysed in the paper:

- S1-1 – Global Container Gateways,
- S1-2 – Ro-Ro and Passenger Hubs,
- S1-3 – Energy Hubs,
- S1-4 – Offshore-Energy and Project-Cargo Bases, and
- S1-5 – Diversified Multi-Purpose Ports.

Each subsection provides a brief overview and a comparative table (Tables S2-S7). Inclusion indicates that an initiative was publicly documented by the cited source. It does not independently verify emissions reduction, cost-effectiveness or long-term performance. The absence of public evidence should not be interpreted as confirmed non-implementation.

Table S2. Documentary evidence coverage by analytical case.

Analytical case	Distinct source records cited in profile	Evidence location
Felixstowe	5	S3; Port of Felixstowe profile and Table S3
London Gateway	3	S3; DP World London Gateway profile and Table S3
Southampton (DP World Container Terminal)	10	S3; Southampton (DP World Container Terminal) profile and Table S3
Dover	5	S4; Port of Dover profile and Table S4
Belfast	3	S4; Port of Belfast profile and Table S4

Analytical case	Distinct source records cited in profile	Evidence location
Hull	4	S4; Port of Hull profile and Table S4
Southampton (ABP Estate)	2	S4; Southampton (ABP Estate) profile and Table S4
Immingham	3	S5; Port of Immingham profile and Table S5
Milford Haven	2	S5; Port of Milford Haven profile and Table S5
Grangemouth	3	S5; Port of Grangemouth profile and Table S5
Tyne	3	S6; Port of Tyne profile and Table S6
Aberdeen	4	S6; Port of Aberdeen profile and Table S6
Liverpool	6	S7; Port of Liverpool profile and Table S7
Tilbury	3	S7; Port of Tilbury profile and Table S7
Teesport	3	S7; Port of Teesport profile and Table S7
London (PLA)	4	S7; Port of London Authority profile and Table S7
Bristol	3	S7; Port of Bristol profile and Table S7

Note: Counts refer to distinct source records cited in each detailed port profile. Some sources support more than one case or dimension. The complete supplementary reference list contains 64 cited records.

S1-1. Global Container Gateways

This category includes the Port of Felixstowe, London Gateway, and Dubai Ports (DP) World Southampton, which represent the UK's principal deep-sea container gateways and serve as primary testbeds for large-scale decarbonisation initiatives. Comparative operational and environmental data for these ports are summarised in Table S3.

Port of Felixstowe

Energy Supply and Management: The Port of Felixstowe has prioritised renewable energy integration and alternative fuel development as core components of its Decarbonisation strategy. Approximately 2,000 solar panels have been deployed across the port's facilities, ensuring that all electricity consumption is sourced from certified renewable energy such as solar and offshore wind, effectively eliminating Scope 2 emissions [36]. In partnership with ScottishPower, Felixstowe is developing a large-scale green hydrogen production facility with an estimated capacity of 40 tonnes per day; enough to power roughly 1,300 hydrogen trucks. This initiative aims to decarbonise both industrial operations and heavy transport activities, positioning the port as a pioneer in renewable hydrogen logistics within the UK maritime sector [37].

Infrastructure and Equipment: Infrastructure modernisation plays a pivotal role in the port's transition toward net-zero operations. Although full-scale shore power systems are still under assessment, investments in renewable infrastructure indicate a strategic commitment to reducing emissions from

berthed vessels [38]. To tackle direct emissions, Felixstowe has replaced diesel-driven machinery with 17 semi-automated electric Rubber-Tyred Gantry Cranes (e-RTGCs) and 48 battery-powered terminal tractors. These upgrades have significantly reduced Scope 1 emissions while improving operational reliability and efficiency [38].

Operational Efficiency: The port has implemented advanced digitalisation and Internet of Things (IoT) technologies to optimise equipment operations through real-time monitoring and predictive maintenance [36]. This digital transformation enhances energy efficiency and minimises idle energy losses. Additionally, the adoption of semi-automated crane systems has improved precision and reduced fuel consumption, further advancing the port's emission-reduction objectives [38].

Transport Connectivity: Enhancing multimodal transport infrastructure is central to Felixstowe's carbon reduction goals. The port's recent rail infrastructure improvements have facilitated a modal shift from road to rail, effectively lowering emissions associated with inland freight movements and mitigating congestion in surrounding regions [39]. As part of the East of England Freeport, Felixstowe actively participates in developing green freight corridors that support low-emission logistics and align with the UK's national Decarbonisation agenda [40].

Policy and Regulations: Felixstowe has established a clear roadmap to achieve net-zero Scope 1 and 2 emissions by 2035, in alignment with the Science Based Targets initiative (SBTi). This commitment underscores the port's adherence to global emission reduction frameworks and its proactive role in fostering sustainable maritime practices [36].

Stakeholder Partnerships: Collaborative innovation underpins Felixstowe's Decarbonisation approach. Partnerships with Ryse Hydrogen and Cranfield University are advancing research into hydrogen-powered port equipment and the creation of a zero-emission energy hub [38]. Additionally, through its involvement in Freeport East, Felixstowe contributes to regional initiatives targeting maritime Decarbonisation, including the establishment of green shipping corridors and sustainable freight networks [40].

DP World London Gateway

Energy Supply and Management: London Gateway has placed renewable energy integration at the core of its Decarbonisation efforts. The port has installed extensive solar arrays that generate a significant share of the terminal's electricity needs, thereby reducing dependence on fossil fuels and aligning with DP World's global net-zero strategy [41]. In addition, the implementation of shore power infrastructure allows berthed vessels to draw electricity directly from the grid, eliminating emissions from auxiliary engines and improving local air quality. This initiative represents a crucial step toward the port's transition to fully electrified maritime operations [42].

Infrastructure and Equipment: The port has undertaken substantial investments in the electrification of cargo-handling equipment, replacing diesel-powered straddle carriers and cranes with electric alternatives. These upgrades substantially reduce Scope 1 emissions while improving reliability and operating efficiency [41]. Complementing these measures, London Gateway's energy-efficient buildings incorporate LED lighting, advanced insulation, and automated energy management systems. Together, these enhancements optimise energy use across administrative and operational facilities [42].

Operational Efficiency: Through automation and the IoT, London Gateway leverages real-time monitoring systems to track energy consumption and equipment utilisation. These technologies facilitate predictive maintenance and minimise energy waste [41]. Moreover, data-driven decision-making enables optimisation of vessel turnaround times and yard operations, reducing idle periods and associated emissions. This analytical approach strengthens the port's commitment to intelligent, low-emission logistics [41].

Transport Connectivity: London Gateway plays a pivotal role in advancing low-carbon freight transport within the UK logistics ecosystem. The port has expanded its rail infrastructure, enabling a significant modal shift from road to rail and connecting key logistics hubs nationwide. This transition helps decrease overland freight emissions and congestion [43]. Furthermore, London Gateway promotes intermodal transport solutions, including short-sea shipping and integrated rail operations, to diversify cargo movement and reduce reliance on high-emission road freight [42].

Policy and Regulations: DP World's London Gateway is firmly aligned with the UK's national Decarbonisation agenda, pledging to achieve net-zero emissions by 2050 through a comprehensive mix of renewable energy use, equipment electrification, and operational optimisation [41]. The port also maintains strict compliance with UK and European Union (EU) environmental standards, targeting reductions in nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) emissions to ensure sustainable operations in accordance with regulatory frameworks [43].

Stakeholder Partnerships: Collaborative partnerships underpin the port's sustainability initiatives. London Gateway works with environmental organisations on projects involving habitat restoration, carbon offsetting, and local biodiversity protection; initiatives that strengthen its environmental stewardship [42]. Additionally, engagement with the Rail Freight Group promotes the expansion of rail freight as a decarbonised logistics solution, reinforcing the port's leadership in sustainable intermodal transport and supporting the UK's broader emission-reduction objectives [43].

Southampton (DP World Container Terminal)

Energy Supply and Management: At DP World's container terminal in Southampton, 100% of the facility's electricity is sourced from renewable generation. The terminal has secured a "green" electric power supply through its landlord, Associated British Ports [44], ensuring that all grid electricity originates from renewable sources. This transition has significantly reduced the terminal's operational carbon emissions compared with previous reliance on conventional energy sources [45].

Infrastructure and Equipment: The terminal continues to modernise its equipment fleet to minimise emissions. More than 120 straddle carriers are now hybrid or fully electric, substantially reducing diesel consumption compared with older models [42,44]. These next-generation carriers consume up to 20% less fuel than previous diesel-electric units, thereby contributing to notable carbon reductions [46]. By 2024, the hybrid straddle carrier fleet reached 82 units, with additional deliveries underway, establishing hybrids as the majority of the fleet [46]. Diesel-powered yard cranes are being phased out, while charging infrastructure for electric vehicles and port machinery has been installed to accommodate the growing electric fleet [47]. These developments align with DP World's global decarbonisation strategy to deploy fuel-efficient, low-carbon port equipment.

Operational Efficiency: Advanced digital systems are central to operational optimisation at Southampton. The Navis N4 terminal operating system, enhanced with AI-driven analytics, enables efficient container handling and planning [48]. The port has developed digital-twin models of its yard and operational processes, allowing virtual scenario testing to identify bottlenecks before real-world implementation. Real-time IoT data further enables dynamic resource allocation, reducing vessel and truck turnaround times and enhancing productivity [48].

Transport Connectivity: To promote a modal shift to rail, DP World Southampton introduced a "Modal Shift Programme" that provides financial incentives for rail use. The initiative offers importers a £100 rebate per container moved by rail rather than by truck [49]. As a result, over 30% of all containers are now transported by train, with plans to increase this share to 40% in the near future [45]. The terminal has also extended gate operating hours and optimised its truck appointment system to smooth out traffic peaks, reducing idling emissions and congestion [44]. Together, these initiatives have improved hinterland efficiency while cutting overland freight emissions.

Policy and Regulations: DP World Southampton complies with all relevant environmental regulations and contributes actively to Southampton’s Port Air Quality Strategy in collaboration with ABP and local authorities [44]. The terminal adheres to MARPOL emission standards and DP World’s corporate sustainability framework, which targets a 42% reduction in Scope 1 and 2 CO₂ emissions by 2030 and net-zero operations globally by 2050 [41,50]. These efforts are consistent with the UK Government’s Clean Maritime Plan and broader international decarbonisation goals.

Stakeholder Partnerships: DP World Southampton collaborates extensively with industry and public partners to advance decarbonisation. Working with Network Rail and freight operators, the port expanded its rail network, launching four new inland services to Birmingham, Cardiff, the East Midlands, and Doncaster [45]. Partnerships with equipment manufacturers such as Kalmar have delivered additional hybrid straddle carriers that now form the majority of the fleet [46]. The port also works with renewable fuel suppliers to transition all diesel equipment, including straddle carriers, to Hydrotreated Vegetable Oil (HVO), a biofuel derived entirely from renewable feedstocks [51]. This switch has reduced operational carbon emissions by 80–90%, while electrification continues to expand [52]. Through collaboration with technology and fuel partners, DP World Southampton demonstrates a comprehensive, partnership-driven pathway toward sustainable port operations.

Table S3. *Decarbonisation initiatives at global container gateways*

Category	Port of Felixstowe	DP World London Gateway	Southampton (DP World Container Terminal)
Port overview	Operated by Hutchison Ports, the UK’s largest container terminal (3.25 M TEU, 35% UK container trade); primary Asia–Europe gateway.	Operated by DP World; semi-automated deep-water terminal (3 berths); integrated logistics park and rail terminal.	Operated by DP World; South Coast gateway (1.5 M TEU yr ⁻¹); 5 berths, 16 m draft; strong rail–road connectivity.
Energy supply and management	2 MW solar arrays; 100% renewable electricity (Scope 2 = 0); 40 t day ⁻¹ green H ₂ plant (ScottishPower JV).	Large-scale rooftop solar generation: 100% renewable (REGO-backed) grid supply; onshore power available at main berths.	Fully renewable power supply; entire equipment fleet on HVO biofuel; future on-site battery storage under review.
Infrastructure and equipment	17 electric RTGs; 48 battery tractors; sitewide LED upgrades; shore power feasibility ongoing.	180 electric straddle carriers; 60 ASCs on green tariff; shore power installed; smart buildings and EV chargers.	>120 hybrid/electric straddle carriers; full HVO fuelling system; shore power readiness; LED and workshop retrofits.

