



From Logistics Corridors to Green Energy Corridors: DC Distribution Networks Reshaping Inland Waterways

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Inland waterways are transitioning from logistics corridors to green inland energy corridors, but present port electrification remains confined to individual terminals. The evolution of inland ports is first traced from logistics nodes to electrified energy hubs and ultimately to energy internet nodes. A DC-enabled corridor framework is then formulated to support controllable power routing, inter-port flexibility sharing, ship-borne flexibility, and hierarchical coordination. Within this framework, energy-carbon symbiosis is defined as the reciprocal coupling between physical energy exchange and carbon governance, and energy-oriented, carbon-oriented, and energy-carbon symbiotic optimization models are compared under a common feasibility and performance framework. This perspective clarifies the distinctive role of DC distribution networks and the technical and regulatory conditions required for practical deployment.

INTRODUCTION

Inland waterways and canal networks provide stable transport corridors that connect ports, cities, industries, and hinterlands. Their predictable routes and moderate operating speeds make ships well suited to electrification. Electric ships are a visible symbol of this transition, but inland waterway electrification involves more than supplying energy to vessels. With the integration of shore power, distributed renewable generation, energy storage, and electrified port equipment into port operations,¹ inland ports are acquiring new energy functions while retaining their core logistics roles. Power supply, storage dispatch, and electrified load management are increasingly becoming integral parts of port operations, making ports key interfaces between waterborne transport and clean energy systems.

This transition, however, remains constrained by the local configuration of port energy systems. At present, shore power facilities, distributed renewable generation, energy storage, and electrified loads are typically planned as local assets, with energy supply and balancing organized within individual port boundaries.² This approach can support early-stage electrification at individual ports, but it is not well suited to inland waterway corridors, where energy resources and electrification demand vary across space and time. With corridor-level coordination, surplus renewable generation or storage flexibility at one port could support another port facing load growth or distribution network constraints. As electrification expands, spatial and temporal mismatches between electricity supply and demand may lead to renewable energy curtailment, peak load concentration, distribution network congestion, repeated grid-connection reinforcement, and underutilization of flexible resources. Therefore, the key challenge is to shift from isolated port-level

electrification toward coordinated energy operation along the corridor.

Because emerging port resources either supply power in DC form or are connected through power electronic interfaces, DC distribution networks are well suited to this next stage. Photovoltaic generation, battery storage, charging facilities, and electrified port equipment can be integrated through a more compatible electrical platform, reducing unnecessary conversion stages compared with conventional AC supply extensions.³ When embedded in a corridor-level coordination framework, port-side DC distribution networks provide controllable interfaces through which local generation, storage, and flexible demand can participate in inter-port scheduling. This enables renewable generation and storage flexibility to be coordinated with ship movements, berth allocation, and port operations. In this way, DC distribution networks provide the electrical foundation for a coordinated energy layer along inland waterways, supporting the transition from individually electrified ports to connected green inland energy corridors.

EVOLUTION OF INLAND PORTS TOWARD A DC-ENABLED GREEN INLAND ENERGY CORRIDOR

As illustrated in Figure 1, inland ports evolve from logistics nodes to electrified energy hubs, and ultimately to energy internet nodes within a green inland energy corridor. The first two stages remain locally organized: energy supports port operations, and even after electrification, optimization and carbon accounting are mainly confined to a single terminal. The decisive change in Stage III is therefore not simply deeper electrification, but the creation of a corridor-scale energy network.

DC distribution networks provide the electrical basis for this transition by converting each port from a passive load center into a controllable energy node. Through bidirectional converters, the power exchanged by a port can be directly scheduled, reversed, and limited according to corridor-level objectives. This allows surplus generation, storage capacity, charging flexibility, and ship-borne flexibility to be coordinated across ports rather than balanced independently at each terminal.⁴ The corridor can therefore perform inter-port energy sharing, congestion relief, reserve support, renewable energy accommodation, and coordinated restoration.⁵

Compared with conventional AC distribution, DC networks provide greater controllability and efficiency for this role. Converter-referenced power transfer avoids reactive-power exchange and frequency synchronization between connected port systems,⁶ while converter-defined boundaries facilitate modular expansion, fault isolation, and controlled islanding.⁷ At the network level, a field-tested DC microgrid achieved 92.6% efficiency versus 90.9% for

