

Article

Logistics–Energy Coordinated Scheduling in Hybrid AC/DC Ship–Shore Interconnection Architecture with Enabling Peak-Shaving of Quay Crane Clusters

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Abstract

With the gradual rise of battery-powered ships, the high-power charging demand during berthing is poised to exacerbate the peak-to-valley difference in the port grid, possibly leading to grid congestion and logistical disruption. To address this challenge, this paper proposes a bi-level coordinated scheduling scheme across both logistical operations and energy flow dispatch. Initially, by developing a refined model for the dynamic power characteristics of quay crane (QC) clusters, the surplus power capacity that can be stably released through an orderly QC operational delay is quantified. Subsequently, a hybrid AC/DC ship–shore interconnection architecture based on a smart interlinking unit (SIU) is proposed to utilize the QC peak-shaving capacity and satisfy the increasing shore power demand. In light of these, at the logistics level a coordinated scheduling of berths, QCs, and ships charging is performed with the objective of minimizing port berthing operational costs. At the energy flow level, the coordinated delay in QC clusters' operations and SIU-enabled power dispatching are implemented for charging power support. The case studies demonstrate that, compared with the conventional independent operational mode, the proposed coordinated scheduling scheme enhances the shore power supply capability by utilizing the QC peak-shaving capability effectively. Moreover, as well as satisfying the charging demands of electric ships, the proposed scheme significantly reduces the turnaround time of ships and achieves a 39.29% reduction in port berthing operational costs.



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1. Introduction

As the global energy transition to a low-carbon future and the maritime industry accelerates its decarbonization [1], green shipping solutions like battery-powered ships are advancing at an unprecedented pace [2–5]. According to the White Paper on the Development of China's Electric Ship Industry (2024) [6], electric ship (ES) fleet exceeded 700 by

the end of 2023 in China, with over 200 supplemented that year. Projections by EVTank estimate this fleet will grow to 1520 ships by 2025 and over 10,000 by 2030. However, the rise of electric ships (ESs), especially container ships [7,8], presents a significant challenge to port operations due to their intense, instantaneous power requirements. Existing inland waterway shore power systems, typically rated between 30 kW and 200 kW [9–11], were designed for the auxiliary power needs of smaller ships and are inadequate for the commercial demands of larger, long-range ESs. For example, the first 120 TEU electric inland container ship in China, the 'Jiang Yuan Bai He' [12], requires over ten hours to fully charge its 4620 kWh battery. Furthermore, the tendency of these ships to charge immediately upon berthing creates a synchronous demand that overlaps with the port's peak operational loads [13]. When a higher penetration rate of ESs occurs, this load stacking can lead to adverse impacts on the port's distribution network [14], such as grid congestion, poor power quality, and increased line losses, potentially compromising the stability and safety of port operations. In addition, a charging power cap may prolong the berth occupation of ESs and reduce berth turnover. The resulting queueing delays extend the in port time of the mixed fleet and increase the operating hours of auxiliary generators. This creates additional indirect emissions and challenges the IMO 2050 net-zero target.

To address these challenges, the academia and industry are exploring solutions from multiple dimensions. The conventional approach relies on physical infrastructure upgrades [15], primarily focuses on directly augmenting power supply capacity of infrastructure. Specific measures include upgrading substations, laying higher-capacity cables, and integrating distributed renewable energy sources, such as photovoltaics and wind power [16,17], within the port area. Furthermore, the deployment of large-scale intra-port battery energy storage systems (BESS) is also considered an effective solution [18,19]. Although these solutions are technically feasible, they typically require substantial upfront capital investment and entail long construction periods. The potential flexibility resources on the port side have not been effectively utilized. More importantly, in busy ports where land resources are extremely constrained, implementing large-scale infrastructure modifications often faces spatial limitations and practical difficulties. On the other hand, an alternative approach, viz., operational strategies optimization, concentrating on logistics dispatching. This involves designing price-based incentive mechanisms to influence the charging behavior of ships or adopting advanced schemes to schedule the allocation of berths and quay cranes (QCs) [20–22]. However, such methods typically prioritize the enhancement of logistics efficiency, often overlooking the feasibility of the corresponding energy dispatch.

Conventional approaches, whether focusing on physical infrastructure upgrades or operational strategies, typically optimize the port's energy and logistics systems in isolation and are thus poorly equipped to handle the challenges of increasing ES penetration. A synergistic relationship exists wherein rational logistics scheduling can promote the optimized operation of the port energy system, while an efficient energy system, in turn, can accelerate logistics turnover and enhance operational efficiency. Recognizing this synergy, scholars have conducted extensive research in this area. The study [23] proposed an energy scheduling method based on a Vehicle-to-Vehicle (V2V) trading mechanism, which encourages ships to share surplus energy and reduces the strain on the shore power supply. The study [24] introduces a scheduling model that leverages the flexibility of multiple energy sources to reshape the port's total demand curve. This is achieved by optimizing ship berthing sequences based on integrated energy models of berths, refrigerated container areas, and shore power. The study [25] employs a two-stage strategy to coordinate logistics optimization and energy allocation. Within this framework, a Stackelberg game is established to model the interaction between the port authority (leader)

and shipowners (followers). This game-theoretic approach determines the optimal energy dispatch plan for the port and the corresponding electricity consumption strategy for ships, ultimately mitigating pressure on the energy supply. The study [26] introduces a unified energy management model that coordinates various electrical loads within a port, including shore power, refrigerated containers, and plug-in ESs. The model is designed for multi-objective optimization, simultaneously aiming to limit emissions, minimize operational costs, and provide grid support. This approach enables the effective regulation of the port's overall electricity demand. The study [27] proposed a two-stage coordinated strategy: the first stage determines berth allocation based on cargo volume, energy needs, and equipment availability, while the second stage establishes the optimal day-ahead schedule for container handling and microgrid asset operations, incorporating forecasts for renewable energy and port loads to enhance the port's energy independence and reliability.

Despite the significant progress made in the coordinated optimization of port logistics and energy flows, a research gap remains. Existing research predominantly addresses the problem from a high-level scheduling perspective, such as berth or QC allocation [21,22,28]. While energy demand is effectively integrated into logistics planning within existing approaches, the underlying power grid topology is often oversimplified. Consequently, critical intra-port physical constraints, such as transformer overloads and feeder congestion, are frequently overlooked. These constraints are significantly exacerbated by the large-scale, shore-based charging of ESs. The potential for such localized congestion to jeopardize the secure and stable operation of the entire port system represents a critical detail that is often not captured in existing optimization models.

As the core operational units of a container port [29], QC clusters represent a significant electrical load, and their aggregated power profile contains largely underutilized, energy flexibility. Through the coordinated scheduling of the QC cluster's operational processes, their aggregated peak power consumption can be effectively flattened—a practice known as peak-shaving—without compromising overall operational efficiency. The study [30] highlights that ports may be equipped with energy storage systems to recover the gravitational potential energy during a crane's descent and release the stored energy during its ascent, thereby improving energy efficiency and reducing consumption. Furthermore, the work [31] demonstrates that by setting delay times between the operations of individual QCs, their collective peak power demand can be reduced, leading to lower energy costs via operational scheduling. Distinct from hardware-based short-duration power smoothing (e.g., via energy storage), this study targets logistics-based day-ahead peak-shaving. The rationale for targeting QC clusters is their high physical and energetic coupling with shore power at the wharf frontier; being co-located at the same berth, they allow the port to utilize deterministic handling schedules to release capacity without additional hardware.

Building on this concept, the aforementioned studies overlook a critical consequence: after peak-shaving, a stable and significant power capacity is released from the grid infrastructure originally provisioned for the QCs. Shore-based charging for ESs is a potential application for this surplus capacity. Yet, its utilization is constrained by the rigid “dedicated-line, dedicated-supply” grid architecture [32]. This architecture physically isolates the feeder lines supplying the QCs from those intended for charging facilities. Consequently, the capacity released on the QC side cannot be effectively dispatched to the ship charging side.

This paper proposes a bi-level coordinated optimization scheduling scheme for ship–shore logistics and energy flow, based on leveraging the peak-shaving flexibility of QCs. The objective is to leverage the operational flexibility of the QC cluster as a quantifiable and dispatchable resource. Serving as the key retrofitting solution, the proposed hybrid AC/DC ship–shore interconnection architecture provides the physical pathway to utilize this “en-

ogenous” power capacity for the high-power charging of ESs. The core contributions of this study can be summarized as follows:

- (1) Quantification and utilization of QC flexibility: To accurately quantify the stable and reliable power capacity that can be released from the QC system, a refined physical model of the operational process for QC clusters is developed, and an orderly peak-shifting scheduling strategy is proposed.
- (2) A novel flexible interconnection architecture: A hybrid AC/DC ship–shore interconnection architecture based on a flexible interlinking device is proposed. This architecture is designed to dismantle the barriers of conventional power supply systems, establishing a physical pathway for the efficient transfer of power capacity released from the QC side to the charging facilities.
- (3) Coordinated optimization model for ship–shore logistics and energy flow: With the objective of minimizing port berthing operational costs, a bi-level coordinated optimization model for logistics and energy flow is established. The model integrates berth allocation, QC scheduling, and charging management, thereby achieving effective coordination between logistics dispatch and energy flow scheduling.

