Funded by
the European Union

HORIZON EUROPE PROGRAMME – TOPIC: HORIZON-CL5-2022-D5-01-02

AENEAS

innovAtive ENErgy storage systems onboArd vesselS

Deliverable D6.6: Roadmap for expansion of application area, including access to public and private funds

Primary Author(s)	Lidia Rossi | ForMare Polo Nazionale per lo Shipping srl (FMAR)
Deliverable Type	Report
Dissemination Level	Public
Due Date (Annex I)	31.01.2026
Pages	46
Document Version	3.0 (Final)
GA Number	101095902
Project Coordinator	Mohsen Akbarzadeh │Flanders Make (FM) (Mohsen.Akbarzadeh@flandersmake.be)

Contributors	
Name	**Organisation**
Lidia Rossi	ForMare
Anesa Begovic	i2m Unternehmensentwicklung GmbH

Formal Reviewers	
Name	**Organisation**
Mohsen Akbarzadeh	Flanders Make (FM)
Arnau Campos Asensio	FUNDACION VALENCIA (FV)
Jaime Sanchez	SOERMAR (SOER)

Version Log			
Rev #	**Date**	**Author**	**Description**
0.1	20.11.2025	Lidia Rossi (FMAR)	Draft
0.2	16.12.2025	Lidia Rossi (FMAR)	Advanced Draft version
0.4	16.01.2026	Mohsen Akbarzadeh (FM)	Quality review
1.0	22.01.2026	Arnau Campos Asensio (FV)	Quality review
1.1	23.01.2026	Jaime Sanchez (SOER)	Quality review
2.0	26.01.2026	Anesa Begovic (i2m)	Formatting check
3.0	30.01.2026	Mohsen Akbarzadeh (FM)	Coordinator review and approval, deliverable ready for submission

Project Abstract

AENEAS aims to contribute towards climate-neutral and environmentally friendly water transport through three new next generation clean energy storage solutions. Eventual impact is an increase of the global competitiveness of the EU waterborne transport sector by European technology leadership for energy storage solutions for diverse waterborne applications. AENEAS will develop three innovative electric Energy Storage Solutions (ESS) for waterborne transport, which are advanced beyond the traditional battery systems, including Solid-state batteries (SSB), Supercapacitors (SC) and a Hybrid system which combines SSB and SC. The solutions enable (partial or full) electric shipping, taking into account conditions specific ships might encounter, including adverse conditions outside sheltered waters or going upstream on rivers. AENEAS will evaluate them for a range of applications and end uses in short-sea shipping and in-land waterways. At the same time AENEAS will define the pathway for the three ESSs for application in different ship types, achieving a comprehensive understanding of the ESSs and their applicability for diverse waterborne transport.

Table of Contents

Public Summary

Deliverable D6.6 provides the roadmap for the expansion of the application area of AENEAS Advanced Electrical (AE) energy storage solutions and for accessing public and private funds. Building on the impact assessment (D6.2), the feasibility and business-case analysis (D6.3), the interim exploitation plan (D6.1), and the technical roadmap towards on-board demonstrators (D6.5), Deliverable D6.6 provides a structured deployment and scaling perspective for Solid-State Batteries (SSB), Semi-Solid-State Batteries (SSSB), Supercapacitors (SC), and hybrid ESS configurations, focusing on implementation pathways, enabling conditions, and funding requirements. The deliverable is articulated into five main components. First, it maps the potential market segments in which AE technologies can be deployed in the medium and long term, extending the fleet segmentation of D6.3 beyond the initial demonstrator use-cases defined in WP1 and the technical roadmap of D6.5. Second, it analyses the drivers and barriers for adoption, integrating environmental and economic evidence from D6.2 and D6.3 with the AENEAS value proposition and SWOT analysis developed in D6.1. Third, the report defines application and business model archetypes for the different AE technologies and vessel segments, clarifying the roles of the main stakeholders and the possible revenue and value-sharing logics along the maritime energy storage value chain. Fourth, it integrates life-cycle assessment (LCA), life-cycle cost (LCC) and total cost of ownership (TCO) results to derive segment-wise indicators of environmental and economic attractiveness, such as relative TCO, greenhouse gas reduction potential and safety-related benefits. Finally, D6.6 maps public and private funding opportunities that can support different phases of deployment, from research and demonstration to early commercial projects and large-scale fleet retrofit, and proposes a multi-phase expansion roadmap up to 2030, aligned with the Revised IMO GHG Strategy 2023 and EU decarbonisation policies. The roadmap connects technical milestones (from D6.5), market expansion steps, regulatory developments and funding windows, thus providing a strategic guide for stakeholders and informing the Final Exploitation Plan (D6.4).

1 Introduction

The large-scale diffusion of Advanced Energy Storage (AE) solutions in the waterborne transport sector is embedded in a rapidly evolving socio-technical context in which regulatory pressure, market restructuring, and infrastructure readiness converge. Over the past decade, maritime decarbonisation has shifted from a long-term aspiration to an operational constraint, driven by binding international and European policy frameworks. At global level, the Revised GHG Strategy of the International Maritime Organization (IMO, 2023) establishes a clear trajectory towards net-zero emissions by or around 2050, with intermediate milestones that already affect technology and investment decisions in the 2020s and early 2030s. At European level, the Fit for 55 legislative package translates climate targets into enforceable instruments for shipping, notably through the FuelEU Maritime Regulation, the inclusion of maritime transport in the EU Emissions Trading System, and complementary measures on port-side electrification and alternative fuels promoted by the European Commission. Within this framework, the role of on-board electrification and energy storage has been progressively reframed. AE solutions are no longer evaluated solely as incremental efficiency measures, but as structural enablers that support compliance with GHG-intensity reduction requirements, zero-emission port operations, and increasingly stringent local air-quality standards. Policy analyses and scenario studies consistently indicate that near- and mid-term decarbonisation targets cannot be achieved through fuel substitution alone, particularly for short-sea shipping, inland navigation and port-intensive operations. Instead, system-level solutions combining fuels, energy efficiency and electrification, explicitly including on-board energy storage, are required already in the current decade (IMO, 2023; International Energy Agency, 2021). At the same time, the market environment for maritime AE technologies remains structurally constrained. Despite significant advances in battery and power electronics technologies, deployment decisions are dominated by vessel-level considerations: mission-dependent load profiles, space and weight limitations, stability margins, safety and fire-risk management, certification transferability, and the availability of charging and grid infrastructures in ports. These factors explain why the potential of AE solutions cannot be interpreted as an abstract or purely technological variable. Instead, it emerges from the alignment between operational profiles, integration requirements at ship-system level, infrastructure conditions, and regulatory trajectories. Industry outlooks such as the Maritime Forecast to 2050 by DNV underline that energy storage will play a pivotal role precisely in those segments where operational flexibility, peak-shaving and zero-emission modes are required, but only where integration risks and lifecycle costs can be credibly managed. From a safety and governance perspective, this transition is accompanied by the gradual consolidation of regulatory and classification guidance for shipboard energy storage. The development of dedicated rules and recommendations by classification societies and maritime authorities, including guidance issued by the European Maritime Safety Agency (EMSA), reflects the movement of AE solutions from experimental applications towards codified deployment domains. This regulatory maturation does not remove constraints; rather, it makes explicit the conditions under which storage systems can be safely and repeatedly integrated on board ships, reinforcing the need for evidence-based deployment strategies. Against this backdrop, the expansion of AE solutions beyond initial demonstrators must be understood as a conditional and phased process, shaped by both opportunity and constraint. Public and private stakeholders increasingly recognise the environmental and operational value of electrification, yet investment decisions remain sensitive to residual technological risk, capital intensity and uncertainty over long-term regulatory compliance benefits. As a result, the diffusion of AE technologies depends on the availability of structured pathways that link validated technical evidence with market segments, funding mechanisms and geographical contexts where enabling conditions are present. It is within this broader context, characterised by tightening climate policy, cautious but growing market interest, and evolving regulatory and safety frameworks, that the analytical work developed in this deliverable is positioned. The expansion roadmap discussed in D6.6 is therefore not a generic market outlook, but a response to a concrete systemic challenge: identifying where, and under which conditions, advanced energy storage can credibly contribute to near-term emission reductions and energy efficiency improvements in maritime and inland waterway transport, while remaining aligned with medium-term decarbonisation pathways defined at EU and IMO level.

1.1 Rational of this deliverable

Work Package 6 (WP6), *"Impact analysis, business models and exploitation"*, addresses the conditions under which the AE solutions developed within AENEAS can generate verifiable environmental, economic and industrial value for the European waterborne transport sector. Within WP6, Task 6.4, *"Future deployment of technologies"*, focuses on translating validated technical results into structured deployment, replication and exploitation pathways, consistent with the maturity, feasibility and safety boundaries established by the project. Deliverable D6.5 defines the technical deployment backbone of AENEAS. It establishes, through a gate-based and segment-centric logic, the pathway towards two full-scale on-board demonstrators by 2027, advancing selected AE Energy Storage System (ESS) solutions to Technology Readiness Levels (TRL) 7-8. In doing so, D6.5 determines what is technically feasible, under which integration, safety and operational conditions, and within which clearly bounded applicability envelopes. Deliverable D6.6 builds directly on this foundation. Its role is to operationalise the post-demonstration phase, addressing a distinct but complementary question: *where*, *under which constraints*, and *through which mechanisms* validated AE solutions can be replicated. Accordingly, D6.6 focuses on market expansion and scaling conditions beyond the demonstrators, consolidating the exploitation vision formulated in the Interim Exploitation Plan (D6.1) and the feasibility-driven business cases developed in D6.3. This consolidation is performed under a strict methodological constraint: no new application domains, no new performance assumptions and no speculative market projections are introduced. Instead, the deliverable provides a structured "deployment grammar", linking technical readiness, environmental and economic impact, funding structures and regulatory context into a coherent, auditable expansion framework. The rationale of D6.6 is therefore to synthesise the technical, environmental and economic evidence generated across WP6 and the technical Work Packages into a conservative, replication-oriented expansion strategy. This strategy is explicitly aligned with European and international decarbonisation trajectories, i.e., most notably the Revised IMO GHG Strategy 2023 and relevant EU climate and energy policies, while remaining fully subordinate to the feasibility and readiness discipline established by AENEAS. In this sense, D6.6 is designed to support downstream exploitation planning and decision-making without diluting or bypassing the technical constraints validated by the project.

1.2 Objectives

Within this scope, Deliverable D6.6 pursues the following specific objectives:

1. To map potential market segments for AE technologies beyond the on-board demonstrator use-cases, refining and extending the fleet segmentation developed under Task 6.2, while remaining strictly within the applicability envelopes validated by D6.3 and D6.5.
2. To analyse the drivers and barriers shaping the adoption of AE solutions across vessel segments and operational contexts, integrating environmental and economic evidence

from Task 6.1 with feasibility and adequacy outcomes from Task 6.2, and consolidating these elements into a structured SWOT-based interpretation.

3. To define application models and business model archetypes for semi-solid-state batteries (SSSB), supercapacitors (SC) and hybrid ESS configurations, clarifying stakeholder roles, value creation mechanisms and deployment logics across the validated segments.
4. To integrate Life Cycle Assessment (LCA), Life Cycle Cost (LCC) and Total Cost of Ownership (TCO) evidence into segment-level indicators of environmental and economic performance, supporting strategic prioritisation of deployment without re-optimising or extending the assumptions of D6.2.
5. To map public and private funding and financing approaches relevant to the different phases of AE deployment, i.e., demonstration, early deployment and wider replication, organising the mechanisms already referenced within the AENEAS project into a coherent and phase-consistent framework.
6. To develop a multi-phase expansion roadmap up to 2030 that combines technical readiness milestones, bounded replication thresholds, regulatory context and funding logic, and that directly informs the Final Exploitation Plan (D6.4).

All objectives are pursued under a non-negotiable constraint: D6.6 describes what can be deployed, replicated or scaled only when and where feasibility gates are closed, and does not promote or anticipate deployment pathways that are not technically and operationally supported by the evidence generated within AENEAS.

1.3 Relation to other Work Packages and deliverables

Deliverable D6.6 constitutes the exploitation-oriented synthesis of the AENEAS project results and builds on a coherent set of core deliverables and Work Packages. *D6.1 - Interim Exploitation Plan* defines the strategic baseline of AENEAS, identifying the value proposition, the Key Exploitable Results (KERs), and initial exploitation routes. D6.6 operationalises this vision by grounding it in validated feasibility, impact and deployment constraints. *D6.2 - LCIA, LCC, TCO, safety assessment* provides the quantitative environmental, economic and safety evidence comparing AE ESS technologies with conventional lithium-ion solutions at ESS and vessel level. These results are a central input to the prioritisation logic developed in D6.6.
D6.3 - Feasibility analyses in serving EU/IMO targets, including report on business cases delivers fleet segmentation, technical and economic feasibility analysis and business cases across a broad range of waterborne operations. It represents the main analytical bridge between technical validation and deployment relevance and is systematically reused in D6.6 without reinterpretation. *D6.5 - Roadmap towards full scale on-board demonstrators for two ESS solutions by 2027* establishes the gate-based technical readiness logic that controls all subsequent expansion claims. D6.6 remains fully aligned with this logic and does not expand the feasibility domain defined therein. In addition, D6.6 draws on the results of the technical Work Packages (WP1-WP5), including operational profiles, ESS requirements, modelling activities and validation outcomes, which underpin the feasibility, impact and applicability analyses consolidated in WP6. Through this structured integration, D6.6 provides the necessary bridge between validated technical readiness and exploitation planning, ensuring that the Final Exploitation Plan (D6.4) is anchored in auditable evidence and conservative deployment logic rather than aspirational scaling assumptions.