Category	Port of Felixstowe	DP World London Gateway	Southampton (DP World Container Terminal)
Operational efficiency	IoT-based energy dashboard; digital emission monitoring; semi-automated cranes; gate booking system.	Integrated TOS automation; AI-based yard and vessel scheduling; IoT energy load balancing.	Navis N4 TOS with AI analytics; digital twin for planning; ISO 50001 energy management; real-time telemetry.
Transport connectivity	Rail terminal upgrade (35% modal share); Green Freight Corridor; incentives for rail freight.	Longest on-dock rail (775 m); >35% by rail; short-sea routes to UK/Benelux; Thames Freeport corridors.	“Modal Shift Programme” (£100/box rail rebate); rail share >30% → target 40%; daily trains to Midlands/Scotland.
Policy and regulations	Net-zero Scope 1–2 by 2035; SBTi-aligned; IMO/MARPOL-compliant.	Net zero operations by 2050; ISO 14001; UK Clean Maritime Plan compliance.	DP World target: –42% Scope 1–2 by 2030; net zero by 2050; local air quality strategy active.
Stakeholder partnerships	ScottishPower (H ₂ hub); Ryse Hydrogen; Cranfield Univ.; Freeport East cluster.	DP World RandD Centre (automation); Rail Freight Group; Thames Freeport and NGOs (biodiversity offsets).	Network Rail and freight operators; Kalmar (hybrid fleet); DP World (documented HVO transition).
Net-zero goal	Net-zero Scope 1 and 2 by 2035	Net-zero port operations by 2050 (AB/CDP aligned)	DP World global SBTi target: –42 % Scope 1and2 by 2030 vs 2022; net-zero across value chain by 2050

S1-2. Ro-Ro and Passenger Hubs

This category covers Dover, Belfast, Hull and Southampton (ABP Estate), which handle intensive short-sea freight or passenger traffic and play important roles in UK-European logistics. Key documented initiatives, including shore power, electrified ground transport and alternative-fuel trials, are summarised in Table S4.

Port of Dover

Energy Supply and Management: The Port of Dover has prioritised renewable energy and alternative fuel integration as key pillars of its Decarbonisation strategy. The port now operates entirely on green

electricity generated from renewable sources such as wind and solar, significantly reducing reliance on non-renewable energy and associated Scope 2 emissions [53]. To address direct emissions, Dover has adopted HVO as a sustainable alternative fuel for port vehicles and vessels, leading to measurable reductions in Scope 1 emissions across operational activities [54].

Infrastructure and Equipment: Infrastructure upgrades at the Port of Dover have focused on electrification and renewable energy deployment. The port is developing shore power facilities to allow ferries and vessels to connect to the electrical grid while berthed, minimising emissions from onboard auxiliary engines [53]. Complementing this initiative, the installation of solar panels across port buildings provides a substantial portion of the port's energy needs, supporting self-sufficiency in renewable power generation and further reducing the carbon intensity of port operations [53]. These steps, alongside the electrification of port vehicles and the introduction of energy-efficient LED lighting, are improving the port's environmental performance. DFDS has announced a €1 billion programme to introduce six battery-electric vessels on the Dunkirk–Dover and Calais–Dover routes, aimed at carrying both passengers and freight between the UK and the EU. The first two ships are expected to enter service by 2030, with the remaining four before 2035[55]. PandO Ferries currently operates two hybrid double-ended vessels (PandO Pioneer and PandO Liberté) on the Dover–Calais route, representing early deployment of low-emission technologies [56].

Operational Efficiency: Operational innovation plays a central role in Dover's emission reduction framework. Through participation in the Clean Maritime Demonstration Competition (CMDC) and the Dover Clean Ferry Power initiative, the port is advancing low-emission ferry technologies and establishing green corridors to facilitate sustainable maritime transport [57]. Additionally, the port's vehicle booking and management system enhances landside logistics by reducing congestion, minimising idling times, and lowering emissions from heavy goods vehicles [53].

Transport Connectivity: Dover's Decarbonisation strategy extends beyond port boundaries through green corridor development initiatives that promote low-emission ferry routes between the UK and continental Europe. These corridors are part of collaborative efforts under the CMDC program to decarbonise cross-channel operations [57]. The port is also investing in intermodal connectivity and modal shift strategies, expanding rail and other sustainable transport modes to reduce dependence on road freight and align with the UK's logistics Decarbonisation objectives [54].

Policy and Regulations: Aligned with the UK's maritime Decarbonisation framework, the Port of Dover has set ambitious targets to achieve significant emission reductions by 2030 and net-zero by 2040 [53]. These targets are underpinned by investments in renewable energy, electrification, and alternative fuels. The port also ensures compliance with UK and EU environmental standards, focusing on reductions of NO_x, SO_x, and PM emissions in line with international regulatory frameworks [58].

Stakeholder Partnerships: Collaboration is a defining feature of Dover's Decarbonisation approach. As a participant in the CMDC, the port works with UK government agencies and industry partners to accelerate innovation in low-emission maritime technologies [57]. Furthermore, Dover engages in cross-channel and European partnerships to develop green maritime corridors with neighbouring ports, fostering collective progress toward emission reduction and advancing sustainable regional shipping practices [53].

Port of Belfast

Energy Supply and Management: Belfast Harbour has made renewable energy adoption central to its Decarbonisation agenda. The port operates entirely on 100% renewable electricity sourced from wind and solar energy, aligning with Northern Ireland's renewable energy and sustainability goals [59]. In addition, Belfast has conducted successful trials using HVO as a diesel replacement for port vehicles and machinery, reducing Scope 1 emissions and demonstrating the port's commitment to integrating low-carbon fuels into daily operations [60].

Infrastructure and Equipment: Infrastructure modernisation is a core aspect of the port's emission-reduction efforts. The installation of energy-efficient LED lighting across facilities and the electrification of the vehicle fleet have significantly decreased overall energy consumption [59]. To further enhance performance, Belfast Harbour has deployed sub-metering systems that provide real-time energy monitoring. This data-driven approach supports targeted efficiency measures and enables informed decision-making for energy management [60].

Operational Efficiency: Belfast Harbour employs IoT technologies to optimise the operation of port equipment and infrastructure, improving resource efficiency and minimising unnecessary energy use [59]. Complementing this, an advanced energy management system regulates and balances load across facilities, contributing to improved performance and supporting the port's pathway toward achieving its net-zero 2030 goal [59].

Transport Connectivity: The port's Decarbonisation plan extends to sustainable logistics and freight systems. Belfast Harbour promotes modal shift initiatives that prioritise rail freight over road transport and enhance intermodal connectivity, reducing overall carbon intensity in logistics chains [60]. The port also actively supports green maritime transport by participating in regional programs that develop low-emission shipping corridors and encourage cleaner fuel adoption among visiting vessels [59].

Policy and Regulations: Belfast Harbour has committed to achieving net-zero emissions by 2030, making it one of the most ambitious ports in the UK regarding Decarbonisation timelines [59]. This commitment is supported by strict adherence to UK and EU environmental standards, including regulatory measures to limit NO_x, SO_x, and PM. These standards reinforce the port's alignment with the Northern Ireland Executive's broader Green Economy Strategy [61].

Stakeholder Partnerships: Collaboration is central to Belfast Harbour's sustainability framework. The port works with local councils, logistics companies, and environmental organisations to enhance sustainable transport and resource efficiency across operations [60]. It also plays an active role in Northern Ireland's regional green economy programs, supporting Decarbonisation projects and promoting innovation in clean energy systems, solidifying its leadership in sustainable port management [61].

Port of Hull

Energy Supply and Management: The Port of Hull serves as a central hub for the UK's offshore wind industry and renewable energy logistics. As the operational base for Siemens Gamesa's wind turbine blade manufacturing facility, Hull plays a key role in supporting projects such as the Dogger Bank Wind Farm and other North Sea developments, emphasising its contribution to the clean energy transition and emissions reduction [62]. Complementing its offshore wind role, the port has also installed on-site solar panels across warehouses and administrative buildings, providing renewable electricity for its operations and decreasing reliance on fossil-based power sources [44].

Infrastructure and Equipment: Through the Green Port Hull initiative, the port has invested heavily in sustainable infrastructure that supports the offshore wind sector. These upgrades include energy-efficient buildings, electric vehicle (EV) charging infrastructure, and renewable-ready facilities designed to minimise environmental impact and promote clean energy logistics [63]. In parallel, Hull has advanced the electrification of port equipment, replacing diesel-powered cranes and heavy machinery with electric alternatives, aligning operational practices with ABP's carbon reduction goals [62].

Operational Efficiency: Hull has implemented IoT technologies to monitor energy use and optimise machinery performance in real time, thereby reducing unnecessary consumption and emissions [44]. Additionally, advanced energy management systems enable efficient load balancing and energy

distribution across terminal operations. This system improves overall energy efficiency and supports the port's pathway toward net-zero operations [63].

Transport Connectivity: Hull's rail infrastructure expansion facilitates a modal shift from road to rail freight; significantly lowering carbon emissions associated with land-based transport [64]. Furthermore, the port's strategic role in offshore wind logistics enables efficient transportation, assembly, and distribution of turbine components, strengthening the renewable energy supply chain and integrating port activities into national Decarbonisation efforts [63].

Policy and Regulations: ABP, as the operator of the Port of Hull, has committed to achieving net-zero emissions by 2040, aligning with the UK government's maritime Decarbonisation policy [62]. This objective is being pursued through renewable energy integration, electrification of assets, and energy optimisation strategies. The port also maintains strict compliance with UK and EU environmental standards, targeting the reduction of NO_x, SO_x, and particulate matter emissions from operations [64].

Stakeholder Partnerships: Strategic partnerships form the foundation of Hull's sustainability success. Collaboration with Siemens Gamesa has positioned the port as a key player in offshore wind manufacturing and logistics, directly contributing to the UK's renewable energy targets [63]. In addition, Hull cooperates with regional authorities, environmental groups, and transport organisations to promote waste reduction, carbon offsetting, and sustainable economic development across the Humber region [64].

Port of Southampton (ABP Estate)

Energy Supply and Management: The Port of Southampton, managed by Associated British Ports (ABP), has integrated renewable energy generation as a core element of its sustainability strategy. Solar installations across port facilities now supply a significant portion of the terminal's energy demand, reducing reliance on fossil fuels and cutting operational emissions [62]. In collaboration with Fawley Refinery, Southampton is advancing plans for a regional hydrogen hub designed to produce and distribute low-carbon hydrogen fuel. This initiative aims to decarbonise both port operations and heavy transport sectors, supporting local industries and contributing to the UK's broader clean energy transition [44].

Infrastructure and Equipment: Substantial investments in electrification and cleaner fuels underpin Southampton's infrastructure upgrades. A shore power system installed at the Horizon Cruise Terminal enables vessels to connect to the local grid while berthed, eliminating emissions from auxiliary engines and improving air quality in surrounding areas [44]. To reduce direct emissions, ABP has replaced diesel-powered machinery with electric forklifts, equipment fitted with Euro VI engines, and the adoption of HVO fuel across its fleet. These improvements have substantially reduced the port's Scope 1 emissions and operational carbon footprint [62].

Operational Efficiency: Southampton has implemented a vehicle booking and traffic management system to optimise port access and minimise truck congestion. This digital system reduces idle time and emissions from landside vehicles, improving logistical efficiency and air quality [62]. Additionally, the integration of IoT technologies enables real-time monitoring and optimisation of energy use across terminal operations. These digital solutions streamline workflows, enhance data-driven decision-making, and reduce energy consumption [62].

Transport Connectivity: The port's rail terminal expansion supports a strategic modal shift from road to rail, increasing freight capacity while significantly reducing greenhouse gas emissions associated with inland transport [44]. Further contributing to national Decarbonisation goals, Southampton participates in green hinterland initiatives aimed at improving intermodal connectivity and developing sustainable logistics corridors between the port and inland destinations [62].

Policy and Regulations: ABP has committed to achieving net-zero emissions by 2040, in alignment with the UK government’s maritime Decarbonisation objectives [62]. The strategy encompasses renewable energy integration, electrification of port assets, and operational optimisation measures designed to ensure compliance with evolving environmental standards and the UK’s Clean Maritime Plan.

Stakeholder Partnerships: Collaborative partnerships are central to Southampton’s Decarbonisation progress. Through cooperation with Fawley Refinery, the port is developing a hydrogen hub that will serve as a regional source of clean fuel for heavy-duty vehicles and maritime operations [44]. In addition, ABP engages with local governments, environmental groups, and maritime stakeholders to implement joint sustainability initiatives, fostering a collective approach to emission reduction and environmental protection [62].