The remainder of this paper is organized as follows. Section 2 details the peak-shaving of QC clusters and the flexible interconnection architecture, including the refined modeling of the QC cluster, the quantification of its peak-shaving potential, and the proposed ship–shore flexible interconnection framework. Section 3 formulates the mathematical model for the coordinated optimization of ship–shore logistics and energy flow, and elaborates on the solution methodology. In Section 4, detailed case studies are presented to validate the effectiveness and economic viability of the proposed method. Finally, Section 5 concludes the paper and discusses future research directions.

2. QC Cluster Peak-Shaving and Interconnection Architecture

To achieve ship–shore coordination, it is necessary to investigate the dynamic power characteristics and peak-shaving potential of QC clusters. Concurrently, a novel ship–shore interconnection architecture based on flexible interconnection must be proposed, as this architecture provides the physical foundation for energy dispatch.

2.1. Power Characteristics and Peak-Shaving Potential of QC Cluster

Figure 1 illustrates the structure of a single QC and a diagram of its complete operational cycle. To accurately assess the power capacity that can be released from the transformer of the port’s QC cluster, it is necessary to precisely simulate the dynamic power characteristics of a QC during a typical operational cycle. This is accomplished by constructing a piecewise function model based on physical principles.

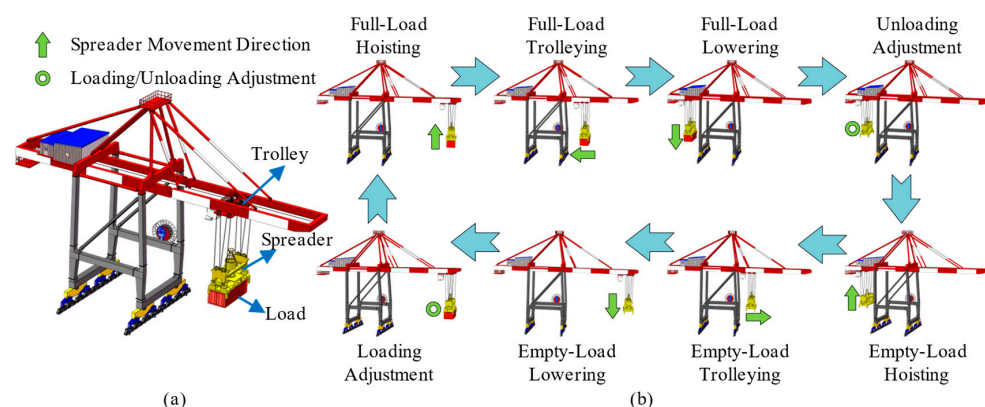


Figure 1. A single QC. (a) The structural diagram; (b) The schematic diagram of the operation cycle.

2.1.1. Dynamic Power Modeling of a Single QC

The complete operational cycle of a QC, T_{cycle} , is defined as a series of ordered physical processes: loaded hoisting, loaded trolleying, loaded lowering, unloading adjustment, empty hoisting, empty trolleying, empty lowering, and loading adjustment. Among these, the unloading/loading adjustment periods are taken as fixed durations, while the other six motion processes each consist of three sub-stages: acceleration, constant velocity, and deceleration.

The total instantaneous power of the QC at any time t , $P_{\text{crane}}(t)$, is the sum of the power of the hoisting system, $P_{\text{hoist}}(t)$, and the power of the trolleying system, $P_{\text{trolley}}(t)$:

$$P_{\text{crane}}(t) = P_{\text{hoist}}(t) + P_{\text{trolley}}(t) \quad (1)$$

The power of the hoisting system primarily serves to overcome changes in gravitational potential energy and to drive changes in vertical kinetic energy. Its instantaneous power, $P_{\text{hoist}}(t)$, is composed of two components: the potential power, $P_{\text{pot,h}}(t)$, and the kinetic power, $P_{\text{kin,h}}(t)$:

$$P_{\text{hoist}}(t) = P_{\text{pot,h}}(t) + P_{\text{kin,h}}(t) \quad (2)$$

where the potential power, $P_{\text{pot,h}}(t)$, is calculated as follows:

$$P_{\text{pot,h}}(t) = \frac{M_h(t) \cdot g \cdot v_h(t)}{\eta_{\text{pot}}(v_h)} \quad (3)$$

where $M_h(t)$ is the system mass undergoing vertical motion (kg), which is the sum of the load mass (M_{load}) and the spreader mass (M_{spreader}) under the loaded condition, and only the spreader mass under the empty condition; g is the gravitational acceleration (m/s^2); and $v_h(t)$ is the instantaneous vertical velocity (m/s), with upward motion being positive and downward motion negative. The maximum velocities for loaded hoisting, loaded lowering, empty hoisting, and empty lowering are $v_{\text{full,up}}$, $v_{\text{full,down}}$, $v_{\text{empty,up}}$ and $v_{\text{empty,down}}$. $\eta_{\text{pot}}(v_h)$ is the efficiency of the transmission system related to potential energy, which depends on the direction of energy flow: during hoisting ($v_h > 0$), it is the motor driving efficiency, η_{motor} , and during lowering ($v_h < 0$), it is the energy regeneration efficiency, η_{regen} .

The kinetic power, $P_{\text{kin,h}}(t)$, is calculated as follows:

$$P_{\text{kin,h}}(t) = \frac{M_h(t) \cdot a_h(t) \cdot v_h(t)}{\eta_{\text{kin}}(v_h, a_h)} \quad (4)$$

where $a_h(t)$ is the instantaneous vertical acceleration (m/s^2), which takes the value a_{up} during hoisting and a_{down} during lowering. $\eta_{\text{kin}}(a_h, v_h)$ is the composite efficiency related to kinetic energy: when the motor performs positive work to increase the system's total energy, i.e., during acceleration ($a_h \cdot v_h > 0$), it is the motor driving efficiency, η_{motor} ; during deceleration ($a_h \cdot v_h < 0$), it is the energy regeneration efficiency, η_{regen} .

The power of the trolleying system is primarily used to overcome operational friction and to drive changes in horizontal kinetic energy. Its instantaneous power, $P_{\text{trolley}}(t)$, consists of two parts: the friction power, $P_{\text{fric,t}}(t)$, and the kinetic power, $P_{\text{kin,t}}(t)$:

$$P_{\text{trolley}}(t) = P_{\text{fric,t}}(t) + P_{\text{kin,t}}(t) \quad (5)$$

where the friction power, $P_{\text{fric,t}}(t)$, is calculated as:

$$P_{\text{fric,t}}(t) = \frac{F_{\text{fric}} \cdot |v_t(t)|}{\eta_{\text{motor}}} \quad (6)$$

where F_{fric} is the equivalent frictional force of the system (N). Its value, which depends on the roughness of the trolley rail, can be calculated from the power consumed during constant velocity motion. $v_t(t)$ is the instantaneous horizontal velocity of the trolley (m/s), with a maximum value of v_{trolley} . As overcoming friction is always an energy-consuming process during trolleying, the efficiency term is consistently η_{motor} .

The kinetic power is calculated as:

$$P_{\text{kin},t}(t) = \frac{M_t(t) \cdot a_t(t) \cdot v_t(t)}{\eta_{\text{kin}}(v_t, a_t)} \quad (7)$$

where $M_t(t)$ is the total system mass undergoing horizontal motion. Under the loaded condition, it is the sum of the trolley mass (M_{trolley}), the spreader mass and the load mass; under the empty condition, it is the sum of the trolley and spreader masses. $a_t(t)$ is the instantaneous horizontal acceleration, taking the value a_{trolley} during the acceleration phase. $\eta_{\text{kin}}(v_t, a_t)$ is a composite efficiency coefficient. During acceleration ($a_t \cdot v_t > 0$), its value is η_{motor} . During decelerative braking ($a_t \cdot v_t < 0$), most of the trolley's kinetic energy is dissipated as heat, while a portion is converted back into electrical energy and fed back to the grid. Therefore, in this case, $\eta_{\text{kin}}(v_t, a_t)$ is given by $(\eta_{\text{regen}} \cdot \beta)$, where β is the feedback ratio, representing the proportion of the released kinetic energy that is permitted to be regenerated.

2.1.2. Aggregated Power Model of the QC Cluster

Assume that the N QCs in the port are of the same model, possessing identical power-time characteristics, and that all follow the standard operational cycle model for a single crane, $P_{\text{crane}}(t)$. In a typical operational state of the port, the start-up times of individual QCs are stochastic and mutually independent. A start-up delay time sequence, Δt_{vector} , is defined as an N -element vector:

$$\Delta t_{\text{vector}} = [\Delta t_1, \Delta t_2, \dots, \Delta t_N] \quad (8)$$

where Δt_i represents the start-up delay time of the i -th QC relative to the zero-time point ($t = 0$). This delay time sequence can be generated using random numbers or set according to actual data, thereby simulating various complex operational scenarios.