1.4 Structure of the document

The deliverable is structured as follows. Section 2 describes the methodological approach adopted in D6.6, clarifying the gate-based logic inherited from D6.5, the analytical boundaries of the work, and the sources of evidence used to ensure consistency with validated feasibility and readiness results. Section 3 presents the market segmentation framework and identifies priority application clusters for AE solutions beyond the on-board demonstrators, building on the fleet segmentation and adequacy analysis developed in D6.3 and constrained by the applicability envelopes defined in D6.5. Section 4 analyses the main drivers and barriers influencing the adoption of AE solutions across different vessel segments and operational contexts. Technical, economic, operational and regulatory factors are integrated and consolidated into a structured SWOT-based interpretation, without introducing new assumptions beyond those validated within the project. Section 5 defines application models and business model archetypes for the AE solutions considered in AENEAS, including semi-solid-state batteries, supercapacitors and hybrid configurations. The section clarifies stakeholder roles, value creation mechanisms and deployment logics, remaining aligned with the exploitation framework introduced in D6.1 and the feasibility-driven business cases developed in D6.3. Section 6 integrates the environmental and economic evidence generated in D6.2, combining Life Cycle Assessment (LCA), Life Cycle Cost (LCC) and Total Cost of Ownership (TCO) results into segment-level indicators of environmental and economic attractiveness. These indicators support the prioritisation of deployment while preserving the assumptions and boundaries of the original analyses. Section 7 maps public and private funding and financing approaches relevant to the different phases of AE deployment, from demonstration to early deployment and wider replication. The section organises the funding mechanisms already referenced within the AENEAS project into a coherent and phase-consistent framework, without introducing new external programmes or speculative instruments. Finally, Section 8 presents the expansion roadmap towards 2030, integrating technical readiness milestones, bounded market replication thresholds, regulatory context and funding logic into a single, multi-layer framework.

2 Method

This section defines the methodological framework adopted to translate technically feasible Energy Storage System (ESS) solutions into deployable, scalable and financeable application pathways. it introduces a deployment-oriented logic that complements, without duplicating, the feasibility assessment conducted in D6.5. The focus is on market readiness, financial bankability and institutional alignment, which determine whether technically sound solutions can progress beyond pilot demonstrations toward scaling and replication. A core premise of this deliverable is to address whether, where and how these solutions can realistically be deployed, financed and scaled. This distinction is critical in EU-funded innovation programmes, where a large share of technically successful demonstrators fail to progress due to non-technical barriers. To structure this transition, D6.6 introduces three additional and non-compensable analytical domains, hereafter referred to as deployment envelopes, which operate alongside technical feasibility:

- Market envelope: defines whether a sufficiently mature, addressable and replicable demand exists for a given application-segment combination.
- Financial envelope: defines whether viable funding pathways exist, including public funding instruments, private investment, and blended finance structures.
- Institutional and policy envelope: defines whether regulatory frameworks, policy incentives and governance conditions enable (or constrain) deployment and scaling.

Only solutions that remain viable across all envelopes are considered eligible for inclusion in the deployment and scaling roadmap. This envelope-based framing ensures that D6.6 remains selective by design, avoiding the inflation of application scenarios that are technically attractive but structurally non-deployable. Consistent with the engineering discipline applied in D6.5, D6.6 adopts a gate-based deployment logic, rather than scoring, ranking or weighting approaches. This choice is deliberate and grounded in three considerations:

1. Avoidance of arbitrary scoring. Scoring-based approaches allow compensation between fundamentally different dimensions (e.g. weak bankability offset by strong policy support), masking structural blockers that typically emerge during real deployment.
2. Alignment with EU project best practices. Horizon Europe demonstrator and scale-up projects increasingly rely on gate-based decision logics to ensure traceability, auditability and credibility toward public authorities, financial institutions and industrial stakeholders.
3. Consistency across the AENEAS exploitation chain. The gate-based logic ensures continuity between technical feasibility (D6.5), environmental-economic evidence (D6.2) and deployment planning (D6.6), while preserving the distinct function of each deliverable.

The deployment logic is articulated as a sequential gate chain, where failure at any stage excludes progression to the scaling roadmap:

1. Technical feasibility gate. Confirmation that the application-segment pairing satisfies all non-compensable feasibility conditions defined in D6.5.
2. Economic viability gate. Verification that lifecycle cost, TCO and value creation mechanisms (as assessed in D6.2) are compatible with real operational contexts.

3. Market readiness gate. Assessment of demand maturity, replicability potential, stakeholder readiness and timing.
4. Financial bankability gate. Identification of credible funding pathways, including public grants, private capital, or blended finance instruments.
5. Policy and regulatory alignment gate. Verification that deployment is supported (or at least not structurally hindered) by existing and forthcoming regulatory and policy frameworks.

Only application pathways that pass all gates sequentially are retained within the D6.6 roadmap for expansion and access to funding. This methodological framework has three direct implications for the structure and content of D6.6. The roadmap developed in subsequent sections is selective, not exhaustive: exclusion reflects structural constraints, not analytical omissions. Deployment pathways are framed around funding logic and institutional readiness, not only technological attractiveness. The roadmap explicitly differentiates between near-term deployable applications and longer-term expansion domains, ensuring realism and credibility. By enforcing a gate-based, envelope-driven methodology, D6.6 provides a robust decision backbone for the expansion of ESS application areas and the mobilisation of public and private capital. This framework ensures that the roadmap is not merely aspirational, but implementable, financeable and aligned with EU policy and funding architectures.

3 Mapping potential market segments

This section defines the market segmentation used to translate the technical feasibility evidence of AENEAS AE solutions into deployable and replicable market segments in maritime and inland navigation contexts. The objective is not to explore the full spectrum of potential markets for battery or hybrid systems, nor to promote emerging applications beyond demonstrated readiness. Rather, the focus is on identifying where market deployment is credible, under which operational and institutional conditions it can occur, and within which boundaries replication can be pursued without violating the feasibility envelopes already established at project level (IEA Bioenergy, 2025). Market segments are therefore retained only when they remain compatible with at least one validated functional envelope (energy-dominant, power-dominant or mixed profiles) and when they are characterised by mission repeatability, plausible ship-shore interfaces and manageable integration and safety constraints. Put differently, segmentation helps ensure that feasibility domains remain robust and credible, instead of being stretched to include applications that fall outside their realistic limits. Figure 1 summarises this logic as a traceability chain linking technical feasibility domains, deployment-eligible market segments and replication pathways. Starting from the technology-segment matching matrix, the applicability sheets and the validated envelopes developed in D6.5, the analysis passes through the fleet segmentation of D6.3 (port-centric, short-sea and inland waterway vessels) and leads to deployment-relevant market segments such as ferry operators, tug and port service operators, inland corridor operators and coastal service operators. The final step in the chain is the definition of near-term deployment (2025-2027) and mid-term scaling (to 2030) pathways, always within the boundaries of the previously validated feasibility conditions.

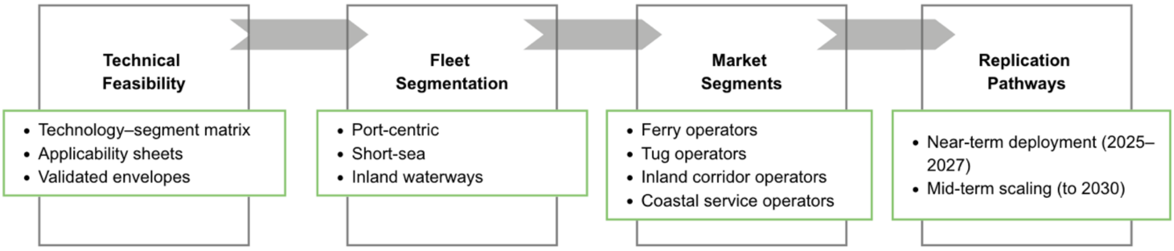


Figure 1: Mapping potential market segments process

Rather than relying on vessel typologies alone as a proxy for markets, the segmentation logic adopts a functional and decision-oriented perspective, consistent with best practices for regulated socio-technical systems. Market segments are thus defined by ownership structures, investment and risk profiles, operational constraints and regulatory exposure, that is, by the determinants that ultimately govern deployability and replication speed. Evidence from maritime decarbonisation research corroborates this selection: deployment results are influenced less by nominal vessel categories than by factors such as mission regularity, energy-power demand patterns, infrastructure coupling and certification requirements (Halim et al., 2018; CIMAC & Maritime Battery Forum, 2024; DNV, 2024). Each segment outlined below is therefore specified in terms of deployment-relevant characteristics and does not entail any reinterpretation of the technical findings (IEA Bioenergy, 2025). Figure 2 presents a conceptual mapping between the functional boundaries and the decision contexts in which they are applicable. On the left-hand side, functional clusters (A-E) represent the primary technical profiles (energy-dominant, mixed, power-dominant, and hybrid-only). On the right-hand side, these clusters pertain to specific decision domains, including short-sea ferry operators, inland corridor operators, tug and port service providers, coastal workboat operators, and port short-task units. For each segment, a concise set of keywords signifies typical risk appetite and primary constraints, such as passenger safety, TCO-driven choices, interface standardisation). The figure does not present quantitative estimates or penetration targets; its primary aim is to clarify how technical boundaries correspond to various governance and decision-making contexts.

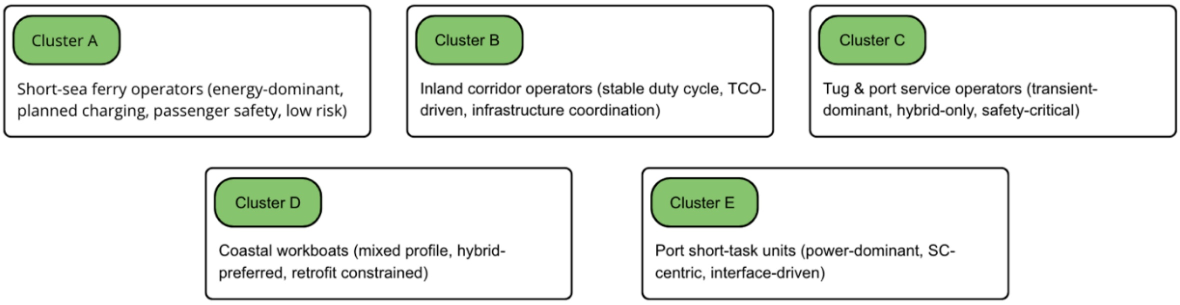


Figure 2: Clusters market segments

3.1 Deployment-relevant segments by functional profile

The following subsections describe the main deployment-relevant segments, organised by their dominant functional profile. In each case, the description combines operational characteristics, decision structures and key constraints that determine whether and how AE solutions can be replicated without departing from the feasibility domains established in D6.2, D6.3 and D6.5.

Energy-dominant short-sea passenger and Ro-Pax operators

This segment comprises operators of short-sea passenger ferries and Ro-Pax vessels running repetitive routes with predictable port stays, high hotel-load demand and stringent passenger-safety requirements. These are typically asset-intensive owner-operators, often subject to public service obligations and operating under strong regulatory oversight and conservative risk profiles (CIMAC & Maritime Battery Forum, 2024; IEA Bioenergy, 2025). Multiple industry assessments converge on the view that battery-centric solutions are most credible in such contexts when charging opportunities are predictable and tightly integrated into port operations (EMSA, 2023). Classification society guidance further stresses that, for passenger vessels, certification complexity and compartmentation requirements are decisive in investment decisions (DNV, 2024). In this segment, replication potential is structurally tied less to energy cost differentials and more to three interdependent conditions: availability of shore-side electricity and adequate grid capacity; maturity of certification-by-design strategies and safety cases; and the ability to integrate AE systems into ship and port procedures without compromising redundancy or evacuation plans (EMSA, 2023; CIMAC & Maritime Battery Forum, 2024). Hybridisation with high-power devices is possible but remains explicitly conditional: it is justified only where transient loads materially affect thermal or lifetime margins and where such configurations remain within the validated envelopes.

Inland waterway corridor operators and fleet aggregators

This segment includes inland cargo operators, corridor authorities and fleet aggregators coordinating vessels, terminals and charging infrastructure along rivers and canals. Governance is often decentralised at vessel level but coordinated at corridor level, with strong emphasis on total cost of ownership and infrastructure standardisation. International analyses consistently identify inland navigation as a favourable early market for battery-centric solutions, due to stable duty cycles, proximity to shore infrastructure and comparatively harmonised regulatory frameworks (Piątek, 2019; CCNR, 2023; IEA Bioenergy, 2025; Port of Rotterdam and Gemeente Rotterdam, 2025). In these contexts, technology risk is generally subordinate to interoperability and long-term asset utilisation: the key questions concern the standardisation of interfaces, the coordination of corridor-wide investments and the alignment of public and private incentives. Consequently, replication in this sector is chiefly limited by the coordination of corridor-level investments and policy alignment, rather than by persisting technological obstacles. AE systems are feasible to the extent that they can be integrated into common corridor plans and that charging logistics can be arranged without undermining service reliability (Port of Rotterdam and Gemeente Rotterdam, 2025).

Tug, offshore support and high-dynamics port service operators

This segment covers harbour tugs, offshore support vessels and other high-dynamics service units operating in safety-critical environments. Operators typically manage relatively small fleets with mission-critical availability requirements and display very low tolerance for operational instability or loss of manoeuvring capability. Evidence from sector literature and demonstrators shows that battery-only architectures are generally misaligned with such transient-dominated profiles, whereas hybrid battery-supercapacitor systems can significantly improve robustness and lifetime under frequent power peaks (Tao et., 2023; Kolodziejski and Michalska-Pozoga, 2023; DNV, 2024; Wärtsilä Corporation, 2025). In these contexts, adoption decisions are driven by reliability, protection speed, thermal resilience and class acceptance, rather than by fuel savings alone (EMSA, 2023; Wärtsilä Corporation, 2025). Replication beyond pilot installations is therefore conditional on mature safety cases, high-quality monitored operational data and clear class guidance. Within AENEAS, this translates into a hybrid-only admissibility for this functional cluster, as defined in D6.5, and into a requirement that any scaling remains anchored to demonstrator-level evidence (EMSA, 2023; CIMAC & Maritime Battery Forum, 2024).