Table S4. Decarbonisation initiatives at Ro-Ro and Passenger Hubs

Category	Port of Dover	Port of Belfast	Port of Hull	Southampton (ABP Estate)
Port overview	Operated by Dover Harbour Board; Europe’s busiest ferry port (≈ 9 M passengers yr^{-1}); key UK–France link.	Operated by Belfast Harbour Commission; Northern Ireland’s main freight and passenger hub (24 Mt cargo, 1.7 M passengers yr^{-1}).	Operated by ABP; key Ro-Ro and offshore-wind hub on Humber Estuary; central to Humber clean energy cluster.	Operated by ABP; UK’s main Ro-Ro hub (≈ 480 k vehicles yr^{-1}) and leading cruise port (≈ 3 M passengers).
Energy supply and management	1.6 MW solar; 100% renewable electricity; port-wide HVO fuel use; DFDS battery-electric ferries (2030 target).	1.6 MW solar + 4 MWh battery storage; 100% renewable power since 2019; ongoing HVO adoption.	6.5 MWp solar (largest UK port PV); 100% renewable electricity; hydrogen hub FEED 2025.	1.6 MW solar; 100% REGO electricity; Fawley 250 MW hydrogen hub (FID 2025).
Infrastructure and equipment	OPS at cruise berth; 2×3 MVA shore power for ferries (planned); hybrid ferries in service; EV chargers and smart grid.	6 HVO-ready cranes; pilot autonomous EV tractors; LED and sub-metering; EfW plant (14 MW export).	Siemens Gamesa OandM facility; hybrid cranes and HVO fleet (80%); OPS feasibility; hydrogen-ready quays.	OPS (2×3 MVA) at cruise berths; straddle and yard fleet on HVO; EV forklifts; LED rollout; private 5G IoT grid.

Category	Port of Dover	Port of Belfast	Port of Hull	Southampton (ABP Estate)
Operational efficiency	Dover TAP digital traffic management; IoT berth sensors; AI berth optimiser; ISO 14064 reporting.	IoT metering and Power BI EMS; AI berth optimisation; ESG dashboard.	IoT monitoring; Power BI energy analytics; 5 G yard optimisation; ISO 14064 inventory.	5G-enabled IoT dashboard; vehicle booking and AI berth scheduling; ISO 14064 reporting.
Transport connectivity	Green Corridor (Calais–Dunkirk zero-carbon route); freight rail feasibility via GCSS.	Rail terminal upgrade; Belfast–Liverpool green corridor; offshore-wind logistics quay.	Daily intermodal rail, inland barge pilot; Freeport hydrogen corridor.	3 on-dock rail terminals; Modal Shift rebate (30 → 40 % rail share); Solent green logistics corridor.
Policy and regulations	Net zero 2040; 50 % CO ₂ reduction 2030; MARPOL VI and Clydebank Declaration.	Net zero port 2030 (estate 2040); Air Quality Strategy; full MARPOL/CE RS compliance.	ABP “Ready for Tomorrow” plan → Net zero 2040; Humber Clean Air Zone.	ABP “Ready for Tomorrow” plan → Net zero 2040; Solent Clean Air Zone; Clean Maritime Demo.
Stakeholder partnerships	Clean Ferry Power consortium (WMG, DFDS, PandO); Green Corridor Short Straits; Kent CC and DFT.	Siemens battery JV; Stena Line corridor; City Deal (£1 bn); Innovate UK CMDC.	Siemens Gamesa Renewables, Humber Freeport and Zero Carbon Humber; local councils.	ExxonMobil/Air Liquide (H ₂ hub); Solent Freeport; Verizon (5 G); Solent Stevedores pilot.
Net-zero goal	Net-zero port ops 2040; 50 % CO ₂ cut by 2030	Net-zero port ops 2030; estate-wide 2040	ABP “Ready for Tomorrow” Net-Zero 2040	ABP “Ready for Tomorrow” Net-Zero 2040

S1-3. Energy Hubs

This group includes Immingham, Milford Haven, and Grangemouth, which serve as the UK's primary energy-handling ports for crude oil, refined products, and liquefied natural gas (LNG). Their decarbonisation focus centres on the transition toward low-carbon fuels, carbon-capture readiness, and integration of renewable-energy infrastructure. Key operational characteristics and sustainability initiatives for these ports are summarised in Table S5.

Port of Immingham

Energy Supply and Management: The Port of Immingham, operated by Associated British Ports (ABP), has prioritised renewable energy production and alternative fuels as part of its pathway to net-zero operations. The port has installed rooftop solar panels and wind turbines that generate clean electricity to power port activities, directly contributing to ABP's goal of achieving net-zero emissions by 2040 [62]. In addition, Immingham is exploring the feasibility of on-site green hydrogen production, designed to supply zero-carbon fuel for port operations and nearby industrial users. This initiative underscores ABP's strategy to advance energy diversification and low-carbon infrastructure [44].

Infrastructure and Equipment: Immingham's infrastructure modernisation includes significant progress in equipment electrification and sustainable energy deployment. The port has introduced electric rubber-tyred gantry (RTG) cranes, electric forklifts, and HVO-powered reach stackers, effectively cutting direct emissions from diesel-powered machinery [65]. While shore power is not yet fully implemented, ABP is assessing its feasibility as part of its long-term infrastructure strategy [62]. Moreover, Immingham plays a key role in developing a Carbon Capture and Storage (CCS) terminal that will capture and sequester CO₂ emissions from both port operations and nearby industries, supporting the Humber region's Decarbonisation objectives [62].

Operational Efficiency: The port leverages digitalisation and automation technologies to enhance efficiency in terminal operations and container handling, reducing emissions linked to logistics processes [44]. Additionally, the implementation of optimised scheduling and route management systems for vehicles and machinery has reduced fuel consumption and idle times, aligning with Immingham's broader emission-reduction goals [62].

Transport Connectivity: To promote sustainable freight transport, Immingham has strengthened its rail infrastructure, facilitating a modal shift from road to rail and significantly reducing carbon emissions from inland cargo movements [65]. The port also collaborates with regional stakeholders on green hinterland connectivity projects, developing sustainable transport links that integrate the port with inland logistics hubs and support the creation of a low-emission supply chain [44].

Policy and Regulations: ABP has made a firm commitment to achieve net-zero emissions across its port network by 2040, aligning with national Decarbonisation policies [62]. This commitment encompasses investments in renewable energy, electrification, hydrogen, and CCS initiatives. Furthermore, ABP implements carbon offset programs across its ports, including Immingham, to compensate for residual emissions and support broader environmental objectives [62].

Stakeholder Partnerships: Immingham's Decarbonisation progress is driven by collaboration with industrial and governmental partners. The port plays a central role in the Humber region's Carbon Capture and Storage (CCS) consortium, facilitating large-scale CO₂ capture and storage to decarbonise regional industry [44]. It also maintains strategic partnerships with energy companies and technology providers to advance hydrogen production and renewable energy deployment, reinforcing the port's role as a leader in sustainable maritime logistics [65].

Port of Milford Haven

Energy Supply and Management: The Port of Milford Haven has positioned renewable energy at the core of its Decarbonisation framework. In partnership with energy companies, the port is leading floating offshore wind (FLOW) projects in the Celtic Sea, providing renewable power for port operations and contributing to regional clean energy generation [66]. Additionally, the port is integrating green hydrogen into its operational and industrial processes to decarbonise maritime activities. All electricity used in port operations is now procured under a renewable energy tariff, ensuring that energy consumption is fully aligned with sustainability objectives [66].

Infrastructure and Equipment: Milford Haven has advanced its infrastructure to enable low-emission port operations. The installation of electric vehicle (EV) charging stations supports fleet electrification, while plans to introduce shore power infrastructure will allow berthed vessels to connect to the grid and eliminate emissions from auxiliary engines [66]. The port has also implemented energy-efficient LED lighting systems and installed solar panels across multiple facilities, significantly improving energy efficiency and reducing the overall carbon footprint of daily operations [67].

Operational Efficiency: Operational optimisation at Milford Haven is supported by the use of digitalisation and IoT technologies, enabling real-time monitoring of energy consumption across equipment and buildings [67]. An advanced energy management system further enhances efficiency by optimising load distribution and energy use, improving both cost-effectiveness and environmental performance while driving progress toward the port's Decarbonisation targets [67].

Transport Connectivity: The port's green hinterland initiatives aim to integrate sustainable logistics solutions by improving low-emission connections between the port and inland distribution networks. Collaboration with local authorities ensures that these projects reduce transport-related emissions and support regional climate goals [66]. In addition, Milford Haven promotes a modal shift toward rail and short-sea shipping, aligning with the UK's national strategy for cleaner freight transportation and reduced dependence on high-emission road haulage [66].

Policy and Regulations: The Port of Milford Haven has formally committed to achieving net-zero emissions by 2040, aligning with UK government Decarbonisation policies [66]. This target is supported by a multi-pronged approach involving renewable energy generation, adoption of alternative fuels, and infrastructure modernisation, ensuring compliance with evolving environmental standards and contributing to long-term emission reductions.

Stakeholder Partnerships: Collaboration lies at the foundation of Milford Haven's Decarbonisation efforts. The port partners with government bodies and leading energy firms to advance green hydrogen and floating offshore wind projects in the Celtic Sea, enhancing the UK's renewable energy capacity while bolstering regional energy resilience [66]. Moreover, the port engages with regional stakeholders, environmental groups, and local businesses to balance economic development with ecological protection, reinforcing its role as a leader in sustainable port management [67].

Port of Grangemouth

Energy Supply and Management: The Port of Grangemouth sources sustainable energy for its operations. It has installed over 1 MW of rooftop solar PV across its warehouses, supplying part of the port's electricity demand with on-site renewable generation [68]. The remainder of Grangemouth's electricity is procured via a 100% renewable supply contract, ensuring that all port operations run on green power [68]. In addition, plans are underway to develop a green hydrogen production hub at Grangemouth in collaboration with industry partners, which would support the port and the nearby industrial cluster with low-carbon fuel [69].

Infrastructure and Equipment: Grangemouth is upgrading its equipment and infrastructure to reduce emissions. The port has recently added three new ship-to-shore container cranes, one of which is fully electric, eliminating diesel use during loading operations [68]. It has also introduced five hybrid

rubber-tyred gantry cranes (from Konecranes) that cut fuel consumption by combining electric drives with fuel-efficient diesel engines [68]. Grangemouth is enhancing its shore power infrastructure as well, enabling vessels at berth to connect to the local grid and turn off their auxiliary engines [70]. Furthermore, energy-efficient LED lighting has been installed throughout the port, reducing power consumption for lighting [68].

Operational Efficiency: The port has implemented several initiatives to improve operational efficiency and sustainability. A recent upgrade to the Terminal Operating System (TOS) and deployment of IoT yard telemetry now provide granular, real-time data on equipment status, container locations, and energy use across the port [70]. These digital tools allow for optimised scheduling of cranes and vehicles, minimising idle running time. Grangemouth is also promoting sustainable procurement practices, favouring low-carbon materials and integrating circular economy principles (such as recycling of waste materials and refurbishment of equipment) into its operations [70]. This focus on efficiency and resource reuse not only cuts costs but also reduces the port's environmental impact.

Transport Connectivity: Grangemouth has strengthened its intermodal transport links to facilitate lower-carbon freight movement. The port has expanded its rail services and now runs daily intermodal trains connecting Grangemouth with the Port of Tilbury in southern England and with distribution hubs in the Midlands [68]. By increasing the share of cargo moving by rail, the port helps to decrease HGV traffic on long-distance routes. Looking ahead, as part of the Forth Green Freeport initiative, Grangemouth is involved in plans to reconnect the nearby Port of Rosyth to the rail network, which will further promote a modal shift from road to rail across the region [68]. These efforts align with Scotland's national transport strategy to decarbonise freight transport.

Policy and Regulations: Grangemouth's decarbonisation targets are aligned with government climate policies. The port is in full compliance with Scottish Environmental Protection Agency (SEPA) regulations and the UK Clean Maritime Plan guidelines, adhering to all permits and standards for air and water quality [68]. Grangemouth has set an ambitious timeline to reach carbon-neutral operations by 2032 and to achieve full net-zero status by 2042 [68]. These targets go together with Scotland's national goal of net-zero by 2045 and the UK's 2050 target, positioning Grangemouth as a leader in climate alignment. The port's strategy is also guided by local frameworks, such as the Scottish Government's Climate Change Plan, ensuring that port development and operations contribute to broader decarbonisation efforts.