Therefore, the instantaneous power of the i -th QC at time t , $P_i(t)$, is the result of shifting the standard single quay crane power curve, $P_{\text{crane}}(t)$, to the right by its corresponding start-up delay, Δt_i . Its mathematical expression is:

$$P_i(t) = P_{\text{crane}}(t - \Delta t_i) \cdot H(t - \Delta t_i) \quad (9)$$

where Δt_i is the specific start-up delay time for the i -th QC, and $H(\cdot)$ is the Heaviside step function, defined as:

$$H(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (10)$$

This function ensures that the power of the i -th QC is zero before its respective start-up time Δt_i (i.e., for $t < \Delta t_i$).

Consequently, the total power of the N QCs at time t , $P_{\text{total},N}(t)$, is the linear superposition of the instantaneous powers of all N cranes, expressed as follows:

$$P_{\text{total},N}(t) = \sum_{i=1}^N P_i(t) \quad (11)$$

By substituting the expression for $P_i(t)$, the final model for the aggregated power of N cranes, each starting with a specific delay, is obtained as:

$$P_{\text{total},N}(t) = \sum_{i=1}^N P_{\text{crane}}(t - \Delta t_i) \cdot H(t - \Delta t_i) \quad (12)$$

2.1.3. Modeling of Available Capacity from QC Cluster Peak-Shaving

When configuring the power supply transformer for a QC cluster, the determination of its rated capacity is a comprehensive process involving multiple factors, rather than a simple summation of the peak power of individual cranes. According to relevant industry design specifications [33,34], the load calculation for a QC cluster must account for the cluster's simultaneity factor, the demand factor of a single unit, and the power factor. This design principle provides the theoretical foundation for releasing the latent capacity of the transformer through the optimization of operational strategies.

Under the typical random operational mode, the required apparent power for the QC cluster, $S_{T,\text{uncoordinated}}$, can be estimated by the following equation:

$$S_{T,\text{uncoordinated}} = \frac{N \cdot P_{\text{qc,peak}} \cdot k_{\text{sim}} \cdot k_{\text{demand}}}{\cos \varphi \cdot k_{\text{load}}} \quad (13)$$

where N is the total number of QCs; $S_{\text{qc,peak}}$ is the peak active power of a single QC; k_{sim} is the simultaneity factor, reflecting the probability of multiple cranes operating at their peak power simultaneously; k_{demand} is the demand factor of a single crane; $\cos \varphi$ is the power factor; and k_{load} is the transformer design load factor, which represents the ratio between the QC cluster load and the transformer capacity. Furthermore, ports typically select a standard capacity rating, $S_{T,\text{rated}}$, which is greater than $S_{T,\text{uncoordinated}}$, as the final configuration [35].

In actual port operations, the QCs in a cluster do not start their cycles in perfect synchrony, but rather with inherent, random delays. When the orderly peak-shifting scheduling strategy is employed, the aggregated peak active power of the QC cluster, $P_{\text{agg,peak}}$, is significantly reduced. Consequently, the apparent power required to sustain the QC cluster's operation, $S_{T,\text{coordinated}}$, becomes:

$$S_{T,\text{coordinated}} = \frac{P_{\text{agg,peak}}}{\cos \varphi \cdot k_{\text{load}}} \quad (14)$$

Since the orderly peak-shifting schedule significantly reduces the aggregated peak power ($P_{\text{agg,peak}} < N \cdot P_{\text{qc,peak}} \cdot k_{\text{sim}} \cdot k_{\text{demand}}$), within a transformer system already configured with a rated capacity of $S_{T,\text{rated}}$, the apparent power capacity, S_{disp} , that can be stably released and flexibly dispatched to other loads (such as electric ship charging) can be quantified as:

$$S_{\text{disp}} = S_{T,\text{rated}} - S_{T,\text{coordinated}} \quad (15)$$

This released apparent power, S_{disp} , constitutes the core "dispatchable energy resource" within the ship–shore coordination framework proposed in this paper. Its corresponding dispatchable active power, S_{disp} , is $S_{\text{disp}} \cdot \cos \varphi_{\text{load}}$, where $\cos \varphi_{\text{load}}$ is the power factor of the load receiving this power. The essence of the proposed strategy is to transform the random QC load into a deterministic and controllable curve, thereby accurately quantifying the transformer's surplus power.

Under low utilization scenarios, although the "peak-shaving" effect is less pronounced, the transformer naturally retains a substantial capacity margin due to the low base load. Conversely, under high utilization scenarios, where grid congestion typically occurs, the

orderly peak-shaving strategy becomes critical. It effectively suppresses the aggregate peak to releasing available capacity. Thus, the system ensures a reliable power supply across varying operational intensities.

2.2. Hybrid AC/DC Ship–Shore Interconnection Architecture

To ensure that the released capacity from QC peak-shaving can be accurately and efficiently delivered to high-power ship charging loads, the proposed hybrid AC/DC ship–shore interconnection architecture is introduced to enable power sharing across previously isolated feeder lines.

2.2.1. Conventional Ship–Shore Grid Topology

In port power supply systems, a zoned, radial topology is typically adopted to ensure the operational independence and reliability of different functional areas [32,36,37]. As illustrated in Figure 2a, a conventional configuration includes two or more independent transformers that supply specific load groups within the port via dedicated feeders. In this architecture, transformer T1 is dedicated to the QC cluster, while transformer T2 supplies the shore power (ship charging) facilities. Under normal operating conditions, these two supply circuits are completely decoupled at the load side, creating a physical isolation.

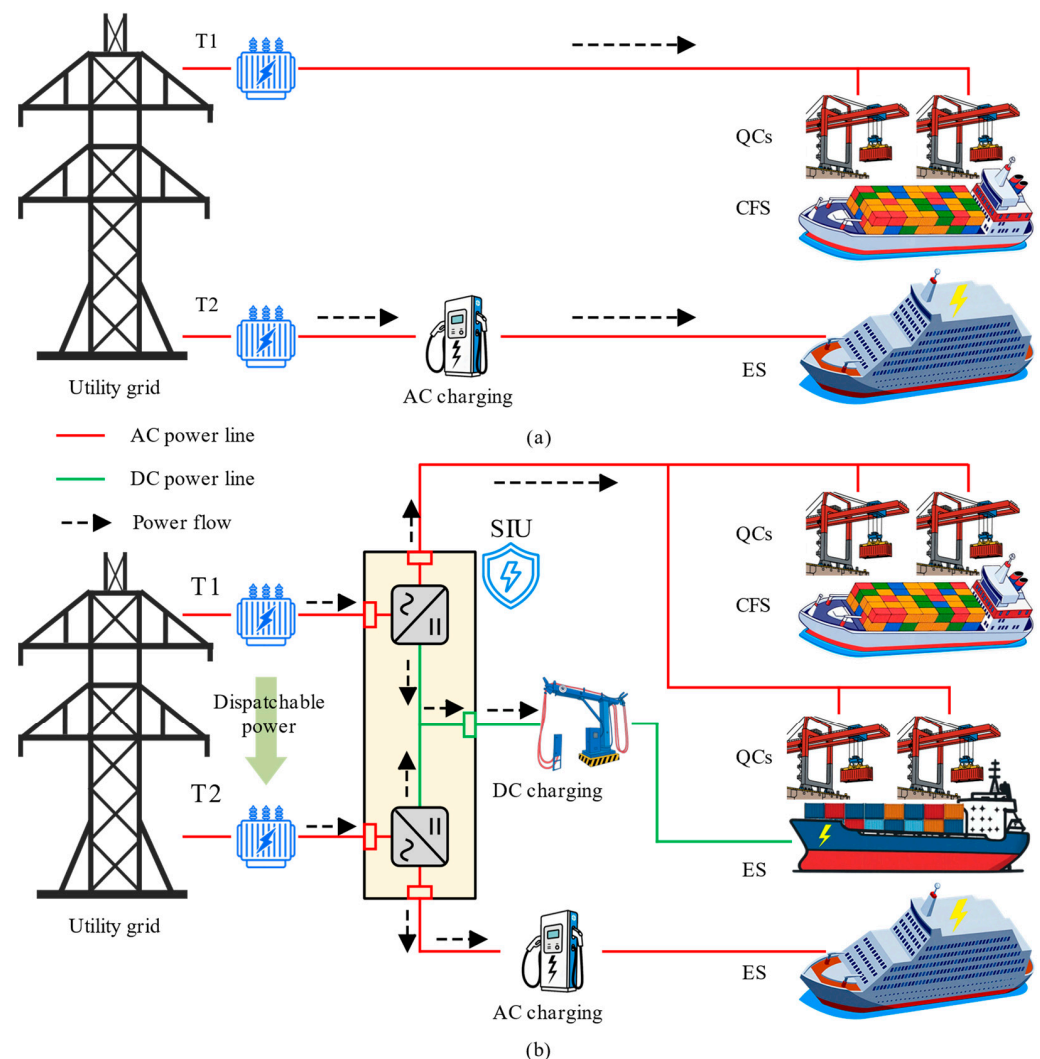


Figure 2. Ship–shore interconnection architectures. (a) Conventional ship–shore interconnection topology; (b) Proposed hybrid AC/DC ship–shore interconnection architecture.