Coastal workboats and mixed-profile service operators

This segment comprises coastal workboats, fast service craft and mixed-profile logistics units where both energy demand and power variability are relevant. Operators are typically private entities with moderate risk appetite and often face significant retrofit constraints due to vessel age, available space and existing powertrain configurations. Industry reports indicate that such vessels constitute a transitional market, where hybrid architectures are generally preferred to manage variability without excessive oversizing of battery systems (Bureau Veritas Marine & Offshore, 2025). For these operators, lifecycle robustness, thermal management and integration complexity are the dominant factors shaping adoption decisions (CIMAC & Maritime Battery Forum, 2024). Replication is therefore conditional on demonstrating that hybrid ESS configurations operate within the safety and thermal margins validated in D6.5 and can be integrated with acceptable retrofit effort. Without such evidence, this segment remains an opportunity of principle rather than a deployment pathway.

Port service units and short-task terminal operations

This segment includes port service craft and terminal-based units performing short, repetitive tasks with frequent power transients, such as yard tractors, short-range workboats and terminal support units. This segment includes port service craft and terminal-based units performing short, repetitive tasks with frequent power transients, such as yard tractors, short-range workboats and terminal support units. Technical and market assessments indicate that supercapacitor-based solutions are ideally suited for power-dominant applications, whereas battery-centric systems are often misaligned in scenarios with modest energy requirements and fast transients (Miller, 2011; PEMA, 2023). In this segment, the maturity of technology is a lesser limitation compared to the standardising of interfaces and protective methods within port electrical systems (EMSA, 2023; PEMA, 2023). Replication is primarily regulated by interface standards, protection coordination, and inclusion into port safety protocols. Only configurations that adhere to the SC-centric, power-dominant profile outlined in WP3-WP4 and D6.5 are deemed acceptable to remain inside AENEAS feasibility parameters.

3.2 Extended deployment-eligible segments

Table 1 consolidates the segments eligible for deployment, categorising them by macro-segment, predominant functional profile, primary AE function, and indicative time frame. The table does not present new technical assumptions; rather, it consolidates data from D6.3 and D6.5, categorising each segment within a conservative temporal framework (demonstrator, near-term extension, mid-term opportunity, or enabling pathway). The last column specifically documents boundary conditions, encompassing technology selections (e.g., SSSB-centric or hybrid-only), infrastructure requirements, and regulatory or certification constraints.

Table 1: Classification of market segments

Market segment	Macro-segment	Dominant functional profile	Main AE function	Time horizon	Boundary conditions
Harbour tugs	Port-centric vessels	Power-dominant, highly dynamic	Peak shaving; manoeuvre support	2025-2027 (demonstrator)	Hybrid SSSB+SC only; battery-only excluded; certification-by-design required (DNV, 2024; AENEAS D6.5, 2025; Wärtsilä Corporation, 2025)
Short-sea Ro-Ro / Ro-Pax	Short-sea vessels	Energy-dominant / mixed	Hotel loads; port-stay abatement	2025-2027 (demonstrator)	Predictable charging; passenger-safety constraints; SSSB-centric; hybrid conditional (AENEAS D6.3, 2025; AENEAS D6.5, 2025; EMSA, 2024; Bureau Veritas Marine & Offshore, 2025; IEA Bioenergy, 2025)
Inland cargo / push boats	Inland waterways	Energy-dominant, stable	Mission energy buffering	2025-2027 (baseline replication)	Corridor charging plausibility; SSSB-centric; interface harmonisation critical (CESNI, 2019; Port of Rotterdam and Gemeente Rotterdam, 2025)
Regional passenger ferries	Short-sea vessels	Energy-dominant	Hotel loads; zero-emission port stay	Near-term extension (2025-2027)	Shore-side electricity availability; certification readiness (DNV, 2024; IEA Bioenergy, 2025)
Inland passenger vessels	Inland waterways	Mixed	Continuity of service; buffering	Near-term extension (2025-2027)	Stable duty cycles; terminal charging; regulatory clarity (CCNR, 2023; Port of Rotterdam and Gemeente Rotterdam, 2025)

Harbour craft & port service units	Port-centric vessels	Power-dominant	Transient handling; peak shaving	Near-term extension (2025-2027)	Interface standardisation; protection coordination (EMSA, 2023; PEMA, 2023; DNV, 2024; Wärtsilä Corporation, 2025)
Coastal feeder / short-sea container vessels (incl. feeder container ships)	Short-sea vessels	Mixed	Auxiliary hybrid support	Mid-term opportunity (to 2030)	Retrofit feasibility; infrastructure maturation (CIMAC & Maritime Battery Forum, 2024; DNV, 2024)
Inland service units	Inland waterways	Power-oriented / mixed	Operational support; peak management	Mid-term opportunity (to 2030)	Modular integration; terminal interfaces (Piątek, 2019; IEA Bioenergy, 2025; Port of Rotterdam and Gemeente Rotterdam, 2025)
Shore-side ESS for ports	Port infrastructure (enabler)	Power-oriented	Cold ironing; peak shaving	Enabling pathway	Treated as infrastructure enabler only; not an onboard AE expansion unless separately validated (IEA Bioenergy, 2025; PEMA, 2023; CIMAC & Maritime Battery Forum, 2024; EMSA, 2024).

Shore-side ESS are regarded as facilitators of deployability that influence market and bankability thresholds, rather than an extension of the onboard AE application domain, unless substantiated by specific technical validation (IEA, 2021; EMSA, 2023; PEMA, 2023; CIMAC & Maritime Battery Forum, 2024). Upcoming extensions (2025-2027) encompass regional passenger ferries, inland passenger vessels, and specific port service units when infrastructural and regulatory conditions are already advantageous and align with the feasibility domains utilised in AENEAS. Mid-term potential (by 2030), including feeder vessels and inland service units, remains contingent upon the maturation of infrastructure, the feasibility of retrofitting, and the validation of assumptions outlined in D6.2 and D6.3.

3.3 Market archetypes as deployability boundary conditions

Within this framework, market archetypes are characterised as sets of deployability constraints, rather than as descriptive market profiles. Their role is to formalise the process of investment decision-making, delineate risk allocation, and identify predominant cost sensitivities within each segment, as these elements directly influence a segment's ability to meet the deployment criteria outlined in Section 2 (i.e., economic viability, market readiness, bankability, and policy/regulatory alignment). This approach is consistent with EU practice for exploitation-oriented deliverables, where market segmentation is used to limit deployment claims and to ensure traceability to technical evidence (CIMAC & Maritime Battery Forum, 2024). The archetypes delineated below are entirely governed by the feasibility domains established in D6.5 and by the fleet and operational data presented in D6.3, further substantiated by sector-level evaluations of maritime and energy transitions (EMSA, 2023; IEA Bioenergy, 2025; DNV, 2024). Table 2 summarises these archetypes for the main segments, highlighting ownership models, primary decision-makers, risk appetite, CAPEX/OPEX sensitivities, retrofit versus newbuild preferences and the resulting deployability implications.

The table does not introduce new criteria; it organises the information already implicit in the preceding analysis into a set of explicit patterns.

Table 2: Market archetypes per segment

Market segment	**Ownership model**	**Primary decision-maker**	**Risk appetite**	**CAPEX**	**Retrofit vs newbuild bias**	**Deployability implication**
Short-sea passenger & Ro-Pax (Cluster A; near-term ferries)	Owner-operator fleets; often public service obligations	Technical director and fleet engineering; early class involvement	Low-moderate (passenger safety, reputational exposure) (EMSA, 2023; IMO, 1974)	CAPEX-sensitive; justified by compliance and operational savings (IEA Bioenergy, 2025; DNV, 2024)	Retrofit dominant; newbuild only with secured shore interface	Only battery-centric solutions within the energy-dominant domain are replicable; hybridisation conditional (AENEAS D6.5, 2025)
Tug / OSV / high-dynamics port services (Cluster C)	Private operators; port-authority-linked contractors	Operations and safety leadership with engineering oversight	Very low (availability-critical) (DNV, 2024; EMSA, 2023)	Balanced; robustness and compliance dominate	Retrofit highly constrained; replication anchored to demonstrator evidence	Only hybrid SSSB+SC admissible; battery-only excluded (AENEAS D6.5, 2025)
Inland corridor operators & aggregators (Cluster B)	Fleet operators; corridor authorities; terminal operators	Asset/infrastructure coordinator (PPP governance)	Moderate with regulatory clarity (CESNI, 2019; IEA Bioenergy, 2025)	TCO-driven; replication economic-central	Retrofit dominant; modularity critical	Replication governed by interface standardisation and charging logistics (AENEAS D6.3, 2024; DNV, 2024)
Coastal workboats & fast service craft (Cluster D)	Private operators; heterogeneous fleet ages	Technical operations lead	Low-moderate; conditional on lifetime robustness	OPEX savings valued only with proven reliability	Retrofit prevalent; integration complexity decisive	Hybrid preferred; replication conditional on lifecycle and thermal validation (AENEAS D6.5, 2025)
Port short-task units & harbour craft (Cluster E)	Port operators; municipal contractors	Port operations and safety compliance	Low; preference for modular, certifiable systems	CAPEX-sensitive; continuity dominate	Retrofit common; space/ protection constraint	Replication constrained by interface and protection coordination (DNV, 2024; EMSA, 2024).

Within this archetype framework, replication is considered authorized for a given segment only when all three conditions are simultaneously satisfied:

1. Feasibility consistency: the segment is compatible with at least one validated feasibility domain (technology-segment matching matrix and applicability constraints) as defined

in D6.5, and does not require extrapolation beyond the operational envelopes analysed in WP1-WP5;

2. Deployment gate passage: the segment passes the deployment gates set out in Section 2 (i.e., economic viability, market readiness, bankability, policy/regulatory alignment) under conservative assumptions consistent with D6.2 and D6.3 (EMSA, 2023; CIMAC & Maritime Battery Forum, 2024).
3. No domain inflation: conditional configurations remain explicitly conditional; no implicit upgrade from “conditional” to “replicable” is made without additional evidence, and no new application domains are introduced beyond those covered by the AENEAS feasibility assessments (CIMAC & Maritime Battery Forum, 2024).

Segments excluded or not validated in the feasibility assessment remain excluded from scaling pathways. Conditional configurations are treated as conditional deployment candidates and require explicit mitigation evidence at later gate stages. Shore-side ESS infrastructures are treated as deployment enablers that affect market and bankability gates, not as an expanded onboard application domain, unless subsequent technical validation justifies updating the feasibility matrix (EMSA, 2023; PEMA, 2023; Port of Rotterdam and Gemeente Rotterdam, 2025).

4 Adoption drivers and structural barriers

The analysis presented is grounded exclusively in consolidated project evidence and institutional reference frameworks. Specifically, it draws on: (i) LCIA, LCC and TCO results developed in WP6 (AENEAS D6.2, 2025); (ii) segment-wise feasibility, applicability and business-case constraints (AENEAS D6.3, 2025); (iii) validated technical envelopes and readiness limits (AENEAS D6.5, 2025); and (iv) international and European regulatory frameworks relevant to maritime decarbonisation and onboard energy systems, with particular reference to the Revised IMO GHG Strategy and to the legislative measures adopted under the EU Fit-for-55 package, including FuelEU Maritime and the extension of the EU ETS to maritime transport (European Commission, 2021; European Parliament & Council, 2023; IMO, 2023; Baresic et al., 2025). Adoption drivers are treated strictly as structural conditions that alter the probability of passing one or more deployment gates. A driver is considered relevant only insofar as it reduces uncertainty, increases predictability, or shifts AE solutions from discretionary upgrades to compliance- or operation-critical assets within validated operating envelopes. Conversely, structural barriers are treated only where they can credibly induce gate failure under conservative, evidence-based assumptions consistent with WP6 baselines.

4.1 Adoption drivers

WP6 evidence supports four adoption drivers that are structurally gate-relevant across the AE application space addressed by AENEAS. These drivers are not interpreted as market opportunities or strategic levers; rather, they are assessed in terms of their causal interaction with specific deployment gates.

1. Regulatory tightening and compliance value emerges as a primary adoption driver because it reshapes the underlying investment logic. Under the Revised IMO GHG Strategy and the measures introduced within the EU Fit for 55 package, emissions performance is increasingly framed as a prerequisite for continued market access rather than as a discretionary optimisation variable (European Commission, 2021; IMO, 2023; DNV, 2024). Within the operational baselines defined in WP6, this driver becomes gate-relevant where port stays, manoeuvring phases and near-shore operations represent the compliance-sensitive segments of the mission profile. In these contexts, AE solutions are evaluated less as fuel-cost arbitrage instruments and more as compliance-enabling assets that mitigate exposure to operational restrictions, port access conditions and enforceable emission limits. This mechanism acts directly on the policy/regulatory-alignment gate and indirectly stabilises economic viability by monetising avoided non-compliance risk, rather than relying on speculative efficiency gains.
2. A second structurally relevant driver is the predictability of the ship-shore interface. For battery-centric and hybrid pathways, adoption becomes credible beyond pilot contexts only when ship-shore interaction is predictable, proceduralised and standardisable. Infrastructure acts as an adoption driver only when it reduces operational uncertainty by embedding charging or cold-ironing routines into port operations and enabling replication across multiple sites without ship-specific redesign. Where shore-side electricity provision is fragmented, ad hoc or governed inconsistently, the same factor becomes a blocking condition, preventing passage of the market readiness and replication readiness gates even when onboard feasibility has been demonstrated at system level (EMSA, 2023; IEA Bioenergy, 2025; AENEAS D6.3, 2025;). This applies not only to short-sea passenger operations but also to container ship operations where SSE (Shore-Side Electricity-also known as cold ironing / onshore power supply) during manoeuvring/port-related phases can deliver measurable fuel-reduction benefits, subject to interface and governance readiness.