Stakeholder Partnerships: Grangemouth works closely with both public and private partners to advance low-carbon projects. The port is collaborating with Scottish Enterprise and other stakeholders to establish a hydrogen hub and related infrastructure, which will form the centrepiece of an emerging low-carbon industrial cluster in the Forth Valley [69]. Grangemouth is also a key player in the Forth Green Freeport consortium, partnering with industries and government to attract investment in renewable energy, clean fuel production, and green manufacturing in the port area [70]. In addition, the port has a technical partnership with Kalmar (a cargo-handling equipment provider) to pilot the use of hybrid and electric port equipment in daily operations, sharing knowledge that can be replicated at other ports. Grangemouth's community engagement includes working with the local authority on skills development programs and emissions reduction initiatives for the surrounding community, ensuring that the port's decarbonisation delivers socio-economic benefits locally.

Table S5. Decarbonisation initiatives at energy hubs

Category	Port of Immingham	Port of Milford Haven	Port of Grangemouth
Port overview	Operated by ABP; 46 Mt yr ⁻¹ ; UK's 2nd-busiest port; key energy logistics hub in Humber "Energy Estuary."	Trust Port; ≈34.7 Mt yr ⁻¹ ; UK's largest energy port; LNG, oil, and renewables hub in Wales.	Operated by Forth Ports; ≈9 Mt yr ⁻¹ ; Scotland's main petrochemical and container port.
Energy supply and management	4.5 MW solar array; 100 % renewable electricity; 76 000 t yr ⁻¹ green H ₂ plant [71].	14.5 MW combined solar (port + Dragon LNG); 100 % renewable power; 300 MW Celtic Sea H ₂ hub (10 MW phase 1).	>1 MW solar; 100 % green electricity; Hydrogen Hub feasibility with Scottish Enterprise.
Infrastructure and equipment	3 hybrid LHM cranes; electric RTGs; shore power FEED under ABP 2040 plan; 50 % fleet on HVO; ISO 50001 EMS.	Seven berths OPS (2024–27 design); EV fleet and chargers; LNG compressor electrification; FLOW assembly yard.	3 STS cranes (1 electric); 5 hybrid straddle carriers; shore power-ready quays; 80 % mobile fleet on HVO; ISO 50001.
Operational efficiency	IoT cargo flow platform; digital GHG inventory (ISO 14064); automated vehicle scheduling reduces idling.	AI berth scheduler for LNG tankers; 5 G/IoT Port Energy Platform (EMS); ISO 14064 GHG dashboard.	Upgraded TOS with IoT yard telemetry, real-time energy dashboard, rail slot optimiser, and public ESG KPI portal.
Transport connectivity	Gauge-enhanced rail links; Green Hinterland Freight initiative; CO ₂ pipeline integration (Viking CCS).	Rebuilt rail interchange; green freight corridor (rail + barge); Celtic Sea FLOW supply chain network.	Daily Tilbury and Midlands rail services; rail rebate boosts modal share; Forth Green Freeport corridor.
Policy and regulations	ABP Net Zero 2040 plan; Zero Carbon Humber and Viking CCS cluster participant; MARPOL compliant.	Trust Port Net Zero 2040 roadmap; Air Quality Strategy; Clean Maritime Demonstration participant.	Carbon neutral 2032 → Net Zero 2042; SEPA and Clean Maritime Plan compliant; eco-tariff pilot (2026).

Category	Port of Immingham	Port of Milford Haven	Port of Grangemouth
Stakeholder partnerships	Air Products H ₂ plant; Zero Carbon Humber alliance; UK Track 1 CCS funding; VPI and Phillips 66 industrial tenants.	RWE and Dragon LNG solar projects; Celtic Freeport (RWE, Valero); Marine Energy Wales and Crown Estate FLOW projects.	Scottish Enterprise H ₂ hub; Forth Green Freeport consortium; Kalmar hybrid tech pilot; local skills programs.
Net-zero goal	ABP Net-Zero 2040 strategy; port-specific roadmap	Trust-port Net-Zero 2040 roadmap; 50 % cut by 2030	• Carbon-neutral operations 2032 and Net-zero whole-port 2042

S1-4. Offshore Energy and Project-Cargo Bases

This category includes the Port of Tyne and Port of Aberdeen, which specialise in supporting offshore wind construction, maintenance, and large-scale project logistics. Their decarbonisation measures focus on renewable-energy integration, hydrogen-powered service vessels, and digital technologies for operational optimisation. Key operational characteristics and sustainability initiatives for these ports are summarised in Table S6.

Port of Tyne

Energy Supply and Management: The Port of Tyne has positioned itself as a major logistics hub for renewable energy through the establishment of its Renewable Energy Hub, which supports offshore wind projects such as the Dogger Bank Wind Farm, one of the world's largest renewable energy developments [72]. In parallel, the port is exploring green hydrogen production to fuel port operations and contribute to the Decarbonisation of the maritime and industrial sectors. This initiative aligns with regional and national efforts to transition toward alternative, low-emission energy sources [73].

Infrastructure and Equipment: As part of its modernisation efforts, the Port of Tyne has implemented the Digital Clean Tyne Project, an advanced real-time digital platform that monitors and optimises energy use across port operations. This system plays a crucial role in reducing emissions through data-driven energy management [74]. The port has also invested in electric and hydrogen-powered equipment, including feasibility studies for hydrogen vehicles and heavy machinery. These developments aim to replace diesel-based systems, significantly reducing operational emissions [72].

Operational Efficiency: Tyne's Decarbonisation approach relies heavily on digitalisation and IoT technologies for performance monitoring and energy optimisation. These tools allow for real-time adjustments to operations, improving efficiency and minimising energy waste [74]. Additionally, integrated energy management systems ensure load balancing and smart energy distribution, enhancing overall resource efficiency and reducing carbon intensity across terminal operations [72].

Transport Connectivity: The Port of Tyne actively supports the UK's modal shift agenda through rail infrastructure investments designed to increase rail freight capacity and reduce emissions from road transport [73]. It also plays a central role in the development of green logistics corridors, fostering sustainable transport routes that connect the port with regional and national logistics networks, thus contributing to emission reductions and enhanced connectivity [72].

Policy and Regulations: The Port of Tyne has committed to achieving net-zero emissions by 2030, one of the most ambitious targets among UK ports [72]. This commitment encompasses renewable energy deployment, equipment electrification, and process optimisation to meet the UK's maritime Decarbonisation objectives. Furthermore, the port adheres to stringent UK and EU environmental regulations, focusing on reducing NO_x, SO_x, and particulate matter emissions as part of its comprehensive sustainability framework [73].

Stakeholder Partnerships: Collaboration is a cornerstone of Tyne's Decarbonisation success. The port maintains partnerships with energy companies and governmental bodies to support offshore wind development and associated logistics, reinforcing its role as a key facilitator in the renewable energy supply chain [74]. Additionally, its cooperation with the North East Local Enterprise Partnership (LEP) promotes low-carbon transport innovation and strengthens the region's identity as a centre for sustainable logistics and clean energy infrastructure [73].

Port of Aberdeen

Energy Supply and Management: The Port of Aberdeen has made renewable energy integration central to its Decarbonisation strategy. The port operates on-site wind turbines and solar panel systems that generate a substantial portion of its electricity demand, reducing dependency on fossil fuels and supporting Scotland's transition to clean energy [75]. In addition, the port has implemented shore power facilities, allowing vessels to draw electricity directly from the grid while berthed. This significantly cuts emissions from auxiliary engines, contributing to improved local air quality and overall operational sustainability [76].

Infrastructure and Equipment: Sustainability has been embedded into the design and construction of South Harbour, which includes energy-efficient buildings, EV charging stations, and environmentally responsible infrastructure that minimises ecological impact [77]. The port has also committed to electrifying its operational fleet and equipment, transitioning from diesel-powered machinery to electric alternatives. This investment enhances energy efficiency and supports the port's long-term emission reduction objectives [75].

Operational Efficiency: Digitalisation plays a pivotal role in Aberdeen's emission-reduction efforts. The port utilises IoT-based monitoring systems to track and manage energy use in real time, enabling optimised operations and minimising energy waste [75]. Furthermore, the introduction of just-in-time scheduling for vessel arrivals and port operations has reduced idle periods and fuel consumption, directly lowering greenhouse gas emissions from maritime activities [78].

Transport Connectivity: The Port of Aberdeen is actively improving its rail and intermodal connectivity to facilitate a modal shift from road to rail, thereby decreasing overland freight emissions in alignment with regional sustainability priorities [79]. Additionally, the port participates in green hinterland initiatives, collaborating with regional stakeholders to develop sustainable transport links between the harbour and inland logistics centres, reducing the environmental footprint of supply chains [75].

Policy and Regulations: Aberdeen has committed to achieving net-zero emissions by 2040, aligning with Scotland's national climate and Decarbonisation objectives [79]. In pursuit of this goal, the port ensures compliance with UK and EU environmental standards, targeting the reduction of NO_x, SO_x, and particulate matter emissions, and maintaining its adherence to Scotland's rigorous environmental regulations [77].

Stakeholder Partnerships: The Port of Aberdeen has established strong partnerships with local and international energy firms to advance green hydrogen development, positioning itself as a key node in Scotland's emerging hydrogen economy [79]. Additionally, the port collaborates closely with Aberdeen City Council, environmental agencies, and private sector stakeholders to promote

sustainable infrastructure projects and ensure that Decarbonisation aligns with community and regional economic objectives [77].

Table S6. *Decarbonisation initiatives at offshore-energy and project cargo bases*

Category	Port of Tyne	Port of Aberdeen
Port overview	Operated by Port of Tyne Authority; ≈ 60 Mt cargo, 0.6 M passengers yr^{-1} ; hub for Dogger Bank offshore-wind logistics.	Operated by Aberdeen Harbour Board; ≈ 3 Mt cargo, 0.17 M passengers yr^{-1} ; North Sea oil, gas and offshore-wind service hub.
Energy supply and management	1 MW solar; 100 % renewable (REGO); Dogger Bank 3.6 GW OandM base; hydrogen pilot (LEP 2023).	1.5 MW solar + micro-wind; 100 % renewable power; 10 MW bp–Scottish Enterprise H ₂ hub (phase 1).
Infrastructure and equipment	6 HVO-ready cranes; hybrid RTG pilot; OPS feasibility (CMDC 3); heavy-lift Clean Energy Park quay; 80 % fleet on HVO; e-pilot boat 2025.	£420 M South Harbour (1,450 m quay, 15 m draft); OPS ready; 6 HVO MHCs + electric cranes; EV chargers; 4 MWh battery study; ISO 50001.
Operational efficiency	Clean Tyne IoT EMS (Newcastle Univ.); AI berth/rail optimiser; private 5 G data network; ISO 14064 dashboard.	Smart Port real-time EMS; AI berth and gate optimiser; Just-in-Time arrival pilot; ISO 14064 GHG monitoring.
Transport connectivity	Tyne Dock intermodal terminal; daily automotive rail links; Green North Sea corridor (Tyne–Amsterdam/Gothenburg).	Nestrans rail upgrade study; modal shift incentives for bulk cargo; integration with Energy Transition Zone (ETZ).
Policy and regulations	Port Air Quality Strategy; MARPOL compliance; Clydebank Declaration green corridor pilot; Net Zero 2030 (fully electric estate 2040).	Net Zero 2040 (£55 M capex); MARPOL and UK Clean Maritime compliant; carbon intensity KPI in annual report.
Stakeholder partnerships	Equinor and SSE (Dogger Bank base); North East LEP H ₂ projects; Innovate UK CMDC grants; Tyne Estuary 2030 biodiversity partners.	bp / Scottish Enterprise H ₂ hub; Siemens shore power project; Nestrans and City Deal transport partners; ETZ cluster collaboration.
Net-zero goal	Net-zero port ops 2030; all-electric estate 2040	Net-zero whole port 2040 (55 m capex)

S1-5. Diversified Multi-Purpose Ports

This group covers London, Liverpool, Tilbury, Teesport, and Bristol, which manage a broad mix of cargo types and play a key role in regional and national logistics networks. Their decarbonisation initiatives involve renewable-energy deployment, hydrogen-powered terminal equipment, and rail-

connectivity improvements supporting modal shift. Comparative information on their operational characteristics and sustainability measures is presented in Table S7.

Port of Liverpool

Energy Supply and Management: The Port of Liverpool, managed by Peel Ports Group, has positioned renewable energy production at the centre of its Decarbonisation efforts. In partnership with E.ON, the port is developing the UK's largest roof-mounted solar energy system, installing approximately 63,000 panels across 26 facilities. Once operational, the system will generate nearly 31 MW of renewable electricity annually, offsetting more than 6,500 tonnes of CO₂ emissions per year and establishing Liverpool as a national leader in clean energy integration [80,81]. In parallel, the port has transitioned sections of its equipment and fleet to HVO, a low-carbon biofuel that reduces CO₂ emissions by up to 90%. Trials of hydrogen-powered trucks are also underway to assess the feasibility of large-scale hydrogen deployment in logistics and freight operations [82,83].