Although this “dedicated-line, dedicated-supply” model guarantees operational stability, its inherent rigidity exposes several significant drawbacks in the face of the growing demand for high-power charging from ESs:

- (1) The ‘Energy Silo’ Effect: The QC power supply and the shore power charging systems operate in isolation, lacking a mechanism for power coordination. This operational paradigm prevents the flexible transfer of energy between them. The QC-side transformer (T1) is typically configured with a substantial capacity margin to handle transient peak loads during operations. However, this underutilized capacity during the QC cluster’s off-peak periods cannot be dispatched to support the increasingly burdened shore power system. The two systems operate like isolated “energy silos,” leading to low utilization of the port’s overall energy assets and insufficient grid operational resilience.
- (2) Charging capacity limitation: In the traditional architecture, the port’s total charging power is capped by the rated capacity of the shore-side transformer T2 and the ampacity of its corresponding supply circuit. As the demand for large-scale shore-based energy consumption emerges, this limited capacity becomes a critical bottleneck. The direct consequence of this infrastructure limitation is an involuntary extension of charging times, which in turn increases the in-port turnaround time for ships, thereby reducing the port’s operational efficiency and berth utilization rate.
- (3) High upgrade cost and investment risk: To overcome the charging bottleneck, the conventional path-dependent solution is to physically expand the capacity of transformer T2, and potentially the main upstream transformer and associated cables. Upgrading transformers and long stretches of cable entails enormous costs. Furthermore, in busy ports with limited land resources and stringent requirements for continuous operation, large-scale construction and retrofitting are often infeasible and can disrupt normal port activities. More importantly, the increasing penetration of ESs is a gradual and uncertain dynamic process, which poses a severe strategic challenge to the traditional “one-off,” capital-intensive investment model. A large-scale, pre-emptive investment to meet long-term demand would result in new, high-capacity assets operating at low load factors or even remaining idle for an extended period during the demand ramp-up phase. This leads to low capital efficiency and constitutes a significant diseconomy.

In summary, the traditional, rigid power supply architecture lacks the flexibility to adapt to the new demands of port electrification. A new type of architecture is urgently needed—one that can break down systemic barriers and enable the flexible sharing of energy.

2.2.2. Hybrid AC/DC Ship–Shore Interconnection Topology

To overcome the limitations of the conventional topology, this paper proposes an SIU-based ship–shore interconnection architecture, as shown in Figure 2b. The core of this architecture is the use of a power-electronics-based SIU to flexibly couple the previously isolated QC power supply system and the shore power charging system, thereby enabling on-demand, bidirectional energy flow.

The design of this architecture is based on two key considerations: first, to satisfy the demand for DC charging for ESs, the proposed architecture could provide the corresponding DC charging interfaces; second, to enable flexible energy sharing, the SIU is introduced as the central hub [38,39].

The SIU typically consists of two back-to-back (B2B) voltage source converters (VSC-1 and VSC-2). As depicted in Figure 2b, VSC-1 and VSC-2 are connected to the secondary

AC sides of transformers T1 and T2. They work in concert to efficiently convert AC power to DC, maintaining a stable common DC bus voltage.

The key advantage of this architecture lies in its flexible operational modes. When the enhanced charging mode is activated, the port implements the orderly peak-shifting schedule for the QCs, which significantly reduces the load pressure on the QC-side transformer, T1. Subsequently, the port's energy management system (EMS) can issue dispatch commands to the SIU. Through its advanced control strategies, the SIU precisely regulates the active power drawn by VSC-1 from the T1 side, allowing it to exceed the QC's own consumption. This surplus power (i.e., the quantified dispatchable capacity, P_{disp}) is instantaneously transferred via the common DC bus to the VSC-2 side and ultimately supplied to the high-power charging load. Therefore, the total available charging power, $P_{\text{charge,total}}$, is dynamically boosted to the sum of the charging-side transformer's base capacity and the dispatched capacity from the QC side:

$$P_{\text{charge,total}} = P_{\text{T2,total}} + P_{\text{disp}} \quad (16)$$

In practical engineering, the dispatched power setpoint is constrained by converter ratings, transformer thermal limits, and protection coordination. Standard protections such as AC side overcurrent protection, DC bus overvoltage protection, and fast fault blocking can be implemented in the SIU. If an abnormal condition is detected, the SIU is blocked and the two feeders return to independent operation. This fail-safe behavior preserves the basic radial protection philosophy of the port grid.

Compared to the conventional architecture, the proposed flexible interconnection solution offers the following distinct advantages:

- (1) Enhanced energy efficiency and system resilience: By enabling power sharing across different feeders, the architecture mitigates the "energy silos" effect. It not only improves the utilization of existing transformer assets but also enhances the port grid's ability to handle load fluctuations, boosting overall operational resilience.
- (2) Dynamic expansion of charging capability: The key advantage of this scheme is its ability to dynamically increase the port's total available charging power through intelligent dispatch, without resorting to expensive physical upgrades. This provides the port with significant flexibility to manage sudden or concentrated high-power charging demands.
- (3) Reduced life-cycle cost and investment risk: By leveraging the latent capacity of existing assets, the proposed solution avoids the high upfront investment and long construction periods required for large-scale hardware upgrades, offering a more economical and sustainable technological pathway for expanding shore power infrastructure.

3. Bi-Level Coordinated Optimization Scheduling of Ship–Shore Logistics and Energy Flow Based on the SIU Interconnection Architecture

Building upon the proposed ship–shore flexible interconnection architecture, a bi-level coordinated optimization scheduling model for ship–shore logistics and energy flow is established. This model aims to achieve the optimal scheduling of berths and QCs at the logistics level, and the power coordination between the ship and shore sides at the energy flow level, with the objective of minimizing the total operational costs of the port. Concurrently, to enhance the solution efficiency, a customized genetic algorithm (GA) is designed to solve the proposed model.

3.1. Problem Description and Model Assumptions

Based on the problem description and assumptions outlined above, this section will establish a mathematical model for the bi-level coordinated optimization of ship–shore logistics and energy flow. Targeted at the day-ahead tactical planning level, the model aims to establish an optimal performance baseline for the SIU-based interconnection architecture. The model will encompass the objective function, which aims to minimize the total operational costs of the port, and the relevant constraints.

3.1.1. Problem Description

Unlike conventional fuel ships (CFSs), battery-powered ships must not only complete cargo handling operations during their port stay but also undertake the critical task of battery charging. This study focuses on addressing the integrated problem of berth and QC allocation and charging scheduling for a mixed fleet (comprising both ESs and CFSs).

The problem scenario is defined as follows: A fleet, consisting of multiple ESs and CFSs, has already arrived at the port's anchorage at the beginning of the planning horizon ($t = 0$), awaiting assignment to a set of discrete and homogeneous berths. Each berth is equipped with charging facilities. The core decision-making tasks for the port operator include determining, for each ship, its assigned berth, the specific berthing time, and the number of QCs allocated to it.

As illustrated in Figure 3, the ships' operational cycle in port is meticulously defined, comprising three core time phases:

- (1) **Waiting time:** This refers to the duration from a ship's arrival at the anchorage ($t = 0$) to its actual berthing time (S_i). During this period, CFSs and ESs consume diesel and electricity, respectively, to maintain basic ship operations. The electricity consumed by an ES must subsequently be replenished at the port. This waiting cost is borne by the port operator.
- (2) **Service time:** This is the duration from the berthing time (S_i) until the completion of all in-port operations and final departure (D_i). A key characteristic of this phase is the decoupling of charging and cargo handling operations. An ES can commence charging immediately upon berthing, while its cargo handling operation can only begin once the assigned QC resources become available. Consequently, its service time is determined by the maximum of the charging duration and the cargo handling duration. For a CFS, the service time is equivalent to its cargo handling duration.
- (3) **Delay time:** This is the period by which a ship's actual departure time (D_i) exceeds its expected departure time (e_i). This triggers a punitive delay cost, which is also borne by the port operator.

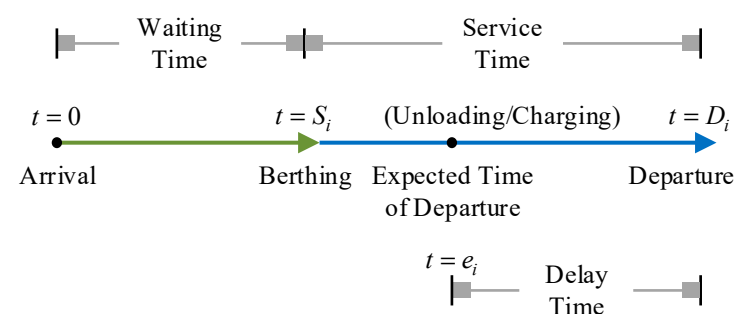


Figure 3. The operation cycle of the ship in port.

To mitigate the grid pressure imposed by the ES charging loads, the model introduces a critical strategic decision: the port can opt to activate an enhanced charging mode. If this mode is enabled, the port will implement a peak-shifting schedule for QC operations, re-

leasing a regulated amount of additional grid capacity (P_{disp}) and transferring it exclusively for ship charging via the flexible interconnection architecture. This strategy significantly boosts the total available power at the charging facilities, thereby shortening the charging time for ESs.