3. Operational resilience and system robustness constitute a third driver, particularly in availability-critical or safety-critical operations. In these segments, adoption is driven less by energy cost displacement and more by transient handling capability, peak shaving, power-quality stabilisation, redundancy and the reduction of stress on conventional generation assets (Trombetta et al., 2024; DNV, 2023). This driver is explicitly bankability-relevant because it affects downtime probability, service continuity and the credibility of cash-flow assumptions. However, it is admissible only where safety case maturity, monitoring evidence and class/authority expectations support predictable performance within the validated envelopes defined in D6.5 (EMSA, 2023; DNV, 2024; AENEAS D6.5, 2025).
4. Finally, TCO convergence under high utilisation and repeatability is treated as an adoption driver only under restrictive conditions. WP6 evidence supports TCO-based logic as gate-relevant exclusively where utilisation is high and duty cycles are repeatable, thereby reducing degrees of freedom in economic assessment. In such cases, the combination of energy displacement and compliance value stabilises the investment case under conservative assumptions (Danielis et al., 2018). Outside these boundary conditions, TCO arguments lose gate relevance and cannot be used to justify replication or scaling (AENEAS D6.2, 2025).

Table 3 consolidates these drivers by explicitly linking each of them to the deployment gates they affect and to the conservative mechanisms through which they operate. Importantly, the presence of adoption drivers does not imply prioritisation and does not justify deployment outside validated application boundaries; it only qualifies when passing one or more gates becomes structurally more plausible under evidence-based assumptions.

Table 3: Adoption drivers

Adoption driver	Deployment gates affected	Gate-relevant mechanism
Regulatory tightening and compliance pressure	Policy/regulatory alignment; economic viability	Reframes AE from discretionary upgrade to compliance-enabling asset in emission-constrained mission phases (port stay, manoeuvring, near-shore); reduces exposure to restrictions/access constraints (EMSA, 2023; IMO, 2023; AENEAS D6.2, 2025)
Predictable ship-shore interface availability	Market readiness; replication readiness	Reduces operational uncertainty; enables multi-site replication by standard procedures/interfaces instead of ship-specific redesign (IEA Bioenergy, 2025; AENEAS D6.3, 2025)
Operational resilience and system robustness	Bankability; market readiness	Availability/continuity value stabilises risk profile and cash-flow assumptions, conditional on safety case maturity and monitoring evidence (DNV, 2024; AENEAS D6.2, 2025)
TCO convergence under high utilisation	Economic viability; bankability	TCO comparability becomes admissible only under repeatable/high utilisation profiles; extrapolation outside validated use-cases is excluded (AENEAS D6.2, 2025; AENEAS D6.3, 2025, AENEAS D6.5, 2025).

4.2 Structural barriers

Structural barriers are documented solely when they can plausibly cause gate failure under conservative assumptions aligned with WP6 baselines and proven feasibility and readiness criteria. They are characterised not as generic "innovation obstacles," but as deployment risks that delineate the external validity criteria for replication and scalability.

1. CAPEX concentration and first-of-a-kind (FOAK) risk represent a primary structural barrier. AE deployment involves upfront investment that include not only the storage technology but also integrated engineering, safety measures, redundancy, testing, and certification. This barrier is significant only when it threatens bankability due to non-financeable risk-adjusted returns or when it undermines economic viability under

conservative assumptions. It is fundamentally more significant in segments characterised by small margins, short contractual durations, or limited ability to leverage compliance or resilience value (AENEAS D6.2, 2025; AENEAS D6.3, 2025).

2. A second barrier arises from integration complexity and retrofit bias. Onboard integration constraints are segment-dependent and include space and weight allocation, thermal loads, electrical integration (EMS/BMS/PMS interfacing) and protection coordination. Retrofit-heavy fleets amplify this barrier because ship-specific engineering reduces standardisation, increases per-unit engineering effort and slows replication. As a result, market readiness and replication readiness may fail even when system-level feasibility has been validated (Trombetta et al., 2024; AENEAS D6.3, 2025; AENEAS D6.5, 2025; Bureau Veritas Marine & Offshore, 2025).
3. Certification and safety-case burden constitute a further structural barrier in regulated maritime contexts. Safety assurance is a dominant deployability determinant, and the maturity of the safety case, early and continuous engagement with class, and completeness of evidence (documentation, testing, operational procedures and emergency preparedness) directly condition policy/regulatory alignment and bankability. Where evidence is incomplete or fragmented, deployment stalls regardless of technical performance claims, because the approval pathway becomes non-predictable (EMSA, 2023; SEA-LNG, 2023; AENEAS D6.5, 2025; Nordic Innovation, 2025).
4. Infrastructure-related obstacles are identified through ship-shore dependency and fragmented governance. Charging and cold-ironing readiness generally require the collaboration of multiple stakeholders, including port authorities, terminal operators, grid operators, and shipowners. Whenever governance responsibilities are disjointed or ambiguous, infrastructure functions as a bottleneck for replication, even when onboarding feasibility has been established. This barrier has significance for replication, as multi-site scalability necessitates standardised interfaces, consistent operational procedures, and reliable permitting and connection pathways (EMSA, 2023; ITF, 2023; AENEAS D6.3, 2025).
5. Finally, regulatory fragmentation across jurisdictions is treated strictly as a gate risk. Even under an overarching IMO strategy, implementation measures and technical interpretations vary regionally and locally, increasing transaction costs and uncertainty. This barrier matters only when it prevents reliable regulatory alignment for a specific targeted segment or application; it is not framed as a general statement on policy quality (PortXchange, 2021; ERCST, 2022; IMO, 2023; AENEAS D6.3, 2025).

Table 4 captures these barriers and their corresponding gate-failure mechanisms.

Table 4: Structural barriers

Structural barrier	Deployment gates affected	Gate-failure mechanism
CAPEX concentration and FOAK risk	Economic viability; bankability	Upfront CAPEX plus integration/safety/certification prevents financeability or fails risk-adjusted returns under conservative assumptions (AENEAS D6.5, 2025)
Integration complexity and retrofit bias	Market readiness; replication readiness	Ship-specific engineering reduces standardisation and slows replication; space/thermal/protection constraints impede readiness (AENEAS D6.3, 2025; Trombetta et al., 2024)
Certification and safety-case burden	Policy/regulatory alignment; bankability	Approval pathway becomes non-predictable without complete safety evidence; delays and cost escalation block financing and readiness (EMSA, 2023; IMO, 2023)

Infrastructure dependency and governance fragmentation	Market readiness; replication readiness	Multi-actor coordination failure blocks predictable ship-shore operations and multi-site scaling (AENEAS D6.2, 2025; PortXchange, 2024, Nordic Innovation, 2025)
Regulatory fragmentation across jurisdictions	Policy/regulatory alignment	Unpredictable compliance interpretation increases transaction costs and prevents reliable alignment for targeted deployments (ERCST, 2022; IMO, 2023).

4.3 SWOT Analysis

To facilitate direct reuse within the D6.6 roadmap, the previously identified adoption drivers and structural barriers are integrated into a deployment-oriented SWOT analysis (Table 5). The purpose of the SWOT is to deliver a consistent synthesis of validated evidence, ensuring that subsequent roadmap phases refer to a common analytical foundation without the necessity to reinterpret sources or assumptions.

Strengths indicate validated emission reduction performance across recurring and port-related operational profiles, where AE substitutes or complements traditional auxiliary power generation. Additional value is evident in hybrid and power-oriented configurations, where AE facilitates transient management, enhances operational stability, and optimises energy efficiency. Modular architectures facilitate phased implementation within validated technical and safety boundaries, aligning with emergent risk-based certification approaches for innovative technologies (DNV, 2023; IMO, 2023; American Bureau of Shipping, 2024).

Weaknesses encompass the reliance on substantial initial capital investment, the susceptibility to FOAK risks, and the complexities of system integration, especially within retrofit-intensive sectors. These dynamics augment engineering efforts, prolong commissioning schedules, and confound bankability evaluations under conservative financial conditions. Heterogeneous maturity levels across AE functions exacerbate these constraints and hinder scalability in the absence of structured de-risking mechanisms (EMSA, 2023; ITF, 2023).

Opportunities emerge from the gradual conversion of performance improvements into compliance benefits under new regulatory frameworks, alongside a growing focus on predictable ship-port energy coordination. Frameworks that facilitate shore-side interfaces, digital optimisation, and collaborative operational planning enhance the business justification for AE deployments when integrated with monitoring and verification systems (IMO, 2023; EMSA, 2023; European Commission, 2023; Global Centre for Maritime Decarbonisation & Boston Consulting Group, 2023).

Threats pertain to the changing certification and safety-case standards, uneven infrastructure governance across ports and regions, and ongoing investor risk aversion in the lack of comprehensive and large-scale monitored operational data. Variations in implementation timelines and technical interpretations can increase perceived risk and hinder decision-making, especially for projects requiring significant capital investment (IMO, 2023; UNCTAD, 2025).

The adoption drivers, structural obstacles, and resulting SWOT analysis do not specify priorities, technology choices, or implementation sequence. Instead, they specify the external validity conditions under which replication and scaling strategies can reliably meet the four deployment gates outlined in the D6.6 roadmap.

Table 5: SWOT analysis

Dimension	Deployment-relevant content
Strengths	Demonstrated potential for GHG and local emission reduction in repetitive/port-related profiles where AE substitutes or complements conventional auxiliary generation; transient-management capability and robustness value in power-oriented or hybrid configurations; modular architectures enabling phased deployment without violating validated envelopes (Cruise Lines

	International Association and SEA Europe, 2022; Trombetta et al., 2024; ABS, 2024; AENEAS D6.2, 2025)
Weaknesses	High initial CAPEX and FOAK risk concentration; integration complexity on existing fleets with space/thermal/protection constraints; non-uniform maturity across AE functions (energy- vs power-dominant) reflected in readiness limitations (ITF, 2023; World Bank, 2023; DNV, 2023; AENEAS D6.3, 2025)
Opportunities	Regulatory tightening converting emissions performance into compliance constraint; increasing local emission constraints in ports/inland nodes; progressive ship-port energy integration increasing relevance of predictable ship-shore procedures within validated domains (Cruise Lines International Association and SEA Europe, 2022; European Commission, 2023; EMSA, 2023; PortXchange, 2024; ABS, 2024; AENEAS D6.5, 2025)
Threats	Evolving certification/safety frameworks for novel ESS configurations; uneven availability and governance of ship–shore infrastructure; persistent risk aversion among operators/financiers in absence of large-scale monitored evidence (DNV, 2023; UNCTAD, 2025; ITF, 2023; ABS, 2024; AENEAS D6.1, 2025).

5 Application models and business model archetypes

This section defines application models and business model archetypes as deployment-structuring devices for AENEAS AE solutions. The purpose is to provide an engineering-consistent deployment grammar that (i) remains strictly within the feasibility, applicability and readiness boundaries validated at project level and (ii) can be reused as an operational interface between the technical deployment envelopes and the funding and replication logic developed in subsequent sections. Within the previous section, application models are defined as recurring engineering deployment configurations that describe how AE storage is employed in terms of: (a) dominant function (energy buffering, power support, hybrid decoupling); (b) integration into the onboard electrical architecture (AC/DC interfacing, EMS/BMS/PMS coordination, protection schemes); and (c) operating conditions (mission phases, manoeuvring, port stay and ship-shore interface dependency) (Nivolianiti et al., 2024). Accordingly, each model is retained only insofar as it can be unambiguously mapped to: (a) a segment cluster already treated in the WP6 evidence base; (b) a validated feasibility and applicability envelope; and (c) a gate-facing deployment condition (economic viability, market readiness, bankability, policy/regulatory alignment).

5.1 Application models

Four application models are retained as deployment-consistent across the WP6 evidence base. They correspond to distinct functional roles of AE storage and to differentiated integration and certification burdens, consistently reported in the technical and scientific literature on marine battery and hybrid systems (DNV GL AS Maritime, 2020; Kolodziejski and Michalska-Pozoga, 2023; Tao et al., 2023). Each model supports replication only where ship-side feasibility, shore-side/interface conditions and safety-case maturity remain passable under the deployment gate sequence (EMSA, 2023; Nivolianiti et al., 2024).

- AM-1 Onboard ESS as primary energy buffer (energy-dominant)

This model covers configurations in which an onboard AE ESS is used primarily for energy buffering, supplying a material share of mission and/or hotel loads, with charging aligned to predictable port stays. This deployment logic is widely documented in electric and hybrid ferry and short-sea applications, where repeatable duty cycles and planned port charging enable energy-centric operation (DNV GL AS Maritime, 2020; Kolodziejski and Michalska-Pozoga, 2023). The model is admissible only for operating profiles characterised by repeatable energy throughput and operationally stable charging logistics. Replication eligibility is therefore conditional upon: (i) segment-level applicability already established within WP6 and (ii) ship–shore interface readiness (procedures, connection availability, turnaround compatibility) sufficient to avoid ship-specific redesign (Nivolianiti et al., 2024). Where shore-side dependency cannot be stabilised operationally, the model remains conditional at the market-readiness and bankability gates (DNV GL AS Maritime, 2020).