Infrastructure and Equipment: Peel Ports is advancing port-wide infrastructure electrification through the planned installation of ship-to-shore power facilities, enabling vessels to connect to the grid and operate on electricity while berthed, eliminating emissions from auxiliary engines and improving air quality around the Mersey [81,84]. Further upgrades include electric cranes powered by renewable energy, port-wide LED lighting systems, and the development of EV charging infrastructure to accommodate the growing electrified fleet. These actions significantly reduce Scope 1 and 2 emissions and enhance overall operational efficiency [81,82].

Operational Efficiency: The Port of Liverpool has adopted advanced digital systems to streamline operations and minimise emissions. An intelligent logistics optimisation platform now manages container movements, reducing idle times and fuel use while improving terminal throughput efficiency [82,83]. Additionally, a vehicle booking system for landside logistics manages truck scheduling, alleviating congestion at port entry points and lowering emissions from idling freight vehicles. Together, these digital enhancements exemplify Liverpool's integration of smart technology into decarbonised operations [81,82].

Transport Connectivity: In support of the UK's sustainable freight objectives, Liverpool has prioritised modal shift initiatives that expand rail freight capacity and promote the transition from road to rail transportation [82]. These investments directly contribute to reduced carbon intensity in overland cargo movement and align with national Decarbonisation frameworks. Additionally, Liverpool's integrated approach to transport planning ensures synergy between its maritime, rail, and logistics operations, reinforcing its role as a central hub for low-emission freight distribution [81].

Policy and Regulations: Peel Ports Group has committed to achieving net-zero emissions across all sites by 2040, a target that surpasses national Decarbonisation milestones [81,85]. The company's sustainability strategy encompasses large-scale renewable energy deployment, electrification of port assets, and the adoption of sustainable fuels. These measures ensure compliance with UK regulatory frameworks on air quality, greenhouse gas emissions, and sustainable energy management while positioning Liverpool as a benchmark port for climate-aligned operations [81].

Stakeholder Partnerships: The Port of Liverpool is an active participant in the UK National Clean Maritime Research Hub (UK-MaRes Hub), a £21.3 million national research consortium led by Durham University and supported by the University of Liverpool. This partnership accelerates innovation in low-carbon maritime technologies and strengthens Liverpool's contribution to the UK's maritime Decarbonisation research agenda [83,86]. Furthermore, the port's Innovation Forum convenes key industry stakeholders across the logistics chain to develop collaborative solutions for emission reduction and operational sustainability, reinforcing its leadership in collective Decarbonisation [82,83].

Port of Tilbury

Energy Supply and Management: The Port of Tilbury, part of the Forth Ports Group, has prioritised renewable energy generation and clean fuel integration as key components of its Decarbonisation strategy. On-site wind turbines and solar panels supply renewable electricity to port operations, aligning with Forth Ports' long-term sustainability agenda and reducing reliance on fossil-based energy [87]. Complementing this, the port has adopted HVO as an alternative to conventional diesel fuel for port machinery and vehicles. This measure significantly reduces Scope 1 emissions, supporting Tilbury's transition toward cleaner and more sustainable operations [88].

Infrastructure and Equipment: Tilbury has made substantial progress in modernising its infrastructure to meet its carbon reduction targets. The port has implemented shore power facilities, enabling berthed vessels to connect directly to the grid and cut emissions from auxiliary engines, thereby improving local air quality [87]. Additionally, major investments have been made in electrifying cargo-handling equipment, deploying LED lighting systems, and upgrading facilities with energy-efficient technologies. These developments contribute to both operational efficiency and long-term reductions in the port's energy footprint [87].

Operational Efficiency: Digital transformation plays a central role in Tilbury's emission-reduction initiatives. Through IoT systems and advanced data analytics, the port monitors real-time energy usage, allowing for precise management of resources and proactive identification of inefficiencies [88]. In addition, the adoption of automation in cargo handling processes has streamlined logistics, minimised idle time, and enhanced throughput efficiency, all contributing to lower emissions per handled unit [88].

Transport Connectivity: The Port of Tilbury has reinforced its commitment to sustainable logistics through expanded rail services, supporting a modal shift from road to rail. This development reduces carbon emissions associated with freight transport and is consistent with the UK's broader Decarbonisation policy for the transport sector [89]. Tilbury also promotes intermodal connectivity, integrating short-sea shipping and rail operations to decrease road dependency. This approach enhances the port's resilience, improves supply chain efficiency, and aligns with national strategies for low-emission freight [87].

Policy and Regulations: As part of the Forth Ports Group, Tilbury has committed to achieving net-zero emissions by 2042, a goal supported by substantial investments in renewable energy, equipment electrification, and emission reduction programs [87]. The port complies with all UK and EU environmental standards, targeting the reduction of NO_x, SO_x, and particulate matter emissions. Adherence to these frameworks reinforces its position as a benchmark for responsible and sustainable port operations [89].

Stakeholder Partnerships: Collaboration is integral to Tilbury's Decarbonisation roadmap. The port works closely with local authorities and environmental organisations on joint initiatives such as waste reduction, ecosystem restoration, and regional sustainability projects [88]. Moreover, Tilbury participates in the Clean Maritime Initiative, contributing to national programs aimed at fostering sustainable maritime practices, advancing technology innovation, and strengthening industry-wide cooperation on emission reduction [89].

Port of Teesport

Energy Supply and Management: The Port of Teesport, operated by PD Ports, has placed renewable energy and clean fuel development at the centre of its Decarbonisation strategy. The establishment of a Renewable Energy Hub supports major offshore wind and biofuel projects, serving as a strategic base for developments in the North Sea, including the Dogger Bank Wind Farm [90]. In collaboration with local and national stakeholders, the port has also launched the Hydrogen Transport Hub, which

promotes the adoption of green hydrogen as a low-carbon fuel alternative for maritime operations and regional industries. This initiative positions Teesport as a national leader in hydrogen innovation and deployment within the UK's emerging clean energy network [91].

Infrastructure and Equipment: The Port of Teesport has taken a pioneering role in implementing Carbon Capture, Utilisation, and Storage (CCUS) technologies through strategic partnerships with industry stakeholders. This initiative enables the capture and storage of CO₂ emissions from port and regional industrial activities, contributing significantly to the UK's carbon sequestration capacity [92]. Alongside this, the port has made substantial investments in equipment modernisation, including the introduction of electric harbour cranes and the transition of operational machinery to HVO fuel. These upgrades have yielded notable reductions in Scope 1 emissions, reinforcing the port's commitment to innovation-driven emission reduction [90].

Operational Efficiency: Digital transformation has been key to advancing efficiency at the Port of Teesport. The port employs IoT-based monitoring systems to oversee energy consumption and equipment performance in real time, optimising operations and minimising unnecessary fuel use [90]. Through the integration of advanced scheduling, load balancing, and vehicle booking systems, the port has streamlined cargo movement and internal logistics, reduced idling emissions and improving energy efficiency across all terminal operations [90].

Transport Connectivity: The Port of Teesport has prioritised the development of rail infrastructure to facilitate a modal shift from road to rail, directly supporting the UK's Decarbonisation agenda and reducing emissions from freight transport [91]. Additionally, the port serves as a central hub for offshore wind logistics, providing specialised facilities for wind turbine assembly, installation, and maintenance. This role strengthens Teesport's position within the UK's renewable energy supply chain and supports the regional transition toward a green industrial economy [90].

Policy and Regulations: PD Ports has committed to achieving net-zero emissions by 2040, aligning with the UK Government's national Decarbonisation strategy and climate objectives [92]. The Port of Teesport also ensures full compliance with UK environmental regulations, including strict controls on NO_x, SO_x, and PM emissions. These compliance measures are embedded within the port's operational and planning frameworks, guaranteeing long-term alignment with sustainability standards and regulatory expectations [91].

Stakeholder Partnerships: Collaboration lies at the heart of the Port of Teesport's Decarbonisation strategy. The port works closely with the Teesport Valley Combined Authority, local councils, and industry partners to advance the Hydrogen Transport Hub and CCUS terminal, transforming the Teesport Valley into a regional powerhouse for sustainable energy and carbon management [91]. Furthermore, the port maintains strategic alliances with energy and technology companies to drive innovation in renewable energy and emissions reduction, reinforcing its leadership role in sustainable maritime development and industrial Decarbonisation [90].

Port of London Authority (PLA)

Energy Supply and Management: The Port of London Authority (PLA) has positioned renewable energy and clean fuel integration as core components of its Decarbonisation framework. The organisation has deployed solar photovoltaic systems across multiple facilities, significantly reducing reliance on grid electricity and fossil-based power sources [93]. In alignment with its Thames Hydrogen Highway initiative, the PLA is developing a network of electric and hydrogen refuelling stations along the River Thames to facilitate the transition toward low-carbon fuels for both vessels and port operations. This initiative forms a key part of the region's strategy to reduce greenhouse gas emissions from maritime activities and enhance local air quality [94].

Infrastructure and Equipment: As part of its infrastructural modernisation, the PLA has committed to establishing the UK's first zero-emission berth by 2025, allowing vessels to connect to the electrical grid while berthed and eliminating the need for onboard auxiliary engines [94]. The authority has also retrofitted its operational fleet with biofuel and hybrid propulsion systems, achieving a 50% reduction in carbon emissions by 2022; three years ahead of its original target. Complementary upgrades, including electrified port equipment and energy-efficient facilities, further enhance the port's sustainability performance [95].

Operational Efficiency: The PLA has integrated IoT systems and digital monitoring platforms to optimise energy use and improve the efficiency of equipment operations [93]. Furthermore, the port promotes just-in-time (JIT) berthing practices, enabling vessels to arrive precisely when berths become available, thereby reducing idling, minimising fuel consumption, and lowering overall emissions. These digital and procedural improvements contribute to both cost efficiency and emission mitigation [93].

Transport Connectivity: The Thames freight strategy under the PLA's Thames Vision 2050 emphasises the modal shift from road to river-based transport, aiming to significantly expand the volume of goods transported via the Thames [94]. By promoting the river as a sustainable freight corridor, the initiative supports a substantial reduction in road congestion, energy consumption, and related emissions; strengthening the Thames' role as a key component of London's low-carbon logistics network.

Policy and Regulations: The Port of London Authority has committed to achieving net-zero emissions by 2040, fully aligning its environmental policies with national and international climate objectives [93]. In addition, the Air Quality Strategy for the Tidal Thames, revised in 2020, sets ambitious reduction targets of 95% for NO_x and PM emissions from inland vessels and 70% for deep-sea shipping, reinforcing the PLA's leadership in port air quality management [94].

Stakeholder Partnerships: Collaboration and data-driven governance are central to the PLA's Decarbonisation approach. In partnership with RightShip, the PLA operates the Maritime Emissions Portal (MEP); a digital platform that provides real-time emissions monitoring and supports the formulation of targeted emission reduction strategies [96]. Furthermore, the Thames Net Zero Coalition, launched in 2023, brings together terminal operators, shipping lines, and logistics stakeholders to co-develop Decarbonisation projects and share technological implementation experience. This collaborative framework reinforces the PLA's role as a catalyst for collective action within the Thames maritime ecosystem [93].

Port of Bristol

Energy Supply and Management: The Port of Bristol, managed by The Bristol Port Company, has placed renewable energy and alternative fuels at the core of its Decarbonisation strategy. The port has installed solar photovoltaic systems across warehouses and operational facilities, directly contributing to its renewable power generation capacity and reducing dependency on non-renewable sources [97]. In parallel, the port is evaluating the large-scale adoption of HVO as a low-carbon substitute for diesel fuel, aiming to cut carbon emissions from port machinery and fleet operations. These initiatives align Bristol's energy transition efforts with the UK's broader renewable energy and climate targets [98].

Infrastructure and Equipment: To enhance sustainability in its infrastructure, the Port of Bristol has completed the installation of energy-efficient LED lighting across terminals and operational areas, significantly lowering electricity consumption [97]. In addition, the port has initiated the electrification of its operational equipment, including cranes and forklifts traditionally powered by diesel. This shift reduces direct (Scope 1) emissions and improves energy efficiency while modernising the port's asset base for future low-emission operations [98].