To clearly illustrate the computational workflow, Figure 4 visualizes the interaction between the energy and logistics systems. The process operates through a bidirectional coupling. From the energy perspective, the system transfers the surplus capacity from the QC transformer to the shore power side via the SIU. This creates a dynamic Power supply constraint, which serves as a real-time power upper limit. Subject to this limit, the logistics layer optimizes berth allocation and QC assignments. These decisions determine the specific charging needs, issuing an Operational mode command to request the required power. Based on this mechanism, Figure 4 illustrates the collaboration between ship–shore logistics and energy flow. The overall objective of this model is to minimize the total port operational cost (comprising waiting and delay costs) by conducting an integrated optimization of berth allocation, berthing times, QC assignments, and the decision to activate the enhanced charging mode, subject to all physical and operational constraints.

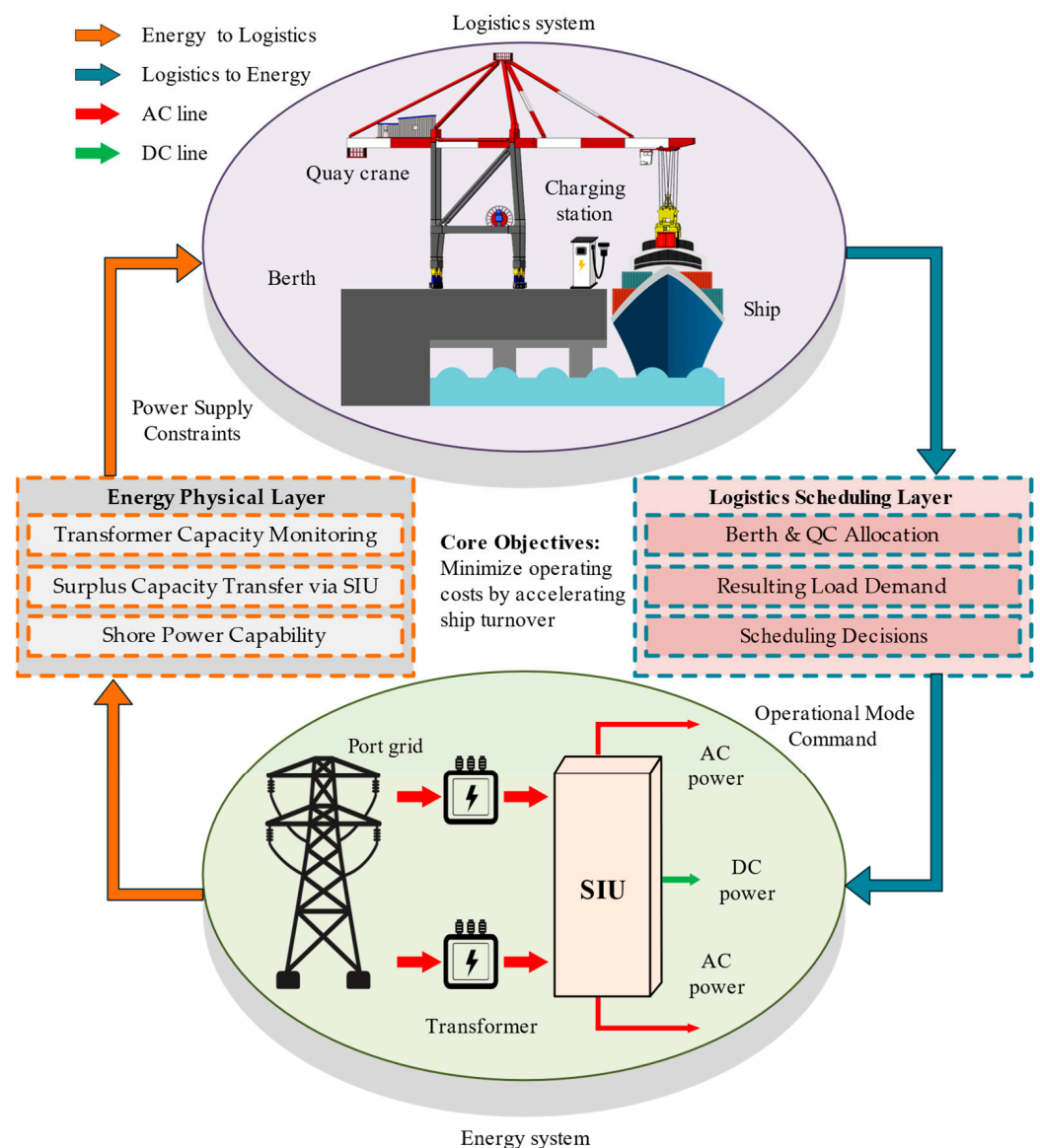


Figure 4. Schematic diagram of ship–shore logistics–energy flow cooperation.

3.1.2. Model Assumptions

To reduce the complexity of the model, the following assumptions are made:

- (1) Decision-making context: Adopting deterministic data and a static arrival scenario is a standard approach for baseline validation in port scheduling literature [21,40].
- (2) Static arrival: All ships are assumed to have arrived at the anchorage at the beginning of the planning horizon ($t = 0$), and all their relevant information is known in advance.
- (3) Homogeneous berths: All berths are homogeneous, possessing identical physical attributes. Each berth is equipped with charging facilities and can serve all types of ships.
- (4) Decoupled and non-preemptive operations: Charging for an ES can commence immediately upon berthing and can be performed flexibly throughout its entire stay ($[S_i, D_i]$). The cargo handling process for any ship is considered an independent and non-preemptive operation. It can start at any point after the ship has berthed ($S_i^H \geq S_i$), but once initiated, it must continue without interruption until completion.
- (5) Constant QC efficiency: Any potential decrease in QC operational efficiency due to the peak-shifting schedule is disregarded. This is because start-up delays are inherent even in the uncoordinated operational state of the QC cluster. The peak-shifting strategy only adjusts the relative start times among QCs within an operational cycle. The imposed delay is in seconds and is small compared with the cargo handling duration measured in hours.
- (6) Linear charging: The State of Charge (SOC) of an ES's battery is assumed to increase linearly during the charging process.
- (7) All parameters used for the day-ahead planning baseline, including ship workloads, initial SOC, port resources, and power limits, are treated as deterministic inputs. Their data sources and calibration logic are described in Section 4.
- (8) Negligible transfer times: The time required for QCs to move between different ships, as well as the navigation time of ships within the port channel, are considered negligible.
- (9) No breakdowns: All equipment, including berths, QCs, and charging facilities, is assumed to be fully available and free from any maintenance or breakdowns throughout the planning horizon.

These assumptions are formulated based on field surveys conducted at inland container port and ensure that the model reflects a realistic engineering baseline.

3.2. Mathematical Programming Model

3.2.1. Nomenclature

To clarify the mathematical programming model, the notations used in the proposed model are categorized below. Table 1 defines the relevant indices and sets, the model parameters are detailed in Table 2, and the decision variables are listed in Table 3.

Table 1. Indices and Sets.

Symbol	Description
i, j	Index of ships
V	Set of all ships to be served, $V = V_e \cup V_f$
V_e	Set of ESs
V_f	Set of CFSs
b	Index of berths
B	Set of all available berths
t	Index of discrete time periods
T	Set of all discrete time periods within the planning horizon
q	Number of QCs assigned to a single ship
Q_i	Set of possible numbers of QCs for ship i , $Q_i = \{q_i^{\min}, \dots, q_i^{\max}\}$

Table 2. Model Parameters.

Symbol	Description
e_i	Expected departure time of ship i
m_i	Workload of ship i (QC-hours)
$q_i^{\min}, q_i^{\max}$	Minimum/maximum number of QCs for ship i
K	Total number of available QCs in the port
E_i^{cap}	Battery capacity of ES i (kWh)
$\text{SOC}_i^{\text{initial}}$	Initial State of Charge (%) of ES i upon arrival
$\text{SOC}_i^{\text{target}}$	Target State of Charge (%) of ES i upon departure
P_i^w	Power consumption rate of ES i at anchorage (kW)
$P_{\text{pile}}^{\text{max}}$	Maximum output power of a single charging station (kW)
$P_{\text{tr}}^{\text{base}}$	Baseline power capacity of the transformer for charging (kW)
$P_{\text{disp}}^{\text{fixed}}$	Fixed additional power available in coordinated scheduling mode (kW)
C_i^w	Waiting cost per unit time for ship i (USD/h), potentially different for V_e and V_f
C_i^d	Delay cost per unit time for ship i (USD/h)
Δt	Duration of each discrete time period (e.g., 1 h)
M	A sufficiently large positive number for linearization

Table 3. Decision variable.