- AM-2 Onboard hybrid ESS with functional decoupling (mixed / transient-dominant)

This model captures hybrid architectures that explicitly decouple energy and power functions: an energy-oriented subsystem (e.g. SSSB-centric) provides buffering, while a power-oriented subsystem (e.g. supercapacitors) delivers fast transient response, peak support and bus stabilisation. The decoupling logic is deployment-relevant because it reduces cycling stress and thermal constraints on energy storage while improving controllability under high-dynamics profiles, as demonstrated in both experimental and commercial marine hybrid systems (Kolodziejski and Michalska-Pozoga, 2023; Nivolianiti et al., 2024). The model is treated as structurally required where battery-only solutions are excluded or conditional due to transient severity, protection-coordination burden or thermal margins (DNV GL AS Maritime, 2020). Replication remains explicitly evidence-bounded and conditional on demonstrator-grade integration proof, safety-case maturity (hazard identification, containment, detection/suppression, emergency procedures) and class-acceptable documentation and testing packages (EMSA, 2023).

- AM-3 Power-centric ESS for short-task and high-dynamics operations (power-dominant).

This model covers configurations in which the ESS is designed primarily for power support, with limited energy throughput, targeting short-task operations characterised by frequent manoeuvres, rapid load variations and high transient demand. Such applications are well documented in port services, offshore support and auxiliary operations, where the ESS contribution is dominated by peak shaving, short-circuit support and power-quality stabilisation rather than energy displacement (Kolodziejski and Michalska-Pozoga, 2023). Deployment logic is dominated by protection coordination and short-circuit contribution management, operational robustness and availability value, and interface standardisation where port-side coupling is involved (DNV GL AS Maritime, 2020). Replication is not driven by energy scaling but by repeatable integration patterns and controllable safety evidence, as the value proposition is centred on robustness and availability rather than fuel displacement (Nivolianiti et al., 2024).

- AM-4 Ship–port coupled deployment (shore-side electricity / cold ironing–enabled operations)..

This model describes configurations in which deployability is materially conditioned by port-side readiness (shore power, charging logistics, operational procedures, permitting and governance). This includes applications on ferries as well as container ships, as SSE has been assessed on a container vessel with a specific focus on fuel reduction during manoeuvring. The critical role of ship–port coupling, including cold ironing, smart charging and bidirectional interaction with port energy systems, is extensively discussed in recent scientific and EU project literature (DNV GL AS Maritime, 2020; Frković et al., 2024). Within Section 4, AM-4 is treated strictly as an enabling condition affecting market readiness and bankability, not as an expanded application area. Replication relevance emerges only where multi-site scaling is supported by stable interface assumptions (technical compatibility, operating procedures and responsibility allocation between ship and port actors) (Frković et al., 2024). Where governance fragmentation prevents predictable operations, AM-4 is treated as a structural replication constraint even when ship-side feasibility is validated (DNV GL AS Maritime, 2020).

Table 6 synthesises these four application models by cross-referencing, for each model, the dominant function, admissible deployment pattern, evidence-bounded segment/cluster fit, primary gate exposure and non-negotiable boundary conditions. The table is intended as a compact operational interface: it allows the roadmap and funding analyses to reference the models directly, without re-deriving their engineering and gate-related constraints.

Table 6: Application models for AE deployment

Application model	Dominant function	Admissible deployment pattern	Segment/cluster fit (evidence-bounded)	Primary gate exposure	Non-negotiable boundary condition
AM-1 Onboard primary energy buffer	Energy buffering	Newbuild (preferred); selective retrofit	Segments with repeatable duty cycles and predictable port stays	Market readiness; Bankability; Economic viability	Requires stable ship–shore charging routines; no replication

					under ad-hoc interfaces
AM-2 Hybrid functional decoupling	Energy + fast power	Newbuild (preferred); controlled retrofit	High-dynamics profiles where battery-only is conditional/excluded	Policy/regulatory alignment; Bankability; Market readiness	Conditional on safety-case maturity and protection-coordination proof
AM-3 Power-centric ESS	Transient handling; peak shaving	Retrofit; port-service upgrades; selective newbuild	Short-task and high-frequency manoeuvre segments	Bankability; Market readiness	Replication driven by robustness evidence, not energy displacement
AM-4 Ship–port coupled	Infrastructure-conditioned operation	Ship–port integrated	Port-centric segments with standardisable interfaces	Replication readiness; Market readiness; Bankability	Requires governance and interface standardisation

Application models are not a prioritisation tool and do not expand the validated domain. They formalise how deployment occurs and provide a reusable, engineering-consistent interface between technical feasibility evidence and subsequent roadmap and funding analyses.

5.2 Business model archetypes

This subsection defines business model archetypes as structuring logics for deployment and replication. They are not financial models and do not constitute market strategies. The archetypes neither introduce new markets nor alter feasibility boundaries. Their sole function is to describe how AE solutions can be deployed, contracted and scaled in a manner consistent with validated technical envelopes, stakeholder roles and conservative bankability and regulatory requirements, in line with established innovation-system and maritime decarbonisation literature (Bach et al., 2020). Each archetype is therefore characterised by three dimensions: (i) asset ownership and responsibility allocation; (ii) risk distribution across actors; and (iii) contractual and value-capture logic, because these dimensions directly condition bankability, market readiness and replication (Bach et al., 2020). The archetypes are derived through integration of the exploitation and stakeholder framework defined in AENEAS D6.1, the segment-wise business cases and deployment constraints analysed in AENEAS D6.3, and the feasibility and applicability limits consolidated in AENEAS D6.5. No archetype is valid outside the application models and segment clusters already qualified within the project.

BM-1 – Owner–operator asset-based deployment (CAPEX-driven).

The shipowner or fleet operator directly procures and owns the onboard AE system as part of the vessel asset. This configuration reflects the dominant ownership model observed in early commercial marine battery deployments, where investment decisions are justified through internalised compliance and operational benefits (Nyamathulla and Dhanamjayulu, 2024). The owner retains responsibility for compliance, operation and lifecycle management, supported by OEM warranties and system-integrator engineering services. Gate compatibility is limited to segments with stable ownership, repeatable utilisation and internalisable compliance value. Bankability relies on conservative TCO assumptions and certification maturity.

BM-2 – Public–private co-investment and risk-sharing deployment.

This archetype applies where public policy objectives, public service obligations or port-level environmental constraints justify partial risk sharing during early deployment. Empirical evidence from ferry electrification and early zero-emission shipping initiatives shows that public co-investment, guarantees or infrastructure support are often decisive in reducing first-of-a-kind exposure (Bach et al., 2020). The logic is risk reduction, not revenue enhancement, and replication remains admissible only under standardised governance conditions. Gate relevance is concentrated on bankability and regulatory alignment.

BM-3 – Performance- and service-oriented deployment (availability/robustness value).

The AE system is positioned as an operational performance enabler rather than an energy-cost optimisation asset. Contracting logic centres on availability, robustness and power-quality outcomes, with partial risk transfer to providers through service-level structures. This archetype is strictly conditional and admissible only where monitoring, verification and safety evidence are sufficiently mature to support enforceable KPIs without regulatory ambiguity, as highlighted by recent analyses of commercial marine BESS performance. It is most compatible with power-dominant SC (Supercapacitors) and selected hybrid configurations in safety-critical segments (Kolodziejski and Michalska-Pozoga, 2023).

BM-4 – Infrastructure-led and corridor-based deployment.

This archetype structures deployment around infrastructure actors (ports, terminals, corridor authorities) that enable replication by standardising interfaces, procedures and operational rules across fleets and sites. System-level, corridor-oriented deployment logics are increasingly discussed in EU projects and recent scientific work on ship–grid and ship–port integration (Frković et al., 2024). Replication readiness improves through reduced transaction costs and stabilised assumptions, but applicability is limited to contexts with demonstrably aligned infrastructure readiness and governance. This archetype does not expand the onboard application domain absent dedicated technical validation.

Table 7 operationalises the relationship between application models and business model archetypes by mapping, for each ESS technology and validated segment cluster, the associated application type, core value proposition, key stakeholders and indicative revenue/financing logic. It is intended as a gate-facing synthesis that can be used directly in roadmap and funding discussions.

Table 7: Business model archetypes

ESS technology	Segment cluster (validated)	Application type	Core value proposition	Key stakeholders	Indicative revenue / financing logic
SSSB	Short-sea passenger; Ro-Pax	Newbuild; selective retrofit	Primary energy buffering; emission reduction in port and manoeuvring	Shipowner, shipyard, OEM, integrator	Owner–operator CAPEX; possible public co-financing

SC	Inland navigation; port services	Retrofit; port-integrated	Transient handling; peak shaving; power-quality stability	Operator, integrator, port authority	Performance-oriented or service-based
Hybrid SSSB+SC	Mixed-profile short-sea; port-adjacent	Newbuild; ship–port integrated	Functional decoupling; system resilience	Shipowner, port, integrator, OEM	Hybrid CAPEX + performance logic
SC (Supercapacitors) / Hybrid	Port and corridor applications	Ship–port integrated	Shore-side electricity (SSE/cold ironing) enabling for ferries and container ships; operational flexibility	Port authority, grid operator, fleet operators	Infrastructure-led, PPP-type structures

The application models and business model archetypes defined constitute a deployment grammar. They structure how AE solutions can be deployed and replicated under conservative, gate-compliant conditions, without introducing new feasibility claims or expanding the validated application domain. By construction, this section is fully aligned with D6.5 feasibility constraints, consistent with WP6 exploitation logic and suitable for direct use in subsequent roadmap and funding analyses (DNV GL AS Maritime, 2020; EMSA, 2023).

6 Integration of LCIA, LCC and TCO results

This section integrates the Life Cycle Impact Assessment (LCIA), Life Cycle Cost (LCC) and Total Cost of Ownership (TCO) results of Deliverable D6.2 into a deployment-oriented perspective that remains fully consistent with the feasibility, applicability and readiness constraints defined in D6.5. All indicators are taken directly from D6.2 and interpreted strictly within the application domain and segment clusters established in D6.1, D6.3 and D6.5 (AENEAS Consortium, 2025). The integration pursues three objectives. First, it extracts segment-level environmental indicators that are directly relevant for deployment and replication. Second, it derives comparative economic indicators, in particular ΔTCO and green premium, that can be used in funding and exploitation discussions without re-optimising the assumptions of D6.2 (Danielis et al., 2018). Third, it clarifies, at cluster level, where the absence of numerical indicators in D6.2 reflects genuine dependence on duty cycles, infrastructure and operating strategies, rather than analytical gaps (Piątek, 2019; Nyamathulla and Dhanamjayulu, 2024).

6.1 Environmental performance

Deliverable D6.2 carries out a comparative LCA of conventional Li-ion battery (LIB) systems and Advanced Energy Storage (AE) options, namely SSB/SSSB, supercapacitors and hybrid configurations. The assessment covers cradle-to-gate and end-of-life contributions at ESS level, use-stage impacts for the representative AENEAS use-cases A, B and C, and a set of scenario analyses on industrial scale-up, pack design optimisation and integration with other decarbonisation options under the WP6 assumptions (AENEAS Consortium, 2025). The methodological set-up follows state-of-the-art practice for energy storage in maritime applications. GWP100 (Climate change) is used as the primary indicator, while additional impact categories such as human toxicity, acidification, eutrophication and ecotoxicity are considered where available and relevant (Nyamathulla and Dhanamjayulu, 2024; Halim et al., 2018). Within D6.6, LCIA results are not revisited or extended. They are used as a prioritisation tool at cluster level under three simple conditions. First, only impact categories explicitly calculated in D6.2 are considered. Second, relative performance is always expressed against the LIB reference to avoid misinterpretation of absolute values. Third, indicators are interpreted exclusively within the use-cases and applicability envelopes validated in D6.3 and D6.5 (AENEAS Consortium, 2025). In this way, the environmental layer in D6.6 remains directly traceable to D6.2 and consistent with international work on life-cycle integration in shipping transition pathways (IEA Bioenergy, 2025).

6.1.1 LCIA as a cluster-wise prioritisation metric

For the purposes of D6.6, LCIA results are read through three complementary lenses. The first lens is the relative difference in life-cycle impact, in particular ΔGHG (GWP100) and, where available, differences in other LCIA categories. By expressing AE performance as a percentage change relative to LIB under the scenarios modelled in D6.2, it becomes possible to identify clusters where AE solutions offer structurally better life-cycle performance once manufacturing and use-phase contributions are combined (Nyamathulla and Dhanamjayulu, 2024; DNV, 2024). The second lens concerns the marginal contribution of AE when combined with other decarbonisation measures. In cases where D6.2 evaluates ESS technologies together with operational improvements, shore power, DC grid integration or alternative fuels, D6.6 recognises the incremental contribution of AE only when this contribution is quantitatively reported. No new combined scenarios are introduced; the analysis remains anchored to the scenario set explicitly treated in D6.2 (Piątek, 2019; IEA Bioenergy, 2025). The third lens relates LCIA outcomes to duty cycles and mission phases. Environmental benefits are interpreted in the context of the operational phases in which AE systems are effectively engaged, such as port stay, manoeuvring or repetitive short-sea sailing. Short-sea, inland and port-centric segments are particularly relevant, as local emission reductions and electrification can have a disproportionate impact on overall performance and regulatory compliance (AENEAS Consortium, 2025; CIMAC & Maritime Battery Forum, 2024). Once these lenses are applied, LCIA indicators are mapped onto the segment clusters A, B and C defined in Section 3, without extrapolating beyond the use-cases and envelopes examined in D6.2.