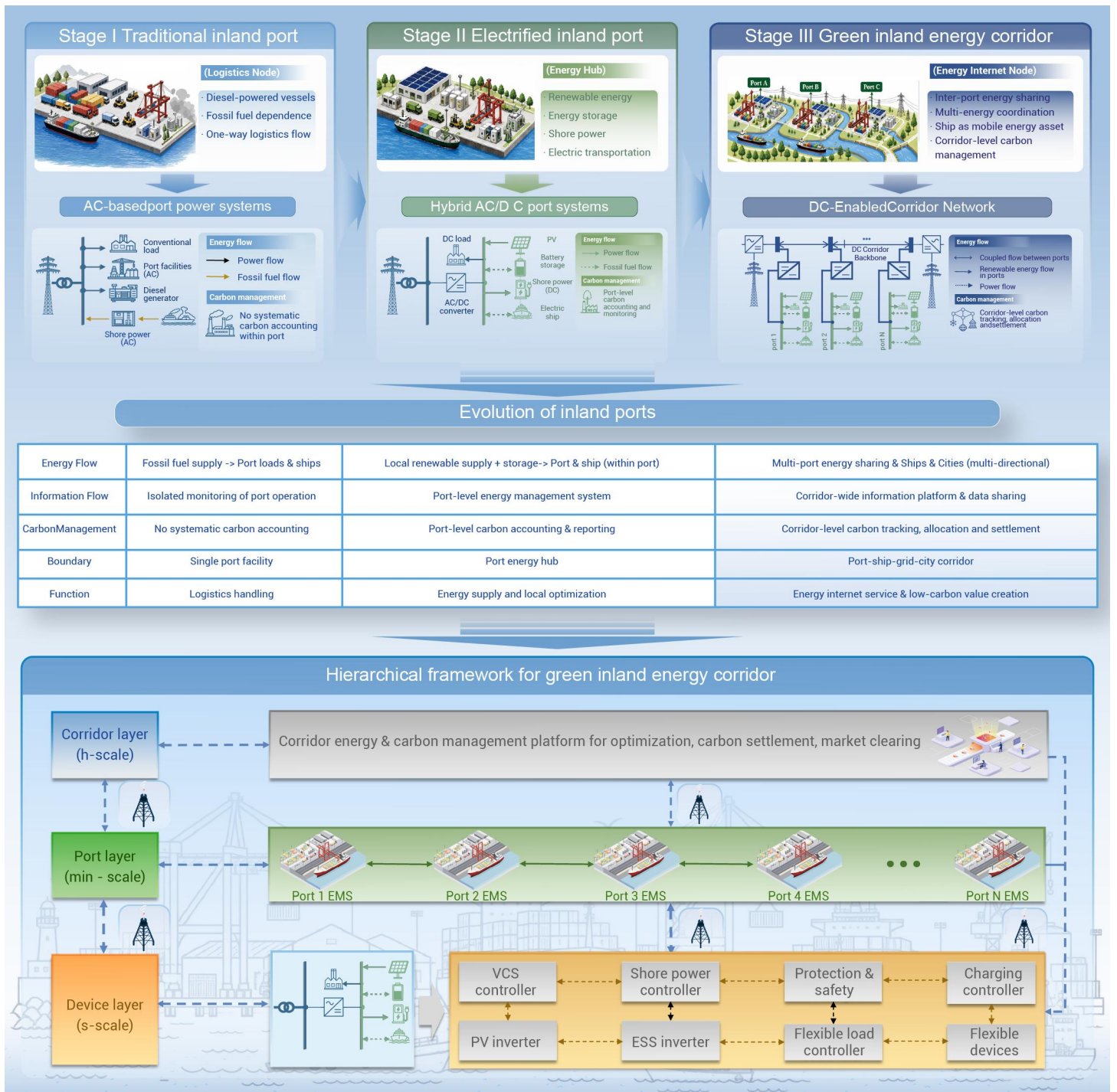


Figure 1. Evolution of inland ports toward a DC-enabled green inland energy corridor.

its equivalent AC network, with load-branch losses reduced by 71%.⁸ These characteristics make DC infrastructure not merely a supply network, but a controllable and efficient coordination layer.

The lower part of Figure 1 shows how this function is implemented. Device-level controllers maintain voltage, current, state of charge, and protection. Port energy management systems aggregate local flexibility and determine each port's feasible import and export range. A corridor-level platform then coordinates inter-port exchange with ship movements, berth schedules, grid constraints, and carbon signals. Accordingly, DC distribution networks reshape inland waterways by linking logistics operation, power routing, and carbon governance within one hierarchical coordination framework.

ENERGY-CARBON SYMBIOSIS ALONG INLAND WATERWAYS

The DC-enabled corridor provides controllable inter-port exchange, but a

green inland energy corridor emerges only when energy operation and carbon governance become mutually coupled. Energy-carbon symbiosis denotes a reciprocal corridor-level relationship in which physical energy exchanges reshape the distribution of carbon responsibilities and low-carbon attributes, while these carbon conditions, in turn, reshape the admissible and preferred patterns of energy routing and logistics-task allocation. It arises from differences among ports in resource availability, network capacity, carbon budgets, low-carbon attributes, and service demand.⁹ Symbiosis therefore does not require external energy input and net carbon responsibility to decrease simultaneously at every port or under every operating condition.

Energy-oriented coordination:

$$\text{mine}(\mathbf{x})$$

$$\text{s.t. } \mathbf{x} \in \Omega_s, \mathbf{z} = \mathbf{z}^0$$

Inter-port energy flexibility is coordinated, while carbon-related resources remain locally fixed.

Carbon-oriented coordination:

$$\min c(\mathbf{x}, \mathbf{z})$$

$$\text{s.t. } (\mathbf{x}, \mathbf{z}) \in \Omega_s, P_{ij} = 0$$

Carbon-related resources are coordinated, while physical inter-port energy exchange is unavailable.