Symbol	Description	Type
x_{ib}	1 if ship i is assigned to berth b ; 0 otherwise	Binary
y_{ij}	1 if ships i and j are at the same berth and i precedes	Binary
z	1 if the port activates the enhanced charging mode; 0 otherwise	Binary
z_{iq}	1 if q QCs are assigned to ship i ; 0 otherwise	Binary
S_i	Berthing time (service start time) of ship i	Continuous
D_i	Departure time (service completion time) of ship i	Continuous
S_i^H	Start time of cargo handling for ship i	Continuous
D_i^H	End time of cargo handling for ship i	Continuous
H_i	Duration of cargo handling for ship i	Continuous
P_{it}^{chg}	Charging power allocated to ES i in time period t	Continuous
ϵ_i^d	Delay duration of ship i	Continuous
w_{it}	1 if ship i is at berth in time period t ($[S_i, D_i]$); 0 otherwise	Binary
w_{it}^H	1 if ship i is undergoing handling in time period t ($[S_i^H, D_i^H]$); 0 otherwise	Binary

3.2.2. Mathematical Model and Constraints

Objective function:

$$\min Z = \sum_{i \in V} (C_i^w \cdot S_i + C_i^d \cdot \epsilon_i^d) \quad (17)$$

Explanation: The objective function aims to minimize the total operational cost of the port berths. This cost is composed of two parts: the first part, $\sum C_i^w \cdot S_i$, is the total waiting cost incurred by all ships from their arrival at the anchorage to their berthing. The second part, $\sum C_i^d \cdot \epsilon_i^d$, represents the total delay cost resulting from the actual departure times of ships being later than their expected departure times.

Constraints:

(1) Berth assignment and sequencing constraints

$$\sum_{b \in B} x_{ib} = 1, \forall i \in V \quad (18)$$

$$S_j \geq D_i - M \cdot (1 - y_{ij}) - M \cdot \sum_{b \in B} (2 - x_{ib} - x_{jb}), \forall i, j \in V, i \neq j \quad (19)$$

$$y_{ij} + y_{ji} \leq 1, \forall i, j \in V, i \neq j \quad (20)$$

$$y_{ij} + y_{ji} \geq \sum_{b \in B} (x_{ib} + x_{jb} - 1), \forall i, j \in V, i \neq j \quad (21)$$

Explanation: Constraint (18) ensures that each ship must be assigned to exactly one berth. Constraint (19) is the core non-overlapping constraint for ships at the same berth. It ensures that if ships i precedes ship j at the same berth ($y_{ij} = 1$), the berthing of ship j (S_j) cannot begin before the departure of i (D_i). Constraints (20) and (21) jointly ensure that for any two ships served at the same berth, a unique service sequence must be established.

(2) Decoupled operations and completion time constraints

$$\sum_{q \in Q_i} z_{iq} = 1, \forall i \in V \quad (22)$$

$$H_i = \sum_{q \in Q_i} z_{iq} \cdot \frac{m_i}{q}, \forall i \in V \quad (23)$$

$$S_i^H \geq S_i, \forall i \in V \quad (24)$$

$$D_i^H = S_i^H + H_i, \forall i \in V \quad (25)$$

$$D_i \geq D_i^H, \forall i \in V \quad (26)$$

Explanation: Constraint (22) ensures that a specific number of QCs is selected for each ship. Based on this selection, Constraint (23) calculates the non-preemptive cargo handling duration, H_i . Constraint (24) enforces the operational decoupling by allowing the cargo handling start time S_i^H to be independent of the ship's berthing time (S_i). This creates a flexible time window, enabling an ES to implement strategies such as 'charge first, handle cargo later' or 'charge while waiting for QCs.' Constraint (25) defines the completion time of cargo handling. Constraint (26) ensures that the ship's final departure time, D_i , must be after the cargo handling is completed.

(3) QC capacity constraint

$$\sum_{i \in V} \sum_{q \in Q_i} (q \cdot z_{iq} \cdot w_{it}^H) \leq K, \forall t \in T \quad (27)$$

Explanation: This constraint ensures that at any discrete time point t , the total number of QCs in use does not exceed the total number available at the port, K . The count of occupied QCs is based on the handling indicator variable w_{it}^H . Specifically, the q QCs assigned to ship i are only counted as occupied if the ship is actually undergoing cargo handling at time t . This accurately reflects scenarios where a ship may be berthed and charging ($w_{it} = 1$) but not undergoing cargo handling ($w_{it}^H = 0$), thus not occupying any QC resources.

(4) ES charging and power system constraints

$$\sum_{t \in T} P_{it}^{chg} \cdot \Delta t \geq E_i^{cap} \cdot (SOC_i^{target} - SOC_i^{initial}) + P_i^w \cdot S_i, \forall i \in V_e \quad (28)$$

$$0 \leq P_{it}^{chg} \leq P_{pile}^{max} \cdot w_{it}, \forall i \in V_e, \forall t \in T \quad (29)$$

$$D_i \cdot \Delta t \geq \frac{E_i^{cap} \cdot (SOC_i^{target} - SOC_i^{initial}) + P_i^{pw} \cdot S_i}{P_{pile}^{max}} + S_i \cdot \Delta t, \forall i \in V_e \quad (30)$$

$$\sum_{i \in V_e} P_{it}^{chg} \leq P_{tr}^{base} + z \cdot P_{disp}^{fixed}, \forall t \in T \quad (31)$$

Explanation:

Constraint (28) is the energy balance constraint. It ensures that the total energy charged to each ES during its port stay is sufficient to cover two demands: first, the energy required to bring its battery from the initial state upon arrival to the target state; and second, the total energy consumed during its waiting time at the anchorage (duration S_i).

Constraint (29) stipulates that charging ($P_{it}^{chg} > 0$) can only occur when ship i is berthed ($w_{it} = 1$), and the charging power cannot exceed the maximum power of a single charging station.

Constraint (30) links the charging demand to the ship's length of stay. It ensures that the total berthing time ($D_i - S_i$) is long enough to meet its total charging demand. If the cargo handling time is short but the charging demand is high, this constraint will force the model to extend the departure time D_i to ensure charging completion. This effectively ensures that the service time is the maximum of the charging and handling durations.

Constraint (31) is the total port charging power constraint. At any time t , the sum of power drawn by all ESs being charged cannot exceed the supply capacity of the transformer. This capacity is determined by the baseline capacity plus any additional power from the coordinated scheduling mode, controlled by the strategic decision variable z .

(5) Logical and cost calculation constraints

$$S_i \leq t \cdot \Delta t + M \cdot (1 - w_{it}), \forall i \in V, \forall t \in T \quad (32)$$

$$D_i \geq (t + 1) \cdot \Delta t - M \cdot (1 - w_{it}), \forall i \in V, \forall t \in T \quad (33)$$

$$S_i^H \leq t \cdot \Delta t + M \cdot (1 - w_{it}^H), \forall i \in V, \forall t \in T \quad (34)$$

$$D_i^H \geq (t + 1) \cdot \Delta t - M \cdot (1 - w_{it}^H), \forall i \in V, \forall t \in T \quad (35)$$

$$\epsilon_i^d \geq D_i - e_i, \forall i \in V \quad (36)$$

Explanation: Constraints (32)–(35), using the Big-M method, precisely link the continuous time variables (S_i, D_i, S_i^H, D_i^H) with the discrete time-period indicator variables (w_{it}, w_{it}^H), defining the exact periods for berthing and cargo handling. Constraint (36), together with the non-negativity constraint for the variable, is used to calculate the delay duration for each ship as $\epsilon_i^d = \max(0, D_i - e_i)$.

(6) Variable domain constraints

$$x_{ib}, y_{ij}, z, z_{iq}, w_{it}, w_{it}^H \in \{0, 1\}, \forall i, j, b, q, t \quad (37)$$

$$S_i, D_i, H_i, S_i^H, D_i^H, \epsilon_i^d, P_{it}^{chg} \geq 0, \forall i, t \quad (38)$$

(7) Model linearization

The Constraint (27) contains a product term of binary variables, $z_{iq} \cdot w_{it}^H$, which makes the model non-linear. To transform it into a standard mixed-integer linear programming (MILP) model, an auxiliary binary variable u_{iqt} is introduced, defined as $u_{iqt} = z_{iq} \cdot w_{it}^H$.

Replace the original constraint (27):

$$\sum_{i \in V} \sum_{q \in Q_i} (q \cdot u_{iqt}) \leq K, \forall t \in T \quad (39)$$

Add linearization constraints:

$$u_{iqt} \leq z_{iq}, \forall i \in V, q \in Q_i, t \in T \quad (40)$$

$$u_{iqt} \leq w_{it}^H, \forall i \in V, q \in Q_i, t \in T \quad (41)$$

$$u_{iqt} \geq z_{iq} + w_{it}^H - 1, \forall i \in V, q \in Q_i, t \in T \quad (42)$$

$$u_{iqt} \in \{0, 1\}, \forall i, q, t \quad (43)$$

Explanation: Through this transformation, the original non-linear model is equivalently converted into a standard MILP model, which can theoretically be solved using commercial or open-source solvers. However, the combinatorial complexity of the problem makes seeking an efficient metaheuristic algorithm a more practical choice for real-world-sized instances.

3.2.3. Genetic Algorithm-Based Solution Framework

Considering the complexity and NP-hard nature of the problem, this study designs a customized GA to solve the problem. The GA simulates the mechanisms of natural selection and genetics to search for high-quality feasible solutions within a complex solution space.

Chromosome representation: A solution (chromosome) is composed of two parts:

- (1) Service sequence (p): A permutation of all ship indices, which defines the priority order in which ships are considered by the scheduling system.
- (2) QC allocation (q): An integer vector where the i -th element represents the number of QCs assigned to ship i .

Notably, the strategic decision variable z is not included in the chromosome. Instead, a scenario-based approach is adopted: the GA is run independently under the settings of $z = 0$ (traditional scheduling mode) and $z = 1$ (coordinated scheduling mode), and the optimal total costs from the two scenarios are then compared.