6.2 Economic performance

In D6.2, LCC and TCO analyses are developed for LIB and AE options both at ESS level and at ship or use-case level. The cost framework includes ESS CAPEX (batteries, supercapacitors, balance-of-plant and integration), OPEX components such as energy, maintenance and replacements, and long-term cost trajectories under fuel and electricity price scenarios consistent with WP6 (AENEAS Consortium, 2025). The approach reflects consolidated practice in techno-economic studies of hybrid and fully electric vessels, where TCO is used as the primary decision metric for comparing alternative propulsion and energy options under uncertainty (Danielis et al., 2018; Piątek, 2019). Within D6.6, LCC and TCO are used only in comparative form. The focus is on ΔTCO with respect to the LIB reference, and only where D6.2 provides explicit numerical results or clearly articulated qualitative rankings. No re-parameterisation, re-optimisation or extension of the cost scenarios is performed. Any residual cost difference between AE and LIB is interpreted as a green premium, in line with the terminology and framing employed both in D6.2 and in current discussions on zero-emission shipping finance and FOAK risk (ITF, 2023). This constrained use of economic indicators is sufficient to identify contexts where AE solutions are already close to cost parity and contexts where additional support or de-risking instruments would be structurally required, without reopening the analytical scope of D6.2 (DNV, 2024).

By combining LCIA and TCO information from D6.2, D6.6 distinguishes three patterns that are directly relevant for the deployment gates. A first group of segments combines favourable life-cycle performance ($\Delta GHG < 0$) with TCO trajectories that approach parity with LIB under conservative assumptions. In these contexts, the green premium is small or tends to vanish as technology matures, and the economic viability and bankability gates are intrinsically easier to satisfy (Danielis et al., 2018). A second group comprises segments where AE solutions deliver measurable environmental benefits but retain a positive ΔTCO. In these cases, the green premium is non-negligible and points to the need for external support or risk-sharing mechanisms if bankability and market readiness are to be preserved. D6.6 limits itself to indicating this structural need; the discussion of funding and risk-sharing logics is addressed in Section 7, under the constraints set by D6.2 and D6.5 (European Commission, 2021). A third group includes segments for which D6.2 explicitly notes a strong dependence of performance and costs on duty cycles, load profiles and infrastructure conditions, without providing consolidated numerical LCIA or TCO indicators. In these contexts, LCC and TCO are inherently case-specific and cannot be generalised at cluster level. D6.6 therefore restricts itself to qualitative statements on potential and uncertainty, signalling that additional, context-specific analysis would be required for robust deployment decisions (Piątek, 2019; Kolodziejski and Michalska-Pozoga, 2023). This threefold classification is sufficient to inform the deployment, replication and funding logic of D6.6 without introducing new criteria or expanding the feasibility domain defined in D6.5.

6.3 Segment-wise integration

To support replication and funding decisions, LCIA and LCC/TCO results are consolidated in a cluster-wise format aligned with the segmentation and use-cases defined in WP1–WP2 and Section 3 (AENEAS Consortium, 2025). For each macro-cluster, D6.6 uses a standard table that reports the representative use-case, the LIB reference and the AE ESS option consistent with the application models in Section 4 (AENEAS Consortium, 2025; Nyamathulla and Dhanamjayulu, 2024), the ΔTCO and ΔGHG (GWP100) values where available from D6.2, and a qualitative descriptor of safety or operational benefits where D6.2/D6.5 provide a comparative basis (EMSA, 2023). When D6.2 does not provide numerical results for a given combination, the corresponding entries are indicated as n.d. (not determined). In such cases, the narrative explicitly acknowledges that this reflects genuine case dependency, not missing analysis. The tables thus form a traceable bridge between the technical evidence of D6.2 and the roadmap and funding discussions in Sections 7 and 8.

6.3.1 Cluster A – Short-sea vessels with high SSSB/Hybrid potential

Cluster A covers short-sea vessels with regular operating profiles and a high incidence of port-stay phases, where AE ESS can significantly affect emission-intensive mission segments (hotel loads in port and short manoeuvres). As shown in Table 8, the representative case is Use-case A (Ro-Ro series – Grimaldi, port stay), for which D6.2 identifies LIB as reference and SSB/SSSB as AE options (AENEAS Consortium, 2025). On the environmental side, D6.2 provides GWP100 per kWh of pack capacity for LIB and SSB across several maturity scenarios. In the pilot-scale configuration, SSB shows higher cradle-to-gate impact than LIB, driven primarily by higher manufacturing energy demand and non-optimised pack integration. Under industrial scale-up and cell-to-pack optimisation scenarios, however, SSB impact decreases substantially and falls below the LIB benchmark. This pattern is consistent with broader evidence on industrial learning and pack-level design in advanced maritime battery systems (Nyamathulla and Dhanamjayulu, 2024; DNV GL AS Maritime, 2020). On the economic side, D6.2 discusses TCO comparatively but does not report consolidated ΔTCO for Cluster A. The analysis indicates that higher CAPEX for SSB and hybrid configurations can be partly compensated by reduced energy costs, extended cycle life and operational savings in emission-constrained profiles. Taken together, these elements position Cluster A as the most advanced context in which AE solutions combine demonstrable LCIA gains with a plausible trajectory towards TCO competitiveness (Danielis et al., 2018; IEA Bioenergy, 2025).

Table 8: Environmental and economic advantages by segment - cluster A

Use-case	**Reference technology**	**AE ESS option**	**ΔTCO vs reference**	**ΔGHG (GWP100) vs reference**	**Qualitative safety / operational benefit**
Use-case A – Ro-Ro series, port stay	LIB = 108.4 $kgCO_2$-eq/kWh (pack production)	SSB – Scenario 1 (industrial scale-up)	n.d.	+100.8 $kgCO_2$-eq/kWh (+93.0%)	n.d. (safety assessment not quantified in D6.2)
Use-case A – Ro-Ro series, port stay	LIB = 108.4 $kgCO_2$-eq/kWh (pack production)	SSB – Scenario 4 (scale-up + pack optimisation)	n.d.	−28.4 $kgCO_2$-eq/kWh (−26.2%)	n.d. (safety assessment not quantified in D6.2)

At present, Cluster A is the only segment in which D6.2 quantitatively demonstrates that, at sufficient technological maturity, AE ESS can outperform LIB in terms of climate impact and move towards cost competitiveness. This directly supports its prioritisation as the primary candidate for early deployment and structured replication within the envelopes validated in D6.5.

6.3.2 Cluster B – Inland waterway vessels (SC/Hybrid)

Cluster B comprises inland waterway vessels characterised by highly repetitive mission profiles and intensive ESS utilisation under well-defined operational conditions. As shown in Table 9, the representative case is Use-case C (INLS Mayon/Anaconda) with hybrid SSSB+SC integration (AENEAS Consortium, 2025; CCNR, 2023). In this cluster, D6.2 provides detailed LCI inventories for supercapacitors and hybrid configurations, but does not report consolidated LCIA, LCC or TCO values suitable for robust cross-cluster comparison. This is consistent with the strong dependence of environmental and economic performance on route-specific duty cycles, loading patterns, charging strategies and river conditions (Tao et., 2023; Piątek, 2019).

Table 9: Environmental and economic advantages by segment – Cluster B

Use-case	Reference technology	AE ESS option	ΔTCO vs reference	ΔGHG (GWP100) vs reference	Safety / cost-effectiveness
Use-case C – INLS Mayon/Anaconda	LIB	Hybrid SSSB+SC	n.d.	n.d. (no LCIA numerical results reported in D6.2)	Qualitative benefits in transient handling and robustness; quantitative metrics context-dependent

From an engineering viewpoint, Cluster B shows significant potential for hybrid architectures in terms of robustness, transient management and operational flexibility (Miller, 2011; Kolodziejski and Michalska-Pozoga, 2023). However, quantitative LCIA and TCO indicators must remain case-specific. D6.6 therefore treats this cluster as promising but conditional, and does not promote it to the same priority level as Cluster A.

6.3.3 Cluster C – Port-related and auxiliary applications (SC/Hybrid)

Cluster C includes port-related and auxiliary applications where ESS are primarily deployed as power-support devices for high-dynamics operations, such as load-levelling, peak-shaving and power-quality stabilisation. As shown in Table 10, the representative case is Use-case B (Cruise series – manoeuvring) with supercapacitor integration (AENEAS Consortium, 2025; PEMA, 2023).

For this cluster, D6.2 documents the data collection and LCI set-up for supercapacitors but does not provide LCIA, LCC or TCO numerical results that would allow a meaningful aggregated comparison with LIB. This is coherent with the nature of the applications, where total energy throughput is limited and the value of AE solutions is primarily associated with local operational and safety benefits, such as reduced equipment stress and improved power quality (Miller, 2011; PortXchange, 2021).

Table 10: Environmental and economic advantages by segment – Cluster C

Use-case	Reference technology	AE ESS option	ΔTCO vs reference	ΔGHG (GWP100) vs reference	Safety / cost-effectiveness
Use-case B – Cruise series, manoeuvring	LIB	Supercapacitors	n.d.	n.d. (no LCIA numerical results reported in D6.2)	Qualitative benefits in peak-shaving, power-quality stabilisation and reduced equipment stress; quantitative metrics context-dependent

As in Cluster B, the absence of consolidated numerical indicators is treated as a substantive finding: it indicates that the environmental and economic performance of ESS in these applications is strongly case-dependent, and that any robust quantification for replication or funding decisions would require additional, tailored modelling beyond the scope of WP6.

6.4 Implications for deployment, replication and funding logic

The integrated reading of LCIA, LCC and TCO results reveals a clear gradient of maturity across the three clusters. Cluster A (short-sea vessels) is supported by quantitative LCIA evidence and a consistent qualitative TCO narrative, showing that AE solutions can surpass LIB in terms of climate impact once industrial scale-up and pack optimisation are achieved, and can move towards cost competitiveness under conservative assumptions. Within the gate-based framework of D6.5, this justifies the designation of Cluster A as the primary candidate for early deployment and structured replication (Nyamathulla and Dhanamjayulu, 2024; Danielis et al., 2018). Cluster B (inland waterways) and Cluster C (port-related and auxiliary applications) exhibit high application potential, particularly in terms of robustness, transient handling and power-quality improvement (Kolodziejski and Michalska-Pozoga, 2023). At the same time, D6.2 and D6.5 converge in indicating that their environmental and economic performance is strongly dependent on specific duty cycles, operating strategies and infrastructure conditions. D6.6 therefore classifies these clusters as conditionally attractive: they are clearly relevant domains for AE deployment, but large-scale replication or funding prioritisation would require additional, case-specific LCIA–TCO analyses and governance alignment (Piątek, 2019; DNV, 2024; ITF, 2023). In conclusion, Section translates the LCIA, LCC and TCO evidence of D6.2 into a concise, gate-facing and cluster-wise picture that identifies where AE deployment is already environmentally and economically aligned, where a structural green premium and support measures are needed, and where further case-specific analysis is a prerequisite.

7 Mapping of public and private funding opportunities

This section consolidates and maps public and private funding approaches relevant to the deployment of Advanced Energy Storage (AE) solutions, strictly within the feasibility, applicability and readiness boundaries. All mechanisms referenced are either explicitly discussed in AENEAS deliverables (D6.1, D6.3) or constitute established EU-level regulatory and financing frameworks that operate as boundary conditions for deployment. Funding is treated as an enabling condition for exploitation and replication only after technical feasibility and applicability have been demonstrated. Funding needs evolve in a predictable manner along the deployment trajectory of AE solutions, in direct correspondence with their maturity and risk profile. During the research and demonstration phase, funding requirements are dominated by non-recurring costs associated with technology development, ESS system engineering, testing, certification and first on-board integration. As documented in the Business Plan (D6.1), at this stage both CAPEX levels and integration costs remain highly sensitive to technological maturity and application-specific constraints. Under these conditions, private investment alone is structurally insufficient. Public research and innovation funding therefore constitutes a necessary enabling condition for progression towards TRL 7–8 within the validated applicability envelopes. The early commercial deployment phase builds directly on the feasibility and business-case assessments presented in D6.3. It is characterised by first commercial installations in selected segments and clusters already validated in D6.5. Cost structures remain predominantly CAPEX-driven, particularly for retrofit solutions, while OPEX benefits begin to materialise but are not yet fully consolidated. Funding in this phase is therefore associated with shipowner-led investments complemented by risk-sharing mechanisms addressing first-of-a-kind exposure. No assumption of full cost competitiveness is made at this stage. In the fleet-scale deployment phase, AE solutions reach a level of maturity that allows a structured evaluation of Total Cost of Ownership. Financing responsibility shifts primarily to shipowners and industrial operators, while public intervention assumes a contextual role focused on risk mitigation, infrastructure readiness and regulatory alignment. Direct technology support is no longer a prerequisite under these conditions.

7.1 Funding and financing instruments

Across the AENEAS project documentation, funding and financing approaches are consistently framed around risk allocation along the value chain rather than around specific programmes. First, public R&I funding supports activities characterised by high technological uncertainty, covering development, validation and demonstration. Horizon Europe and associated EU research frameworks provide the institutional context for such support, already leveraged by AENEAS and fully aligned with its technological scope. Second, sectoral and regional support schemes address external deployment constraints, particularly those related to port infrastructure, energy interfaces and grid integration. These instruments do not alter the technological scope of AE solutions but reduce systemic barriers to their deployment. Third, private and blended finance models progressively dominate as maturity increases. Shipowner investment, vendor financing and leasing arrangements allow redistribution of CAPEX and operational risk across technology providers, yards and operators, and are particularly relevant for retrofit applications characterised by high upfront costs. In this sense, the scope is limited to mapping these already-identified approaches against deployment phases and validated business model archetypes. Table 11 provides a consolidated mapping of funding and financing approaches across deployment phases. It reflects the progressive transition from public to private financing as technological and operational uncertainty decreases.