Operational Efficiency: Bristol has implemented IoT-based monitoring systems that allow real-time tracking of equipment performance and energy usage. These systems enable optimised scheduling, improved operational efficiency, and measurable reductions in energy waste [97]. The port has also introduced advanced energy management systems that employ load-balancing algorithms to evenly distribute electrical demand, minimising consumption peaks and enhancing overall energy performance. This digitalised approach reflects a data-driven commitment to operational sustainability [97].

Transport Connectivity: A key element of Bristol's Decarbonisation plan is its investment in rail infrastructure, designed to promote a modal shift from road to rail for freight movement. This initiative aims to reduce emissions from overland logistics and align with the UK's national strategy for low-carbon freight transport [99]. The port also advocates for the use of inland waterways as sustainable alternatives to road transport, facilitating cleaner connectivity between the port and regional trade corridors. These multimodal strategies reinforce Bristol's position as a low-emission logistics hub in the South West [98].

Policy and Regulations: The Port of Bristol has committed to achieving net-zero emissions by 2040, fully consistent with the UK's national Decarbonisation framework and Bristol City Council's local climate policy [97]. The port ensures compliance with UK and EU environmental standards, particularly those targeting reductions in NO_x, SO_x, and particulate matter emissions. This regulatory alignment supports Bristol's operational resilience and its reputation as a sustainable maritime gateway [99].

Stakeholder Partnerships: Collaboration forms a cornerstone of Bristol's sustainability strategy. The port maintains an active partnership with the South West Rail Partnership to advance rail freight solutions and promote low-carbon logistics across the region [99]. Furthermore, the port works closely with local environmental authorities and municipal councils to implement joint sustainability programs, ranging from waste reduction and resource efficiency initiatives to habitat protection efforts, strengthening both environmental and socio-economic outcomes [98].

Table S7. Decarbonisation initiatives at diversified multi-purpose ports

Category	Port of Liverpool	Port of Tilbury	Port of Teesport	Port of London (PLA)	Port of Bristol
Port overview	Managed by Peel Ports; 28.6 Mt cargo and 0.67 M TEU (2023); main UK-US gateway on River Mersey.	Operated by Forth Ports; 16 Mt Cargo; key South East logistics hub with multimodal access.	Managed by PD Ports; 24 Mt cargo; chemical, energy and offshore-wind hub in Teesport Valley.	Managed by Port of London Authority; ≈50 Mt Cargo; terminals along the Thames; major logistics corridor.	Operated by The Bristol Port Co.; 8.5 Mt Cargo; automotive and energy hub for South West England.

Category	Port of Liverpool	Port of Tilbury	Port of Teesport	Port of London (PLA)	Port of Bristol
Energy supply and management	63,000 solar panels (31 MW) → 6,500 tCO ₂ saved yr ⁻¹ ; 100 % renewable electricity; HVO and hydrogen truck pilot.	9.2 MW wind farm + >1 MW solar; 100 % renewable power; 10 MW H ₂ hub (RWE–Mitsui, scalable 100 MW).	4 MW solar (10 MW planned); 100 % renewable power; Hydrogen Transport Hub (Innovate UK).	1.2 MW solar; 100 % renewable; Thames Hydrogen Highway (H ₂ /electric refuelling).	3×2 MW wind turbines (35 % demand) + 1 MW solar; 100 % REGO electricity; Hydrogen South West concept.
Infrastructure and equipment	Electric STS cranes; LED lighting; OPS design for cruise berth; 90 % fleet on HVO; EV charging network.	Shore power-ready Tilbury2 berths; 12 hybrid straddles; all cranes on HVO; 775 m intermodal rail loop; LED estate.	2 electric harbour cranes; 70 % RTGs electrified; OPS-ready grid; 80 % HVO fleet; energy-efficient warehouses.	Zero-emission berth (2025); hybrid and HVO fleet (–50 % CO ₂ by 2022); solar-equipped facilities; OPS grid upgrades.	Inverter quay cranes; HVO reach stackers (60 % fleet); OPS-ready DSCT; EV chargers; LED and IoT metering.

Category	Port of Liverpool	Port of Tilbury	Port of Teesport	Port of London (PLA)	Port of Bristol
Operational efficiency	Navis N4 TOS + AI routing; Vehicle Booking System cuts idling; energy digital twin.	ISO 50001 EMS; IoT dashboards; automated gate and berth booking; smart lighting and quay SCADA.	PortXchange optimisation platform; IoT energy dashboard; AI berth/rail slot scheduler; ISO 14064 inventory.	Maritime Emissions Portal (RightShip); IoT monitoring; JIT berthing trials; ISO 14064 emissions tracking.	IoT-based EAM + Power BI analytics; 5 G logistics test bed; smart lighting and HVAC; ISO 14064 dashboard.
Transport connectivity	Expanded rail terminal; Liverpool – Scotland/Midlands intermodal; modal shift incentive schemes.	New Tilbury–Manchester/Scotland trains; 775 m rail loop; Thames Freeport green corridor.	27 weekly rail services; Modal Shift rebate; Offshore Gateway for Dogger Bank.	River freight +10 % (2023); modal shift road→river/rail; Freeport corridor links.	Dual rail spurs; daily auto and fuel trains; inland waterway freight on Severn/Avon.
Policy and regulations	ISO 14001 and 50001 certified; Clean Maritime Plan alignment; Net Zero 2040 (carbon-neutral 2032).	Clean Maritime Demonstration; Participant; Eco-tariff for low-emission ships; Net Zero 2042 (Forth Ports).	UN Global Compact Signatory; East Coast CCUS cluster; Net Zero 2040.	Air Quality Strategy (~95 % NOx by 2040); Clean Maritime Plan and MARPOL; Net Zero River Plan 2040.	ISO 50001 certified; Eco-tariff pilot (2026); MCPD/CERS compliant; Net Zero 2040.

Category	Port of Liverpool l	Port of Tilbury	Port of Teesport	Port of London (PLA)	Port of Bristol
Stakeholder partners hips	E.ON solar JV; UK- MaRes Hub (£21 M RandD); Port Innovatio n Forum; local clean air alliance.	RWE/Mitsui H ₂ JV; Thames Freeport consortiu m (DPW LG + Ford); Tarmac CMAT modal shift site.	Teesport Valley Hydrogen Hub (TVCA); East Coast CCUS (BP, Equinor); biodiversi ty and reforestat ion programs .	Thames Net Zero Coalition; RightShip data sharing; Hydrogen Highway consortiu m; local council forums.	Hydrogen South West and Rail Partnersh ip; Konecran es digital retrofit; local NGOs (Avonmo uth Plan).
Net-zero goal	Peel Ports Net-Zero 2040 roadmap (ahead of UK target) and Carbon-n eutral operation s 2032	Carbon-neutra l operation s 2032 and Net-zero whole port 2042 (Forth Po rts plan)	Carbon- neutral operation s by 2027 and a net- zero port- wide 204 0 target	Net-Zero River Plan 2040	Net-zero whole-po rt 2040 roadmap

At the end of this supplementary file, all comparative tables and port-level summaries collectively provide the empirical foundation for the comparative assessment presented in the main text. The detailed scoring frameworks and supporting documentation used to derive these assessments are provided in Supplementary File S2.

File S2. Evidence-Based Evaluation of Documented Decarbonisation Implementation across 16 UK Ports and 17 Analytical Cases

This Supplementary File Section 2 presents matrices used in Section 5 of the main manuscript. The six dimensions contain 24 indicators and 408 case-indicator assessments across 17 analytical cases. Scores are linked to the port-level evidence and sources in Supplementary File S1.

Table S8. Documented implementation maturity codes for Energy Supply and Management

Analytical case	Solar Energy	Wind Energy	Hydrogen Integration
Felixstowe	0.4	0	0.2
London Gateway	0.4	0	0
Liverpool	1.0	0	0
Tilbury	1.0	1.0	0.2
Immingham	0.4	0	0.2
Milford Haven	1.0	0	0.2
Teesport	0.7	0	0.2
Grangemouth	0.4	0	0.2
Dover	0.4	0	0
Belfast	0.4	0	0
Tyne	0.4	0	0
Aberdeen	0.7	0.7	0.2
London (PLA)	0.4	0	0.2
Bristol	0.4	0.4	0.2
Hull	0.7	0	0
Southampton (ABP Estate)	1.0	0	0.2
Southampton (DP World Container Terminal)	0	0	0
Median category	0.4	0	0.2

Table S9. Evidence and source map supporting Table S8.

Analytical case	Coding evidence and justification	Source location
Felixstowe	2 MW solar arrays; 100% renewable electricity (Scope 2 = 0); 40 t day ⁻¹ green H ₂ plant (ScottishPower JV).	Table S3 and the cited energy supply and management paragraph in the Port of Felixstowe profile
London Gateway	Large-scale rooftop solar generation: 100% renewable (REGO-backed) grid supply; onshore power available at main berths.	Table S3 and the cited energy supply and management paragraph in the DP World London Gateway profile
Liverpool	63,000 solar panels (31 MW) → 6,500 tCO ₂ saved yr ⁻¹ ; 100 % renewable electricity; HVO and hydrogen truck pilot.	Table S7 and the cited energy supply and management paragraph in the Port of Liverpool profile
Tilbury	9.2 MW wind farm + >1 MW solar; 100 % renewable power; 10 MW H ₂ hub (RWE–Mitsui, scalable 100 MW).	Table S7 and the cited energy supply and management paragraph in the Port of Tilbury profile
Immingham	4.5 MW solar array; 100 % renewable electricity; 76 000 t yr ⁻¹ green H ₂ plant [71].	Table S5 and the cited energy supply and management paragraph in the Port of Immingham profile
Milford Haven	14.5 MW combined solar (port + Dragon LNG); 100 % renewable power; 300 MW Celtic Sea H ₂ hub (10 MW phase 1).	Table S5 and the cited energy supply and management paragraph in the Port of Milford Haven profile
Teesport	4 MW solar (10 MW planned); 100 % renewable power; Hydrogen Transport Hub (Innovate UK).	Table S7 and the cited energy supply and management paragraph in the Port of Teesport profile
Grangemouth	>1 MW solar; 100 % green electricity; Hydrogen Hub feasibility with Scottish Enterprise.	Table S5 and the cited energy supply and management paragraph in the Port of Grangemouth profile
Dover	1.6 MW solar; 100% renewable electricity; port-wide HVO fuel use; DFDS battery-electric ferries (2030 target).	Table S4 and the cited energy supply and management paragraph in the Port of Dover profile

Analytical case	Coding evidence and justification	Source location
Belfast	1.6 MW solar + 4 MWh battery storage; 100% renewable power since 2019; ongoing HVO adoption.	Table S4 and the cited energy supply and management paragraph in the Port of Belfast profile
Tyne	1 MW solar; 100 % renewable (REGO); Dogger Bank 3.6 GW OandM base; hydrogen pilot (LEP 2023).	Table S6 and the cited energy supply and management paragraph in the Port of Tyne profile
Aberdeen	1.5 MW solar + micro-wind; 100 % renewable power; 10 MW bp–Scottish Enterprise H ₂ hub (phase 1).	Table S6 and the cited energy supply and management paragraph in the Port of Aberdeen profile
London (PLA)	1.2 MW solar; 100 % renewable; Thames Hydrogen Highway (H ₂ /electric refuelling).	Table S7 and the cited energy supply and management paragraph in the Port of London (PLA) profile
Bristol	3×2 MW wind turbines (35 % demand) + 1 MW solar; 100 % REGO electricity; Hydrogen South West concept.	Table S7 and the cited energy supply and management paragraph in the Port of Bristol profile
Hull	6.5 MWp solar (largest UK port PV); 100% renewable electricity; hydrogen hub FEED 2025.	Table S4 and the cited energy supply and management paragraph in the Port of Hull profile
Southampton (ABP Estate)	1.6 MW solar; 100% REGO electricity; Fawley 250 MW hydrogen hub (FID 2025).	Table S4 and the cited energy supply and management paragraph in the Southampton (ABP Estate) profile
Southampton (DP World Container Terminal)	Fully renewable power supply; entire equipment fleet on HVO biofuel; future on-site battery storage under review.	Table S3 and the cited energy supply and management paragraph in the Southampton (DP World Container Terminal) profile

Table S10. Documented implementation maturity codes for Infrastructure and Equipment

Analytical case	Shore Power	Equipment		
		Electrification	Efficient Infra	HVO Fuel
Felixstowe	0.2	0.7	0.4	0
London Gateway	0.2	0.4	0.4	0
Liverpool	0.2	0.4	0.4	0.4
Tilbury	0.2	0.4	0.4	0.4
Immingham	0.2	0.4	0.4	0.4
Milford Haven	0.2	0.4	0.4	0
Teesport	0.2	0.4	0.4	0
Grangemouth	0.2	0.4	0.4	0
Dover	0.2	0.7	0.4	0
Belfast	0.2	0.2	0.4	0
Tyne	0.2	0.4	0.4	0
Aberdeen	0.2	0.4	0.4	0
London (PLA)	0.2	0.2	0.4	0
Bristol	0.2	0.4	0.4	0.4
Hull	0.2	0.4	0.4	0
Southampton (ABP Estate)	0.4	0.7	0.7	0.2
Southampton (DP World Container Terminal)	0.2	1.0	0.4	0.4
Median category	0.2	0.4	0.4	0

Table S11. Evidence and source map supporting Table S10.