Fitness evaluation: This is the core of the GA. For a given chromosome, its fitness (i.e., the total cost) is calculated via a two-stage decoding procedure:

- (1) Physical scheduling phase: The algorithm applies a greedy strategy to arrange berths and times for each ship according to the service sequence p and QC allocation q in the chromosome. Specifically, the algorithm processes ships in the order defined by p , searching for the earliest available time window for each ship that satisfies both berth and QC resource constraints. In this phase, a ship's service time is provisionally estimated as the maximum of its cargo handling time and its ideal charging time.
- (2) Power check and penalty phase: After a complete physical schedule is generated, the algorithm proceeds to the power dispatch check. It simulates the charging process for all ESs under this schedule and calculates the total power demand for each hour. If the total power demand exceeds the grid capacity at any point, or if an ES fails to complete its charging task before departure, a large penalty term is added to its fitness value. This penalty mechanism guides the GA to discard power-infeasible solutions

To ensure the structural realism of the simulation, the input dataset is constructed by integrating four distinct categories of data sources: (a) field surveys (b) engineering standards, technical manuals and authoritative report (c) academic literature and pilot project reports (d) scenario-based generation via sampling. Although the input data originates from multiple sources, representativeness is ensured by the hierarchical alignment of these parameters.

The physical layer (grid and equipment) adheres to strict engineering standards and field specifications, guaranteeing that the simulated system constraints are physically realistic. The operational layer (logistics and energy) reflects typical patterns observed in established pilot projects and literature, ensuring the scenario is consistent with mainstream inland shipping characteristics. Furthermore, the scenario-based sampling is employed strictly within the empirically calibrated ranges derived from the aforementioned surveys and standards. This ensures that the generated values, while capturing necessary statistical heterogeneity, are mathematically bounded by realistic engineering limits and operational logic rather than being arbitrary assumptions.

It is assumed that 60% of the mixed fleet are ESs. The cargo handling workload for each ship ranges from 20 to 40 QC-hours. The waiting costs for CFSs and ESs are set within the ranges of 800–1000 USD/h and 400–500 USD/h, respectively. The battery capacity for the ES is between 4000–5000 kWh, and each ES arrives with an initial SOC ranging from 35% to 50%, with a target SOC of 90%. This configuration implies that the ES fleet has a substantial charging demand.

The detailed physical and operational parameters of the QCs are listed in Table 4. The parameters for the port's ship–shore system are provided in Table 5, the ship–port interaction parameters are presented in Table 6, and QC cluster transformer design parameters are listed in Table 7, Table 8 summarizes the specific origin and calibration logic for each input category.

Table 4. QC Model Physical and Operational Parameters.

Parameter	Value
Load mass(kg)	25,000
Spreader mass (kg)	9000
Trolley mass (kg)	20,000
Loaded hoisting or empty lowering height (m)	20
Loaded lowering or empty hoisting height (m)	15
Trolley travel distance (m)	30
Maximum loaded hoisting velocity ($\text{m}\cdot\text{s}^{-1}$)	1.0
Maximum loaded lowering velocity ($\text{m}\cdot\text{s}^{-1}$)	0.8
Maximum empty hoisting velocity ($\text{m}\cdot\text{s}^{-1}$)	1.5
Maximum empty lowering velocity ($\text{m}\cdot\text{s}^{-1}$)	1.2
Hoisting acceleration ($\text{m}\cdot\text{s}^{-2}$)	0.35
Lowering acceleration ($\text{m}\cdot\text{s}^{-2}$)	0.30
Maximum trolley travel velocity ($\text{m}\cdot\text{s}^{-1}$)	2.5
Trolley travel acceleration ($\text{m}\cdot\text{s}^{-2}$)	0.40
Gravitational acceleration/ ($\text{m}\cdot\text{s}^{-2}$)	9.81
Trolley equivalent friction power (kW)	20
Unloading adjustment time (s)	12
Loading adjustment time (s)	8
Motor driving efficiency	0.92
Energy regeneration efficiency	0.90
Allowable feedback ratio of trolley kinetic energy	0.30

Table 5. Port Ship–Shore System Parameters.

Parameter	Value
Planning horizon (h)	80
Total number of QCs	10
Total number of ships	15
Number of ESs	9
Number of CFSs	6
Total number of berths	5
Range of QCs per ship	[1, 2]
Transformer baseline capacity for charging stations (kW)	1000
Target SOC for ESs (%)	90
Delay cost per ship (USD/h)	2000

Table 6. Port and Ship Interaction Parameters.

Ship Index (Type)	Cargo Workload (QC-Hours)	Waiting Cost (USD/h)	Expected Departure Time (h)	Battery Capacity (kWh)	Arrival SOC (%)	ES Waiting Power Consumption (kW)
1 (ES)	31	497	19.4	4098	46	59
2 (ES)	36	431	24.6	4421	49	54
3 (ES)	25	469	17.6	4958	46	51
4 (ES)	30	488	18.2	4533	39	70
5 (ES)	27	490	18.1	4692	47	56
6 (ES)	26	409	18.6	4316	36	58
7 (ES)	28	404	18.4	4687	42	65
8 (ES)	30	417	18.3	4835	48	52
9 (ES)	31	488	21.1	4018	39	67
10 (CFS)	33	934	23.1	-	-	-
11 (CFS)	31	883	21.2	-	-	-
12 (CFS)	35	912	26.2	-	-	-
13 (CFS)	28	828	19.3	-	-	-
14 (CFS)	38	840	28.1	-	-	-
15 (CFS)	25	960	15.8	-	-	-

Table 7. QC Cluster Transformer Design Parameters.

Parameter	Value
Simultaneity factor	0.4
Demand factor (single unit)	0.75
Transformer design load factor	0.6
QC power factor	0.85

Table 8. Data Sources and Calibration Logic for The Case Study Inputs.

Category	Parameters in This Paper	Source and Treatment
QC equipment and cycle parameters	Table 4, Figure 6	Obtained from equipment specifications [34,41] and field survey records of a container terminal. Used to compute the single-QC power-time curve and the aggregated QC cluster power.
QC cluster transformer sizing	Table 7, Equations (13)–(15)	Derived from field surveys of a specific port and calibrated following industry design codes and standard practice [9–11,33,34]. Used to quantify rated capacity and dispatchable margin.

Table 8. Cont.

Category	Parameters in This Paper	Source and Treatment
Port infrastructure and planning settings	Table 5	Integrated from field surveys, relevant literature [33,34,42,43], and news reports. Configured to provide a reasonable simulation environment for validating the proposed method, including berth resources and baseline capacities.
Ship logistics parameters	Table 6, workloads and expected departure times	Synthesized from academic literature [13,16,18,21,25,29] and field survey records. Workload ranges follow common settings used in berth allocation and QC scheduling studies.
ES energy-related parameters	Table 6, battery capacity and SOC	Sourced from authoritative reports [12,44–46], field surveys, and literature [3,47]. Values are selected within realistic bounds to represent ship heterogeneity [5,43,48,49].
Economic coefficients	Tables 5 and 6, waiting and delay costs	Estimated using reported ranges in port operation studies. These coefficients are used for relative comparison between operational modes under the same fleet inputs.

4.1. Quantification of Available Capacity from QC Cluster Peak-Shaving

Based on the mathematical model established in Section 2 and the data from Table 4, the dynamic power curve of a single QC during a complete operational cycle can be calculated, as shown in Figure 6.

Figure 6 illustrates the highly dynamic characteristics of the QC’s operational power, with its peak active power ($P_{qc,peak}$) reaching 374.54 kW and a single operational cycle lasting 135.7 s. According to the industry specifications detailed in Section 2.1.3, and with the transformer design parameters for this QC cluster shown in Table 7, the apparent power required to maintain normal system operation ($S_{T,uncoordinated}$) is approximately 2203.2 kVA. Taking into account potential power surges and common commercially available transformer ratings, the rated apparent power of the selected transformer ($S_{T,rated}$) is 2500 kVA.

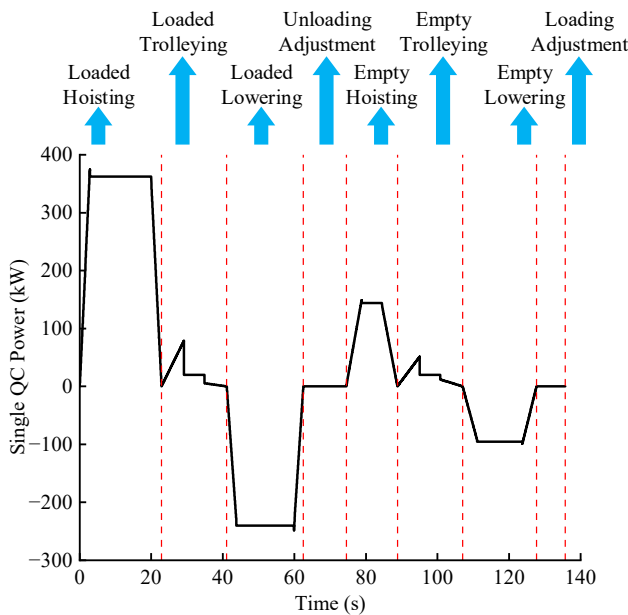


Figure 6. Power-time curve for the complete operational cycle of a single QC.