Energy-carbon symbiotic coordination:

$$\min c(\mathbf{x}, \mathbf{z})$$

$$\text{s.t. } (\mathbf{x}, \mathbf{z}) \in \Omega_s$$

Physical energy flexibility and carbon-related resources are jointly coordinated across ports.

Where $\mathbf{x}$ represents energy and logistics decisions; $\mathbf{z}$ represents transferable carbon-related resources, including carbon allowances, certified carbon sinks, and recognized low-carbon attributes; P_{ij} denotes inter-port energy exchange between ports i and j ; and the vector $\mathbf{z}^0$ represents the initial local allocation of carbon-related resources.

For fair comparison, all three coordination modes must deliver the same transport service and satisfy identical network security, service continuity, and resilience requirements, represented by the common feasible set Ω_s for operating scenario s . Their outcomes are evaluated by (1).

$$e = \frac{E_{\text{ext}}}{W_s}, \quad c = \frac{C_{\text{net}}}{W_s} \quad (1)$$

where W_s is the delivered transport service, E_{ext} is the external energy input, and C_{net} is the net carbon responsibility under a common accounting boundary.

Let $\mathbf{y}_E$ and $\mathbf{y}_C$ denote the normalized energy-carbon outcomes of the first two coordination modes, and let $\mathbf{p}_{\text{EC}}$ denote the non-dominated frontier under energy-carbon symbiotic coordination. The symbiosis degree is defined as (2).

$$S_{\text{EC}} = HV(\mathbf{p}_{\text{EC}}; \mathbf{r}) - HV(\text{ND}\{\mathbf{y}_E, \mathbf{y}_C\}; \mathbf{r}) \quad (2)$$

where ND denotes the non-dominated envelope. Both objectives are normalized to [0,1] using common admissible bounds over Ω_s , with $\mathbf{r}=(1,1)$ as the worst-admissible reference point. If $\mathbf{y}_E$ and $\mathbf{y}_C$ are mutually non-dominated, both are retained by ND; otherwise only the dominant one is retained. Since the first two modes are restricted cases of symbiotic coordination, $0 \leq S_{\text{EC}} \leq 1$; $S_{\text{EC}}=0$ indicates no additional attainable region, whereas a negative numerical value indicates approximation inconsistency.

Notably, S_{EC} is not itself a measure of causal coupling. Energy-carbon symbiosis is identified from the bidirectional non-separability of the coordination problem: (i) physical energy and logistics decisions $\mathbf{x}$ must affect the resulting carbon responsibility or low-carbon attributes through $c(\mathbf{x}, \mathbf{z})$; and (ii) changes in carbon-related resources, budgets, or governance conditions must alter the admissible or preferred energy-routing decisions. Only after both directional dependencies are present is S_{EC} used to quantify the additional attainable performance region enabled by jointly exploiting this coupling. If the energy and carbon decisions are separable and can be optimized independently, a Pareto-frontier expansion alone is interpreted as parallel multi-objective optimization rather than energy-carbon symbiosis.

PATHWAYS TOWARD GREEN INLAND ENERGY CORRIDORS

The transition from electrified ports to a DC-enabled green inland energy corridor requires coordinated progress in infrastructure, operation, governance, and digitalization. Infrastructure development should prioritize modular hybrid AC/DC port systems, interoperable shore and port interfaces, sectionalized protection, and scalable converter-based links, thereby avoid-

ing the wholesale replacement of existing AC systems. Operationally, corridor control must coordinate ship arrivals, berth allocation, charging, storage, clean-fuel production, and inter-port exchange under network security and resilience constraints. Digital twins should further couple traffic information with energy network states and carbon accounting to support prediction, dispatch, and disturbance management.

Implementation also depends on institutional coordination. Inter-port coordination requires settlement mechanisms for shared energy flexibility and carbon-related resources, together with consistent accounting boundaries that prevent double counting. Common data standards, cybersecurity responsibilities, and market access rules are equally necessary because ports, utilities, shipping companies, and local governments operate under different regulatory mandates.

Conclusion

DC distribution networks can reshape inland waterways by turning individually electrified ports into controllable energy nodes and enabling corridor-level energy-carbon symbiosis. Practical deployment, however, faces three immediate bottlenecks: the high capital cost of retrofitting existing AC port distribution networks, insufficient DC protection and multi-energy safety control methods for converter-dominated systems, and fragmented regulation across electricity, transport, clean-fuel, and carbon markets. This study is limited to a conceptual framework and does not quantify investment thresholds, protection performance, or corridor benefits for a specific waterway. Follow-up research should therefore develop staged retrofit strategies, validated models for staged evolution from hybrid AC/DC port systems toward DC-enabled corridor networks, interoperable control and protection standards, and pilot-scale demonstrations comparing isolated operation, energy-oriented coordination, carbon-oriented coordination, and energy-carbon symbiotic coordination. These steps are essential for translating the proposed concept into technically secure and institutionally implementable corridor projects.

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DECLARATION OF INTERESTS

The authors declare no competing interests.