Analytical case	Coding evidence and justification	Source location
Felixstowe	17 electric RTGs; 48 battery tractors; sitewide LED upgrades; shore power feasibility ongoing.	Table S3 and the cited infrastructure and equipment paragraph in the Port of Felixstowe profile
London Gateway	180 electric straddle carriers; 60 ASCs on green tariff; shore power installed; smart buildings and EV chargers.	Table S3 and the cited infrastructure and equipment paragraph in the DP World London Gateway profile
Liverpool	Electric STS cranes; LED lighting; OPS design for cruise berth; 90 % fleet on HVO; EV charging network.	Table S7 and the cited infrastructure and equipment paragraph in the Port of Liverpool profile
Tilbury	Shore power-ready Tilbury2 berths; 12 hybrid straddles; all cranes on HVO; 775 m intermodal rail loop; LED estate.	Table S7 and the cited infrastructure and equipment paragraph in the Port of Tilbury profile
Immingham	3 hybrid LHM cranes; electric RTGs; shore power FEED under ABP 2040 plan; 50 % fleet on HVO; ISO 50001 EMS.	Table S5 and the cited infrastructure and equipment paragraph in the Port of Immingham profile
Milford Haven	Seven berths OPS (2024–27 design); EV fleet and chargers; LNG compressor electrification; FLOW assembly yard.	Table S5 and the cited infrastructure and equipment paragraph in the Port of Milford Haven profile
Teesport	2 electric harbour cranes; 70 % RTGs electrified; OPS-ready grid; 80 % HVO fleet; energy-efficient warehouses.	Table S7 and the cited infrastructure and equipment paragraph in the Port of Teesport profile
Grangemouth	3 STS cranes (1 electric); 5 hybrid straddle carriers; shore power-ready quays; 80 % mobile fleet on HVO; ISO 50001.	Table S5 and the cited infrastructure and equipment paragraph in the Port of Grangemouth profile

Analytical case	Coding evidence and justification	Source location
Dover	OPS at cruise berth; 2×3 MVA shore power for ferries (planned); hybrid ferries in service; EV chargers and smart grid.	Table S4 and the cited infrastructure and equipment paragraph in the Port of Dover profile
Belfast	6 HVO-ready cranes; pilot autonomous EV tractors; LED and sub-metering; EfW plant (14 MW export).	Table S4 and the cited infrastructure and equipment paragraph in the Port of Belfast profile
Tyne	6 HVO-ready cranes; hybrid RTG pilot; OPS feasibility (CMDC 3); heavy-lift Clean Energy Park quay; 80 % fleet on HVO; e-pilot boat 2025.	Table S6 and the cited infrastructure and equipment paragraph in the Port of Tyne profile
Aberdeen	£420 M South Harbour (1,450 m quay, 15 m draft); OPS ready; 6 HVO MHCs + electric cranes; EV chargers; 4 MWh battery study; ISO 50001.	Table S6 and the cited infrastructure and equipment paragraph in the Port of Aberdeen profile
London (PLA)	Zero-emission berth (2025); hybrid and HVO fleet (– 50 % CO ₂ by 2022); solar-equipped facilities; OPS grid upgrades.	Table S7 and the cited infrastructure and equipment paragraph in the Port of London (PLA) profile
Bristol	Inverter quay cranes; HVO reach stackers (60 % fleet); OPS-ready DSCT; EV chargers; LED and IoT metering.	Table S7 and the cited infrastructure and equipment paragraph in the Port of Bristol profile
Hull	Siemens Gamesa OandM facility; hybrid cranes and HVO fleet (80%); OPS feasibility; hydrogen-ready quays.	Table S4 and the cited infrastructure and equipment paragraph in the Port of Hull profile
Southampton (ABP Estate)	OPS (2×3 MVA) at cruise berths; straddle and yard fleet on HVO; EV forklifts; LED rollout; private 5G IoT grid.	Table S4 and the cited infrastructure and equipment paragraph in the Southampton (ABP Estate) profile
Southampton (DP World Container Terminal)	>120 hybrid/electric straddle carriers; full HVO fuelling system; shore power readiness; LED and workshop retrofits.	Table S3 and the cited infrastructure and equipment paragraph in the Southampton (DP World Container Terminal) profile

Table S12. Documented implementation maturity codes for Operational Efficiency

Analytical case	IoT-Based Energy and Equipment Monitoring	Automation and Smart Systems	Energy Management System (EMS)	Just-in-Time (JIT) Ops	Vehicle Booking / Traffic Opt.
Felixstowe	0.4	0.4	0.2	0.2	0.7
London Gateway	0.7	0.7	0.4	0.2	0.4
Liverpool	0.4	0.4	0.2	0	0.4
Tilbury	0.4	0.2	0.2	0.2	0.4
Immingham	0.2	0.2	0.2	0	0.2
Milford Haven	0.2	0.2	0.2	0	0
Teesport	0.4	0.2	0.2	0	0.4
Grangemouth	0.2	0.2	0	0	0.2
Dover	0.2	0.2	0.2	0.4	0.4
Belfast	0.2	0.2	0.2	0	0.2
Tyne	0.2	0.2	0.2	0	0.2
Aberdeen	0.4	0.2	0.2	0	0.2
London (PLA)	0.4	0.2	0.2	0.2	0
Bristol	0.2	0.2	0.2	0	0.2
Hull	0.2	0.2	0.2	0	0.2
Southampton (ABP Estate)	0.7	0.4	0.4	0.4	0.4
Southampton (DP World Container Terminal)	0.7	0.7	0.4	0.4	0.4
Median category	0.4	0.2	0.2	0	0.2

Table S13. Evidence and source map supporting Table S12.

Analytical case	Coding evidence and justification	Source location
Felixstowe	IoT-based energy dashboard; digital emission monitoring; semi-automated cranes; gate booking system.	Table S3 and the cited operational efficiency paragraph in the Port of Felixstowe profile
London Gateway	Integrated TOS automation; AI-based yard and vessel scheduling; IoT energy load balancing.	Table S3 and the cited operational efficiency paragraph in the DP World London Gateway profile
Liverpool	Navis N4 TOS + AI routing; Vehicle Booking System cuts idling; energy digital twin.	Table S7 and the cited operational efficiency paragraph in the Port of Liverpool profile
Tilbury	ISO 50001 EMS; IoT dashboards; automated gate and berth booking; smart lighting and quay SCADA.	Table S7 and the cited operational efficiency paragraph in the Port of Tilbury profile
Immingham	IoT cargo flow platform; digital GHG inventory (ISO 14064); automated vehicle scheduling reduces idling.	Table S5 and the cited operational efficiency paragraph in the Port of Immingham profile
Milford Haven	AI berth scheduler for LNG tankers; 5 G/IoT Port Energy Platform (EMS); ISO 14064 GHG dashboard.	Table S5 and the cited operational efficiency paragraph in the Port of Milford Haven profile

Analytical case	Coding evidence and justification	Source location
Teesport	PortXchange optimisation platform; IoT energy dashboard; AI berth/rail slot scheduler; ISO 14064 inventory.	Table S7 and the cited operational efficiency paragraph in the Port of Teesport profile
Grangemouth	Upgraded TOS with IoT yard telemetry, real-time energy dashboard, rail slot optimiser, and public ESG KPI portal.	Table S5 and the cited operational efficiency paragraph in the Port of Grangemouth profile
Dover	Dover TAP digital traffic management; IoT berth sensors; AI berth optimiser; ISO 14064 reporting.	Table S4 and the cited operational efficiency paragraph in the Port of Dover profile
Belfast	IoT metering and Power BI EMS; AI berth optimisation; ESG dashboard.	Table S4 and the cited operational efficiency paragraph in the Port of Belfast profile
Tyne	Clean Tyne IoT EMS (Newcastle Univ.); AI berth/rail optimiser; private 5 G data network; ISO 14064 dashboard.	Table S6 and the cited operational efficiency paragraph in the Port of Tyne profile
Aberdeen	Smart Port real-time EMS; AI berth and gate optimiser; Just-in-Time arrival pilot; ISO 14064 GHG monitoring.	Table S6 and the cited operational efficiency paragraph in the Port of Aberdeen profile
London (PLA)	Maritime Emissions Portal (RightShip); IoT monitoring; JIT berthing trials; ISO 14064 emissions tracking.	Table S7 and the cited operational efficiency paragraph in the Port of London (PLA) profile

Analytical case	Coding evidence and justification	Source location
Bristol	IoT-based EAM + Power BI analytics; 5 G logistics test bed; smart lighting and HVAC; ISO 14064 dashboard.	Table S7 and the cited operational efficiency paragraph in the Port of Bristol profile
Hull	IoT monitoring; Power BI energy analytics; 5 G yard optimisation; ISO 14064 inventory.	Table S4 and the cited operational efficiency paragraph in the Port of Hull profile
Southampton (ABP Estate)	5 G-enabled IoT dashboard; vehicle booking and AI berth scheduling; ISO 14064 reporting.	Table S4 and the cited operational efficiency paragraph in the Southampton (ABP Estate) profile
Southampton (DP World Container Terminal)	Navis N4 TOS with AI analytics; digital twin for planning; ISO 50001 energy management; real-time telemetry.	Table S3 and the cited operational efficiency paragraph in the Southampton (DP World Container Terminal) profile

Table S14. Documented implementation maturity codes for Transport Connectivity

Analytical case	Rail Infra Expansion	Green Hinterland Transport	Short-Sea / Inland Waterway	Green Maritime Corridor	Offshore- Wind Logistics Support
Felixstowe	0.7	0.4	0.2	0	0
London Gateway	0.7	0.4	0.2	0.2	0
Liverpool	0.4	0.2	0.4	0	0
Tilbury	0.4	0.2	0.4	0	0

Analytical case	Rail Infra Expansi on	Green Hinterla nd Transpo rt	Short-Sea / Inland Waterw ay	Green Maritim e Corridor	Offshore- Wind Logistics Support
Immingham	0.4	0.2	0.2	0	0.2
Milford Haven	0.2	0.2	0.4	0	0.2
Teesport	0.4	0.2	0.2	0	0.2
Grangemouth	0.4	0.2	0.2	0	0.2
Dover	0.2	0.2	0.7	0.4	0
Belfast	0.2	0.2	0.4	0	0.7
Tyne	0.2	0.2	0.2	0	0.7
Aberdeen	0.2	0.2	0.2	0	0.7
London (PLA)	0.4	0.4	0.7	0.2	0
Bristol	0.4	0.2	0.2	0	0
Hull	0.4	0.2	0.2	0	1.0
Southampton (ABP Estate)	0.7	0.4	0.4	0	0.2
Southampton (DP World Container Terminal)	0.7	0.4	0.4	0	0.2
Median category	0.4	0.2	0.2	0	0.2

Table S15. Evidence and source map supporting Table S14.