Table 11: Funding and financing options mapped

Deployment phase	Dominant cost drivers	Risk profile	Prevailing funding approaches	Role of public support
Research and demonstration	Non-recurring R&I, engineering, testing, integration	High (technological)	EU R&I grants; partner co-funding	Enabling and critical
Early commercial deployment	High CAPEX; partially emerging OPEX benefits	Medium–high (FOAK)	Shipowner investment; vendor financing; leasing	Initial risk reduction
Fleet-scale deployment	TCO-driven; consolidated OPEX benefits	Medium–low	Large-scale private investment; blended finance	Contextual and enabling

Public funding is indispensable to overcome technological risk and integration uncertainty in the early phases, while private capital becomes progressively dominant as feasibility and applicability are consolidated. Importantly, the absence of a consolidated numerical financial model at project level is not a limitation but a direct consequence of the current maturity of AE solutions. Financing logic at this stage must be grounded in cost drivers, risk allocation and stakeholder roles rather than point estimates of profitability.

8 Expansion roadmap

This expansion roadmap operationalises the validated feasibility and applicability envelopes into a staged exploitation sequence up to 2030. The roadmap is a deployment grammar: progression is conditional on gate closure and on the consolidation of evidence generated by the two on-board demonstrators planned up to 2027. Any post-demonstration scaling step is admissible only if (i) the demonstrator solutions remain within their validated applicability envelopes, (ii) safety and integration evidence is consolidated at system level, and (iii) operational performance assumptions used in WP6 (including LCA/LCC/TCO framing from D6.2) are confirmed as deployment-relevant under real conditions, within the limits of D6.5 (AENEAS Consortium, 2025). The linking feasibility, applicability, readiness and exploitation is synthesised in Figure 3, which makes explicit that exploitation options are conditional outcomes of demonstrator-level evidence, not parallel market-driven decisions.

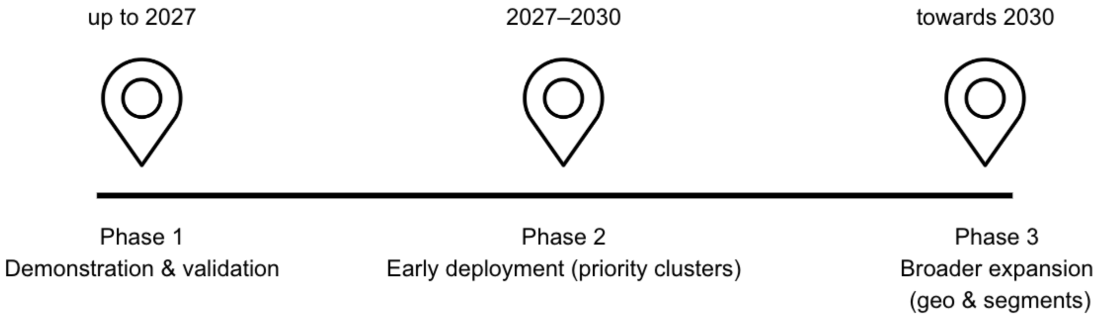


Figure 3: Expansion roadmap

On this basis, the roadmap is structured in three phases.

Phase 1 – Demonstration and validation (up to 2027). This phase is governed by the D6.5 milestone: the two demonstrators are executed to produce replication-grade evidence, not “commercial readiness”. Outputs are: validated integration practices (interfaces, EMS/BMS/PMS coordination logics where applicable), verified safety and operability evidence, and a consolidated set of assumptions usable in exploitation discussions without re-opening feasibility (AENEAS Consortium, 2025). Any replication claim prior to this closure would be methodologically inconsistent with the D6.5 approach and is therefore excluded.

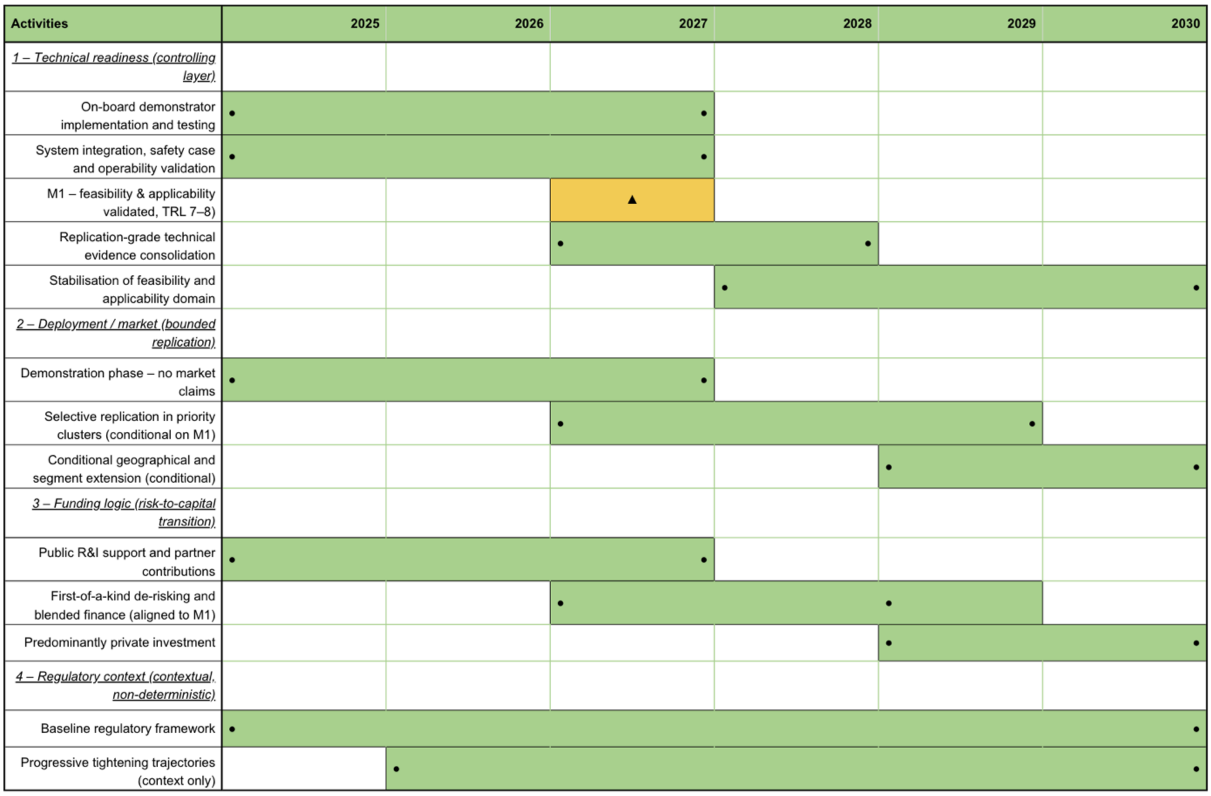
Phase 2 – Early deployment in priority clusters (2027–2030). Early deployment is defined as selective replication limited to the segment clusters already identified and bounded by the same applicability envelopes. In operational terms, this phase is admissible only if the demonstrator evidence supports (i) repeatability of integration, (ii) stable compliance posture (safety/certification evidence that is transferable), and (iii) a gate-facing environmental and economic narrative. This phase is where business model archetypes and funding logics are refined against early adopters, but not redesigned or optimised beyond WP6 evidence.

Phase 3 – Broader geographical and segment expansion (towards 2030). This phase is an optional extension contingent on two non-compensable conditions: (i) transferability of validated system integration practices beyond the initial early-deployment contexts, and (ii) availability and readiness of enabling infrastructures (ship–shore interfaces, port and grid conditions) required by the validated deployment envelopes. Geographical and segment expansion is admissible where these constraints are satisfied. Integration with other decarbonisation measures is acknowledged only insofar.

The 2030 horizon is used to structure post-project exploitation sequencing; it does not extend AENEAS technical objectives beyond the demonstrator scope and gate logic fixed up to 2027 in D6.5.

8.1 Milestones and alignment across technical, market, regulatory and funding layers

The roadmap is implemented as a multi-layer timeline. The purpose is not to narrate how the market will evolve, but to ensure that exploitation decisions remain consistent with readiness evidence and with high-regulation constraints typical of maritime ESS deployment. This multi-layer structure is visualised in Figure 4, which combines the technical milestones defined in D6.5 with the deployment, funding and regulatory layers relevant for post-demonstration exploitation.



Activities	2025	2026	2027	2028	2029	2030
1 – Technical readiness (controlling layer)						
On-board demonstrator implementation and testing	● 🟩	🟩	🟩 ●			
System integration, safety case and operability validation	● 🟩	🟩	🟩 ●			
M1 – feasibility & applicability validated, TRL 7–8)			🟨 ▲			
Replication-grade technical evidence consolidation			● 🟩	🟩 ●		
Stabilisation of feasibility and applicability domain				● 🟩	🟩	🟩 ●
2 – Deployment / market (bounded replication)						
Demonstration phase – no market claims	● 🟩	🟩	🟩 ●			
Selective replication in priority clusters (conditional on M1)			● 🟩	🟩	🟩 ●	
Conditional geographical and segment extension (conditional)					● 🟩	🟩 ●
3 – Funding logic (risk-to-capital transition)						
Public R&I support and partner contributions	● 🟩	🟩	🟩 ●			
First-of-a-kind de-risking and blended finance (aligned to M1)			● 🟩	🟩	● 🟩	
Predominantly private investment					● 🟩	🟩 ●
4 – Regulatory context (contextual, non-deterministic)						
Baseline regulatory framework	● 🟩	🟩	🟩	🟩	🟩	🟩 ●
Progressive tightening trajectories (context only)		● 🟩	🟩	🟩	🟩	🟩 ●

Figure 4: Gantt across technical, market, regulatory and funding layers

Legend:

- ● = start / end activity
- ▲ = critical milestone (system-level gate)

Activities in 2 and 3 beyond 2027 are admissible only if M1 is achieved. Regulatory activities provide context only and do not unlock or block phases.
Multi-layer roadmap integrating technical readiness (D6.5), deployment phases, funding logic and regulatory context. Progression beyond demonstration is conditional on the closure of feasibility and applicability gates; no market scaling is assumed independently of technical evidence.

Technical milestones (controlling layer).

Technical milestones are those defined by D6.5 for TRL progression and demonstrator validation. They remain the controlling layer because market uptake cannot compensate for missing feasibility or safety evidence. The relevant outputs for replication are the closure of system-level integration and safety evidence, plus the stabilisation of design and verification practices that reduce replication uncertainty (AENEAS Consortium, 2025).

Market milestones (bounded replication thresholds).

Market milestones are expressed as replication thresholds, not penetration targets. A threshold is considered met when a solution can be integrated repeatedly within the validated envelopes, with bounded engineering effort and predictable compliance steps. This framing prevents scale claims that are not supported by the evidence available at WP6 level (AENEAS Consortium, 2025).

Regulatory milestones (context layer).

Regulatory trajectories are treated as context conditions that influence the relative value of electrification and onboard ESS solutions across segments, but they do not alter feasibility. Accordingly, D6.6 does not reinterpret regulations or propose compliance strategies beyond the validated envelopes; it only recognises that tightening requirements increase the deployment relevance of solutions that are already technically validated (AENEAS Consortium, 2025).

Funding milestones (risk-to-capital transition).

Funding milestones are aligned to the risk profile implied by the gate logic: Phase 1 is dominated by public R&I support and partner contributions; Phase 2 requires first-of-a-kind de-risking and blended structures consistent with D6.1 and D6.3; Phase 3 is predominantly private-investment-driven where replication uncertainty has been reduced by demonstrator evidence (AENEAS Consortium, 2025).

The admissibility of transitions between phases is further operationalised in Table 12, which maps each deployment phase to the minimum evidence required and to the explicit exclusions that apply if such evidence is not available.

Table 12: Dependency path

Deployment Phase	Technical Feasibility Gate (D6.5)	System Integration & Safety Evidence	Environmental & Economic Evidence (D6.2)	Funding & Bankability Condition	Admissible Outcome	Explicit Exclusions if Gate Not Closed
Phase 1 – Demonstration & Validation (≤2027)	Feasibility and applicability envelopes validated at demonstrator level (TRL 7–8)	System-level integration, safety case and operability validated under real operating conditions	LCA/LCC/TCO assumptions confirmed as demonstrator-relevant	Public R&I support and partner contributions	Replication-grade technical and operational evidence packages	• No replication claims • No early deployment • No scaling or market extension
Phase 2 – Early Deployment (2027–2030)	Feasibility envelopes closed and unchanged; no extension beyond validated domain	Safety and integration evidence transferable to similar operational contexts	Environmental and economic narrative fully traceable to D6.2 assumptions	FOAK de-risking and blended finance consistent with D6.1–D6.3	Selective replication in priority clusters only	• No new vessel classes or segments • No geographical scaling • No redesign/optimisation beyond WP6 evidence

Phase 3 – Broader Expansion (conditional, ≤2030)	Feasibility domain stable and not expanded	Integration, safety and compliance practices consolidated and standardised	TCO and impact assumptions robust across repeated deployments	Predominantly private capital	Conditional geographical and segment expansion	• No expansion where infrastructure readiness is lacking • No extrapolation beyond validated envelopes • No market-driven scaling without closed gates

Each deployment phase is admissible only if the evidence generated in the previous phase satisfies the corresponding gate conditions. The matrix makes explicit what is excluded when gates are not closed. This roadmap is the operational bridge between (i) the demonstrator-centric readiness logic of D6.5 and (ii) the exploitation planning required in D6.4. The function of D6.6 is to ensure that D6.4 is built on a traceable deployment sequence that does not dilute the technical constraints validated in D6.5. Accordingly, D6.4 should use the roadmap to: (a) structure exploitation actions and partner commitments around demonstrator evidence packages; (b) define replication packages (engineering, compliance and operational assumptions) that are demonstrably transferable within the validated envelopes; and (c) specify stakeholder-facing recommendations that remain conservative and auditable because they are conditional on gate closure rather than on aspirational scaling (AENEAS Consortium, 2025).