Analytical case	Coding evidence and justification	Source location
Felixstowe	Rail terminal upgrade (35% modal share); Green Freight Corridor; incentives for rail freight.	Table S3 and the cited transport connectivity paragraph in the Port of Felixstowe profile
London Gateway	Longest on-dock rail (775 m); >35% by rail; short-sea routes to UK/Benelux; Thames Freeport corridors.	Table S3 and the cited transport connectivity paragraph in the DP World London Gateway profile
Liverpool	Expanded rail terminal; Liverpool–Scotland/Midlands intermodal; modal shift incentives.	Table S7 and the cited transport connectivity paragraph in the Port of Liverpool profile
Tilbury	New Tilbury–Manchester/Scotland trains; 775 m rail loop; Thames Freeport green corridor.	Table S7 and the cited transport connectivity paragraph in the Port of Tilbury profile
Immingham	Gauge-enhanced rail links; Green Hinterland Freight initiative; CO ₂ pipeline integration (Viking CCS).	Table S5 and the cited transport connectivity paragraph in the Port of Immingham profile
Milford Haven	Rebuilt rail interchange; green freight corridor (rail + barge); Celtic Sea FLOW supply chain network.	Table S5 and the cited transport connectivity paragraph in the Port of Milford Haven profile

Analytical case	Coding evidence and justification	Source location
Teesport	27 weekly rail services; Modal Shift rebate; Offshore Gateway for Dogger Bank.	Table S7 and the cited transport connectivity paragraph in the Port of Teesport profile
Grangemouth	Daily Tilbury and Midlands rail services; rail rebate boosts modal share; Forth Green Freeport corridor.	Table S5 and the cited transport connectivity paragraph in the Port of Grangemouth profile
Dover	Green Corridor (Calais–Dunkirk zero-carbon route); freight rail feasibility via GCSS.	Table S4 and the cited transport connectivity paragraph in the Port of Dover profile
Belfast	Rail terminal upgrade; Belfast–Liverpool green corridor; offshore-wind logistics quay.	Table S4 and the cited transport connectivity paragraph in the Port of Belfast profile
Tyne	Tyne Dock intermodal terminal; daily automotive rail links; Green North Sea corridor (Tyne–Amsterdam/Gothenburg).	Table S6 and the cited transport connectivity paragraph in the Port of Tyne profile
Aberdeen	Nestrans rail upgrade study; modal shift incentives for bulk cargo; integration with Energy Transition Zone (ETZ).	Table S6 and the cited transport connectivity paragraph in the Port of Aberdeen profile
London (PLA)	River freight +10 % (2023); modal shift road→river/rail; Freeport corridor links.	Table S7 and the cited transport connectivity paragraph in the Port of London (PLA) profile

Analytical case	Coding evidence and justification	Source location
Bristol	Dual rail spurs; daily auto and fuel trains; inland waterway freight on Severn/Avon.	Table S7 and the cited transport connectivity paragraph in the Port of Bristol profile
Hull	Daily intermodal rail, inland barge pilot; Freeport hydrogen corridor.	Table S4 and the cited transport connectivity paragraph in the Port of Hull profile
Southampton (ABP Estate)	3 on-dock rail terminals; Modal Shift rebate (30 → 40 % rail share); Solent green logistics corridor.	Table S4 and the cited transport connectivity paragraph in the Southampton (ABP Estate) profile
Southampton (DP World Container Terminal)	“Modal Shift Programme” (£100/box rail rebate); rail share >30% → target 40%; daily trains to Midlands/Scotland.	Table S3 and the cited transport connectivity paragraph in the Southampton (DP World Container Terminal) profile

Table S16. Documented implementation maturity codes for Policy and Regulations

Analytical case	UK/EU Compliance	Carbon Offset and Emission Reduction	Port-Specific Air-Quality Strategy
Felixstowe	0.4	0.2	0.2
London Gateway	0.4	0.4	0.2
Liverpool	0.4	0.2	0.2
Tilbury	0.4	0.2	0.2

Analytical case	UK/EU Compliance	Carbon Offset and Emission Reduction	Port-Specific Air-Quality Strategy
Immingham	0.4	0.2	0.4
Milford Haven	0.4	0.2	0.2
Teesport	0.4	0.4	0.2
Grangemouth	0.4	0.2	0.2
Dover	0.4	0.7	0.4
Belfast	0.4	0.4	0.7
Tyne	0.4	0.2	0.2
Aberdeen	0.4	0.4	0.2
London (PLA)	0.7	0.4	1.0
Bristol	0.4	0.2	0.2
Hull	0.4	0.4	0.4
Southampton (ABP Estate)	0.7	0.4	0.7
Southampton (DP World Container Terminal)	0.4	0.4	0.4
Median category	0.4	0.4	0.2

Table S17. Evidence and source map supporting Table S16.

Analytical case	Coding evidence and justification	Source location
Felixstowe	Net-zero Scope 1–2 by 2035; SBTi-aligned; IMO/MARPOL-compliant.	Table S3 and the cited policy and regulation paragraph in the Port of Felixstowe profile
London Gateway	Net zero operations by 2050; ISO 14001; UK Clean Maritime Plan compliance.	Table S3 and the cited policy and regulation paragraph in the DP World London Gateway profile
Liverpool	ISO 14001 and 50001 certified; Clean Maritime Plan alignment; Net Zero 2040 (carbon-neutral 2032).	Table S7 and the cited policy and regulation paragraph in the Port of Liverpool profile
Tilbury	Clean Maritime Demonstration Participant; Eco-tariff for low-emission ships; Net Zero 2042 (Forth Ports).	Table S7 and the cited policy and regulation paragraph in the Port of Tilbury profile
Immingham	ABP Net Zero 2040 plan; Zero Carbon Humber and Viking CCS cluster participant; MARPOL compliant.	Table S5 and the cited policy and regulation paragraph in the Port of Immingham profile
Milford Haven	Trust Port Net Zero 2040 roadmap; Air Quality Strategy; Clean Maritime Demonstration participant.	Table S5 and the cited policy and regulation paragraph in the Port of Milford Haven profile

Analytical case	Coding evidence and justification	Source location
Teesport	UN Global Compact Signatory; East Coast CCUS cluster; Net Zero 2040.	Table S7 and the cited policy and regulation paragraph in the Port of Teesport profile
Grangemouth	Carbon neutral 2032 → Net Zero 2042; SEPA and Clean Maritime Plan compliant; eco-tariff pilot (2026).	Table S5 and the cited policy and regulation paragraph in the Port of Grangemouth profile
Dover	Net zero 2040; 50 % CO ₂ reduction 2030; MARPOL VI and Clydebank Declaration.	Table S4 and the cited policy and regulation paragraph in the Port of Dover profile
Belfast	Net zero port 2030 (estate 2040); Air Quality Strategy; full MARPOL/CERS compliance.	Table S4 and the cited policy and regulation paragraph in the Port of Belfast profile
Tyne	Port Air Quality Strategy; MARPOL compliance; Clydebank Declaration green corridor pilot; Net Zero 2030 (fully electric estate 2040).	Table S6 and the cited policy and regulation paragraph in the Port of Tyne profile
Aberdeen	Net Zero 2040 (£55 M capex); MARPOL and UK Clean Maritime compliant; carbon intensity KPI in annual report.	Table S6 and the cited policy and regulation paragraph in the Port of Aberdeen profile
London (PLA)	Air Quality Strategy (–95 % NO _x by 2040); Clean Maritime Plan and MARPOL; Net Zero River Plan 2040.	Table S7 and the cited policy and regulation paragraph in the Port of London (PLA) profile

Analytical case	Coding evidence and justification	Source location
Bristol	ISO 50001 certified; Eco-tariff pilot (2026); MCPD/CERS compliant; Net Zero 2040.	Table S7 and the cited policy and regulation paragraph in the Port of Bristol profile
Hull	ABP “Ready for Tomorrow” plan → Net zero 2040; Humber Clean Air Zone.	Table S4 and the cited policy and regulation paragraph in the Port of Hull profile
Southampton (ABP Estate)	ABP “Ready for Tomorrow” plan → Net zero 2040; Solent Clean Air Zone; Clean Maritime Demo.	Table S4 and the cited policy and regulation paragraph in the Southampton (ABP Estate) profile
Southampton (DP World Container Terminal)	DP World target: -42% Scope 1–2 by 2030; net zero by 2050; local air quality strategy active.	Table S3 and the cited policy and regulation paragraph in the Southampton (DP World Container Terminal) profile

Table S18. Documented implementation maturity codes for Stakeholder Partnerships

Analytical case	Local			
	Industry Collaborations	Government Collaborations	National Collaborations	Research Collaborations
Felixstowe	0.4	0.2	0.2	0.2
London Gateway	0.4	0.2	0.2	0.2
Liverpool	0.4	0.4	0.2	0.2

Analytical case	Industry Collaborati ons	Local Governmen t Collaborati ons	National Collaborati ons	Research Collaboratio ns
Tilbury	0.4	0.2	0.2	0.2
Immingham	0.4	0.2	0.2	0.2
Milford Haven	0.4	0.4	0.2	0.2
Teesport	0.7	0.4	0.4	0.4
Grangemouth	0.4	0.2	0.2	0.2
Dover	0.4	0.4	0.4	0.2
Belfast	0.7	0.4	0.4	0.4
Tyne	0.7	0.4	0.4	0.4
Aberdeen	0.7	0.4	0.4	0.4
London (PLA)	0.4	0.4	0.4	0.4
Bristol	0.4	0.4	0.2	0.2
Hull	1.0	0.4	0.4	0.4
Southampton (ABP Estate)	0.7	0.4	0.4	0.4
Southampton (DP World Container Terminal)	0.4	0.2	0.2	0.2
Median category	0.4	0.4	0.2	0.2

Table S19. Evidence and source map supporting Table S18.

Analytical case	Coding evidence and justification	Source location
Felixstowe	ScottishPower (H ₂ hub); Ryse Hydrogen; Cranfield Univ.; Freeport East cluster.	Table S3 and the cited stakeholder partnerships paragraph in the Port of Felixstowe profile
London Gateway	DP World RandD Centre (automation); Rail Freight Group; Thames Freeport and NGOs (biodiversity offsets).	Table S3 and the cited stakeholder partnerships paragraph in the DP World London Gateway profile
Liverpool	E. ON solar JV; UK-MaRes Hub (£21 M RandD); Port Innovation Forum; local clean air alliance.	Table S7 and the cited stakeholder partnerships paragraph in the Port of Liverpool profile
Tilbury	RWE/Mitsui H ₂ JV; Thames Freeport consortium (DPW LG + Ford); Tarmac CMAT modal shift site.	Table S7 and the cited stakeholder partnerships paragraph in the Port of Tilbury profile
Immingham	Air Products H ₂ plant; Zero Carbon Humber alliance; UK Track 1 CCS funding; VPI and Phillips 66 industrial tenants.	Table S5 and the cited stakeholder partnerships paragraph in the Port of Immingham profile
Milford Haven	RWE and Dragon LNG solar projects; Celtic Freeport (RWE, Valero); Marine Energy Wales and Crown Estate FLOW projects.	Table S5 and the cited stakeholder partnerships paragraph in the Port of Milford Haven profile
Teesport	Teesport Valley Hydrogen Hub (TVCA); East Coast CCUS (BP, Equinor); biodiversity and reforestation programs.	Table S7 and the cited stakeholder partnerships paragraph in the Port of Teesport profile
Grangemouth	Scottish Enterprise H ₂ hub; Forth Green Freeport consortium; Kalmar hybrid tech pilot; local skills programs.	Table S5 and the cited stakeholder partnerships paragraph in the Port of Grangemouth profile

Analytical case	Coding evidence and justification	Source location
Dover	Clean Ferry Power consortium (WMG, DFDS, PandO); Green Corridor Short Straits; Kent CC and DfT.	Table S4 and the cited stakeholder partnerships paragraph in the Port of Dover profile
Belfast	Siemens battery JV; Stena Line corridor; City Deal (£1 bn); Innovate UK CMDC.	Table S4 and the cited stakeholder partnerships paragraph in the Port of Belfast profile
Tyne	Equinor and SSE (Dogger Bank base); North East LEP H ₂ projects; Innovate UK CMDC grants; Tyne Estuary 2030 biodiversity partners.	Table S6 and the cited stakeholder partnerships paragraph in the Port of Tyne profile
Aberdeen	bp / Scottish Enterprise H ₂ hub; Siemens shore power project; Nestrans and City Deal transport partners; ETZ cluster collaboration.	Table S6 and the cited stakeholder partnerships paragraph in the Port of Aberdeen profile
London (PLA)	Thames Net Zero Coalition; RightShip data sharing; Hydrogen Highway consortium; local council forums.	Table S7 and the cited stakeholder partnerships paragraph in the Port of London (PLA) profile
Bristol	Hydrogen South West and Rail Partnership; Konecranes digital retrofit; local NGOs (Avonmouth Plan).	Table S7 and the cited stakeholder partnerships paragraph in the Port of Bristol profile
Hull	Siemens Gamesa Renewables, Humber Freeport and Zero Carbon Humber; local councils.	Table S4 and the cited stakeholder partnerships paragraph in the Port of Hull profile
Southampton (ABP Estate)	ExxonMobil/Air Liquide (H ₂ hub); Solent Freeport; Verizon (5 G); Solent Stevedores pilot.	Table S4 and the cited stakeholder partnerships paragraph in the Southampton (ABP Estate) profile

Analytical case	Coding evidence and justification	Source location
Southampton (DP World Container Terminal)	Network Rail and freight operators; Kalmar (hybrid fleet); DP World (documented HVO transition).	Table S3 and the cited stakeholder partnerships paragraph in the Southampton (DP World Container Terminal) profile

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