9 References

AENEAS Consortium. (2025). D6.1 – Interim Exploitation Plan. Horizon Europe AENEAS Project Deliverable.

AENEAS Consortium. (2025). D6.2 – LCIA, LCC, TCO and safety impact assessment. Horizon Europe AENEAS Project Deliverable.

AENEAS Consortium. (2025). D6.3 – Feasibility and adequacy for a broad range of waterborne operations. Horizon Europe AENEAS Project Deliverable.

AENEAS Consortium. (2025). D6.5 – Roadmap towards full-scale on-board demonstrators. Horizon Europe AENEAS Project Deliverable.

AENEAS Consortium. (2025). D6.6 – Market expansion, funding mapping and expansion roadmap for AE solutions. Horizon Europe AENEAS Project Deliverable.

Akbarzadeh, M., De Smet, J., & Stuyts, J. (2022). Battery hybrid energy storage systems for full-electric marine applications. Processes, 10(11), 2418. https://doi.org/10.3390/pr10112418

American Bureau of Shipping. (2024). Beyond the horizon: Carbon neutral fuel pathways and transformational technologies (ABS Sustainability Outlook). American Bureau of Shipping. Retrieved from https://ww2.eagle.org/content/dam/eagle/publications/whitepapers/2024-sustainability-outlook-web_OCT.pdf

Bach, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., & Steen, M. (2020). Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. Transportation Research Part D: Transport and Environment, 87, 102492. https://doi.org/10.1016/j.trd.2020.102492

Baresic, D., Prakash, V., Stewart, J., Majidova, P., Smith, T., Fricaudet, M., & Rehmatulla, N. (2025). Climate action in shipping: Progress towards shipping's 2030 breakthrough (2025 edition). UCL Energy Institute; Getting to Zero Coalition; Climate High-Level Champions. Retrieved from https://assets.ctfassets.net/gk3lrimlph5v/3InjQiz6GbF7LZQsWkvDTs/5822cca783cfb117a12b755b483eb4c7/Climate_action_in_Shipping_-_Progress_towards_shipping-s_2030_breakthrough_2025.pdf

Bureau Veritas Marine & Offshore. (2025). Maritime electrification report: Maritime battery systems and onshore power supply. Bureau Veritas. Retrieved from https://marine-offshore.bureauveritas.com/system/files/whitepaper/2025-08/ElectrificationReport.pdf

Central Commission for the Navigation of the Rhine (CCNR). (2023). Market Insight 2023: Inland Navigation in Europe. https://inland-navigation-market.org/wp-content/uploads/2025/01/CCNR_annual_report_EN_2023_WEB_rev.pdf

CESNI. (2019). European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN 2019/1). CESNI. Retrieved from https://www.cesni.eu/wp-content/uploads/2018/12/ES_TRIN_2019_en.pdf

CIMAC & Maritime Battery Forum. (2024). Environment for the use of batteries in deep-sea shipping: Joint whitepaper. CIMAC. Retrieved from https://acrobat.adobe.com/id/urn:aaid:sc:EU:aa0ae08e-40be-4f2d-9638-8f5491741663

CIMAC & Maritime Battery Forum. (2025). Deep-Sea Use Cases for Maritime Battery Systems: Joint White Paper. Zero Emission Services

Cruise Lines International Association & SEA Europe. (2022). Joint call for maritime technology to be included in the Green Deal Industrial Plan. Cruise Lines International Association & SEA Europe. Retrieved from https://europe.cruising.org/knowledge_hub/clia-and-sea-europe-issue-joint-call-for-maritime-technology-to-be-included-in-the-green-deal-industrial-plan

Danielis, R., Giansoldati, M., & Rotaris, L. (2018). A probabilistic total cost of ownership model to evaluate the current and future prospects of electric cars uptake in Italy. Energy Policy, 119, 268-281. https://doi.org/10.1016/j.enpol.2018.04.024

DNV GL AS Maritime. (2020). Electrical energy storage for ships (Report No. 2019-0217, Rev. 04). European Maritime Safety Agency (EMSA). Retrieved from https://safety4sea.com/wp-content/uploads/2020/05/EMSA-study-electrical-energy-storage-for-ships-2020_05.pdf

DNV. (2023). Alternative Fuels Insight: Battery-powered vessels – status and outlook (webinar/slide deck – official DNV resource). Maritime Informed

DNV. (2024). Maritime forecast to 2050: Energy transition outlook 2024. DNV. Retrieved from https://brandcentral.dnv.com/original/gallery/10651/files/original/49ba47c0-47c1-4bb1-a8f9-0d728e62b8d6.pdf

Englert, D., & Losos, A. (2021). Charting a course for decarbonizing maritime transport: Summary for policymakers and industry. World Bank. Retrieved from http://documents.worldbank.org/curated/en/680021617997493409

European Commission. (2021). Fit-for-55: Delivering the EU's 2030 climate target on the way to climate neutrality (COM/2021/550 final). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1805

European Commission. (2025). Horizon Europe – Online Manual: Dissemination & Exploitation. Research and innovation

European Maritime Safety Agency (EMSA). (2023). Guidance on the Safety of Battery Energy Storage Systems On-board Ships.

European Maritime Safety Agency (EMSA). (2024). Shore-side electricity (SSE) for ships: Information and guidance. European Maritime Safety Agency

European Parliament & Council. (2023). Directive (EU) 2023/959 amending Directive 2003/87/EC as regards strengthening the EU ETS and extending it to maritime transport. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L0959

European Parliament & Council. (2023). Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime). Official Journal of the European Union. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1805

Frković, L., Ćosić, B., Falkoni, A., Pukšec, T., & Vladimir, N. (2024). Shore-to-ship: Enabling the electrification sustainability of maritime transport with the nexus between berthed cruise ships and renewables in the isolated energy systems. Ocean engineering, 302, 117537.

Global Centre for Maritime Decarbonisation & Boston Consulting Group. (2023). Voyaging toward a greener maritime future: Insights from the GCMD–BCG global maritime decarbonisation survey. Global Centre for Maritime Decarbonisation & Boston Consulting Group. Retrieved from https://www.gcformd.org/wp-content/uploads/2023/09/GCMD-BCG-Voyaging-Toward-a-Greener-Future-vF.pdf

Halim, R. A., Kirstein, L., Merk, O., & Martinez, L. M. (2018). Decarbonization pathways for international maritime transport: A model-based policy impact assessment. Sustainability, 10(7), 2243. https://doi.org/10.3390/su10072243

IEA Bioenergy. (2025). Annual report 2024. IEA Bioenergy Technology Collaboration Programme. Available at: https://www.ieabioenergy.com/wp-content/uploads/2025/06/IEA-Bioenergy-Annual-Report-2024.pdf

International Energy Agency. (2021). World Energy Outlook 2021. OECD Publishing. https://doi.org/10.1787/14fcb638-en

International Maritime Organization (IMO). (1974). International Convention for the Safety of Life at Sea (SOLAS). IMO. Retrieved December 29, 2025, from https://www.imo.org/en/about/conventions/pages/international-convention-for-the-safety-of-life-at-sea-(solas),-1974.aspx

International Maritime Organization (IMO). (2023). 2023 IMO strategy on reduction of GHG emissions from ships. International Maritime Organization. Retrieved December 29, 2025, from https://www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx

International Maritime Organization (IMO). (2023). IMO CARES – Decarbonization of domestic shipping. (Report incl. annexes supporting the 2023 Strategy graphic/trajectory references). International Maritime Organization

ITF (2023), ITF Transport Outlook 2023, OECD Publishing, Paris, https://doi.org/10.1787/b6cc9ad5-en.

Kolodziejski, M., & Michalska-Pozoga, I. (2023). Battery energy storage systems in ships' hybrid/electric propulsion systems. Energies, 16(3), 1122. https://doi.org/10.3390/en16031122

Lucà Trombetta, G., Leonardi, S. G., Aloisio, D., Andaloro, L., & Sergi, F. (2024). Lithium-ion batteries on board: A review on their integration for enabling the energy transition in shipping industry. Energies, 17(5), 1019. https://doi.org/10.3390/en17051019

J. M. Miller, "Ultracapacitor Applications," The Institution of Engineering and Technology, Stevenage, 2011.

Nivolianiti, E., Karnavas, Y. L., & Charpentier, J. F. (2024). Energy management of shipboard microgrids integrating energy storage systems: A review. Renewable and Sustainable Energy Reviews, 189, 114012. https://doi.org/10.1016/j.rser.2023.114012

Nyamathulla, S., & Dhanamjayulu, C. (2024). A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations. Journal of Energy Storage, 86, 111179.

Nordic Innovation. (2025). Nordic Oceans 2050: Future scenarios for the Nordic ocean economy. Nordic Innovation. Retrieved from https://pub.norden.org/nordicinnovation2025-05/nordicinnovation2025-05.pdf

PEMA. (2023). Ultracapacitors in port applications (PEMA International Paper IP08A). Port Equipment Manufacturers Association. Retrieved from https://www.pema.org/wp-content/uploads/2023/01/PEMA_Ultracapacitors_Digital_AW.pdf

Piątek, D. (2019). New concept of hybrid propulsion with hydrostatic gear for inland water transport. Polish Maritime Research, (2), 134-141. https://doi.org/10.2478/pomr-2019-0033

Port of Rotterdam Authority & Gemeente Rotterdam. (2025). Havenvisie Rotterdam 2050. Havenvisiepartners. Retrieved from https://rotterdamraad.bestuurlijkeinformatie.nl/Reports/Document/63a05367-0790-404d-bb39-3fff36e5e367?documentId=89d65696-f01b-4825-9b08-d4e20fa399b2

PortXchange. (2021). Just in time sailing: Reduce fuel consumption and CO_2 emissions every port call (White paper). Retrieved from https://portxchange.wpenginepowered.com/wp-content/uploads/2021/01/Portxchange-e-book-Just-in-Time-Sailing.pdf?utm_source=Newsletter&utm_medium=email&utm_content=Whitepaper&utm_campaign=JIT%20sailing

PortXchange. (2024). How digitalization can unlock green shipping corridors from feasibility study to implementation (White paper). Retrieved from https://port-xchange.com/wp-content/uploads/2024/09/How-Digitalization-Can-Unlock-Green-Shipping-Corridors-from-Feasibility-Study-to-Implementation-PortXchange-Whitepaper.pdf?utm_source=Newsletter&utm_medium=email&utm_content=Whitepaper%3A%20Unlock%20Green%20Shipping%20Corridors%C2%A0&utm_campaign=Green%20corridors%20wp%202&vgo_ee=1d3w81hjAN9GYCZvfP6ZAxVSB2oHHpcilkynKO%2Bn8M0TmZNwjXLs0MqOUfKb%3AWZS8VrltcBCsHj2zGJVoZQI4ouERZLK7

SEA-LNG. (2023). LNG - DELIVERING DECARBONISATION: A VIEW FROM THE BRIDGE. SEA-LNG. Retrieved from https://sea-lng.org/wp-content/uploads/2023/02/2023_A-view-from-the-bridge_WEB_SINGLE-PAGES_feb_23.pdf

Tao, Z., Barrera-Cardenas, R., Akbarzadeh, M., Mo, O., De Smet, J., & Stuyts, J. (2023). Design and evaluation framework for modular hybrid battery energy storage systems in full-electric marine applications. Batteries, 9(5), 250. https://doi.org/10.3390/batteries9050250

United Nations Conference on Trade and Development. (2025). Review of Maritime Transport 2025: Staying the course in turbulent waters. UNCTAD. Retrieved from https://unctad.org/system/files/official-document/rmt2025_en.pdf

Wärtsilä Corporation. (2025). 51 great ways the maritime industry could reduce its greenhouse gas emissions (eBook). Wärtsilä. Retrieved from https://brandhub.wartsila.com/m/640f0512d79cd6d7/original/50-great-ways-the-maritime-industry-could-reduce-its-greenhouse-gas-emissions-eBook.pdf?utm_source=web&utm_medium=bwp&utm_term=marine&utm_content=bwp&utm_campaign=bwp-lead-scoring

10 Acknowledgements and disclaimer

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

#	Partner	Partner full name
1	FM	FLANDERS MAKE
2	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
3	ABEE	AVESTA BATTERY & ENERGY ENGINEERING
4	SIE	SIEMENS INDUSTRY SOFTWARE SAS
5	UVA	VAASAN YLIOPISTO
6	I2M	I2M UNTERNEHMENSENTWICKLUNG GMBH
7	GRIM	GRIMALDI EUROMED SPA
8	INLS	INLAND SHIPPING SRL
9	FV	FUNDACION DE LA COMUNIDAD VALENCIANA PARA LA INVESTIGACION, PROMOCION Y ESTUDIOS COMERCIALES DE VALENCIAPORT
10	AUTH	ARISTOTELIO PANEPISTIMIO THESSALONIKIS
11	SOER	FUNDACION CENTRO TECNOLOGICO SOERMAR
12	FMAR	FORMARE- POLO NAZIONALE PER LO SHIPPING SRL
13	ISSN	INSTITUTE FOR SUSTAINABLE SOCIETY AND INNOVATION
14	FS	CONSTRUCCIONES NAVALES P FREIRE SA

LEGAL DISCLAIMER

Funded by
the European Union

Abbreviations and Definitions

Term	Definition
AENEAS	innovAtive ENErgy storage systems onboArd vesselS
ESS	Energy Storage System
SSB	Solid-State Battery
SSSB	Semi-Solid-State Battery
SC	Supercapacitor
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
NPV	Net Present Value
IRR	Internal Rate of Return
TCO	Total Cost of Ownership
EU	European Union
IMO	International Maritime Organization
EU ETS	European Union Emissions Trading System
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
GHG	Greenhouse Gas
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
CII	Carbon Intensity Indicator

List of Figures

List of Tables