This case study considers three operational scenarios: (a) Fully synchronized start-up, representing the theoretical worst-case scenario; (b) Typical random start-up, where, based on the simultaneity factor of 0.4, four QCs are set to start simultaneously while the remaining six start randomly, to simulate a natural, uncoordinated operational state; and (c) Orderly peak-shifting start-up, which is the strategy proposed in this paper. To simplify the model, an empirical method commonly used in port operations is adopted, which involves uniformly distributing the start-up times. That is, the start-up delay for each subsequent QC is set as the ratio of a single QC's operational cycle duration to the total number of QCs. Thus, in this case, the start-up delay between consecutive QCs is set to 13.57 s.

A comparison of the aggregated power of the QC cluster under the three modes is shown in Figure 7.

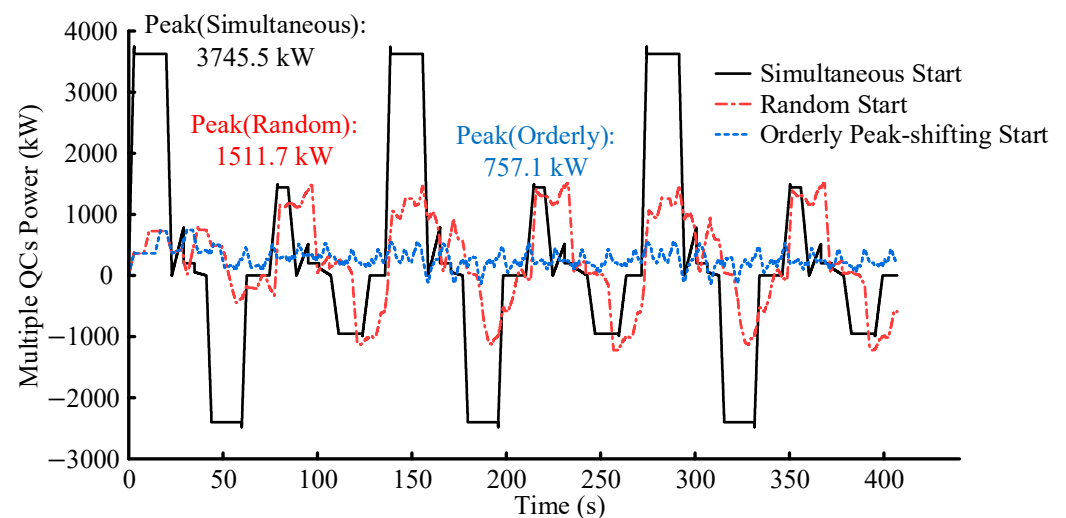


Figure 7. Comparison of aggregated power curves for the QC cluster under different operational scenarios.

As shown in Figure 7, the proposed orderly peak-shifting strategy is highly effective. Compared to the instantaneous peak power of 1511.7 kW under the typical random start-up mode, the orderly peak-shifting mode successfully suppresses the aggregated peak active power of the QC cluster to a stable 757.1 kW, achieving a reduction of 49.9%. This result validates the feasibility and effectiveness of mitigating power peaks through coordinated scheduling.

After implementing the orderly peak-shifting schedule, the apparent power required by the QC cluster drops sharply to 1484.5 kVA. Consequently, within the transformer system with a rated capacity of 2500 kVA, a stable apparent power capacity of up to 1015.5 kVA can be released to support other loads, such as ship charging. Assuming an equivalent power factor of 0.9 for the charging load, this capacity can be converted into approximately 913.9 kW of active power.

4.2. Scenario Setup and Comparative Schemes

To comprehensively evaluate the effectiveness and economic viability of the proposed coordinated optimization scheduling method, a comparison is made between two different operational modes for the port. The simulation model and the proposed genetic algorithm were implemented using MATLAB (Version R2024a, The MathWorks, Inc., Natick, MA, USA).

- (1) Traditional scheduling mode: This mode is based on the conventional independent shore power architecture, meaning the port can only rely on its 1000 kW of baseline power to charge all ships.

- (2) Coordinated scheduling mode: This mode is based on the proposed ship–shore interconnection architecture. Through the, the 913.9 kW of dispatchable power (P_{disp}) released from the QC side is integrated into the charging network, increasing the total available charging power to 1913.9 kW.

To ensure a fair comparison, the berth allocation, QC scheduling, and charging strategies for both modes are independently optimized using the proposed GA framework. The optimization objective in both cases is to minimize the total port operational cost. The solution process is illustrated in Figure 8. The coordinated scheduling model demonstrates superior performance, achieving both a faster convergence speed and a lower final cost compared to the traditional scheduling model. Besides, the objective values become stable before the maximum number of generations, indicating a reliable convergence behavior under the adopted GA settings.

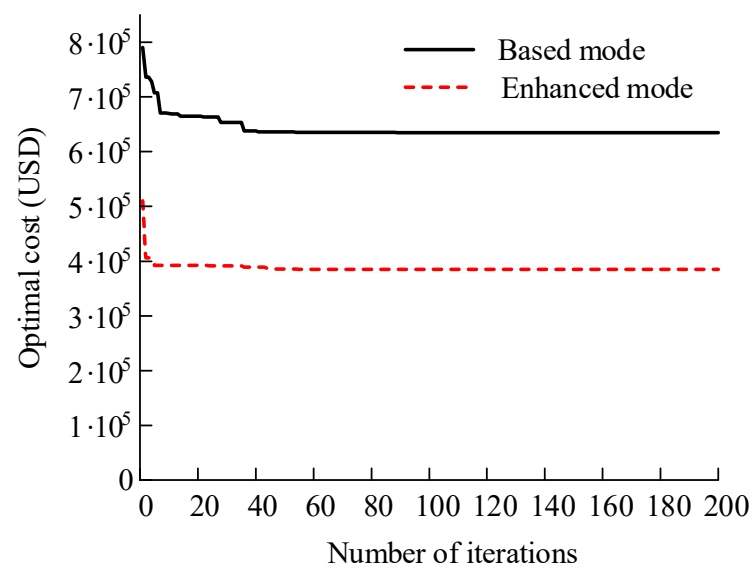


Figure 8. Cost convergence curves for different operational modes.

Figure 9a clearly reveals the substantial difference in operational effectiveness between the two modes. Enabling the “Coordinated scheduling mode” leads to a significant reduction in the total port operational cost, from \$634,550.1 to \$385,240.2, achieving a remarkable cost-saving of 39.29%. This is composed of a 10.73% reduction in waiting costs and a 48.29% reduction in delay costs.

As shown in Figure 9b, delay costs account for a large proportion of the total cost in both modes, representing 76.04% in the traditional scheduling mode and 64.7% in the coordinated scheduling mode, respectively. The reduction in delay costs is therefore key to lowering the total cost. When the port accommodates ESs with high charging demands, the actual departure times for most ships tend to exceed their expected departure times. Consequently, increasing the available charging power to reduce the charging duration for ESs is an effective strategy for reducing the port’s overall operational costs.

Figures 10 and 11 present the Gantt charts for berth-time allocation under the traditional scheduling mode and the coordinated scheduling mode, respectively. In these charts, the colored bars represent a ship’s berthing period, the charging process for ESs is indicated by white dashed boxes, and the text on each bar denotes the ship type and the number of assigned QCs.

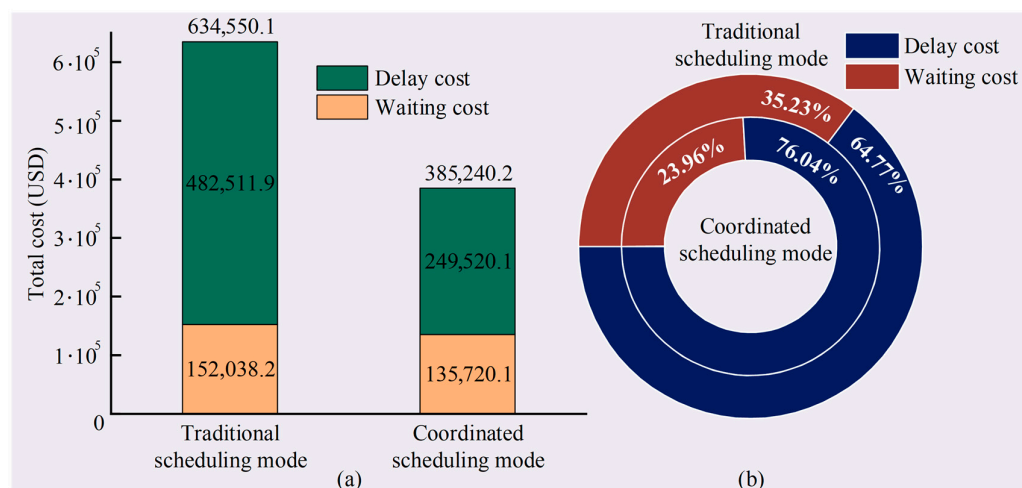


Figure 9. Cost analysis under different operational modes. (a) Absolute cost comparison; (b) Proportional cost comparison.

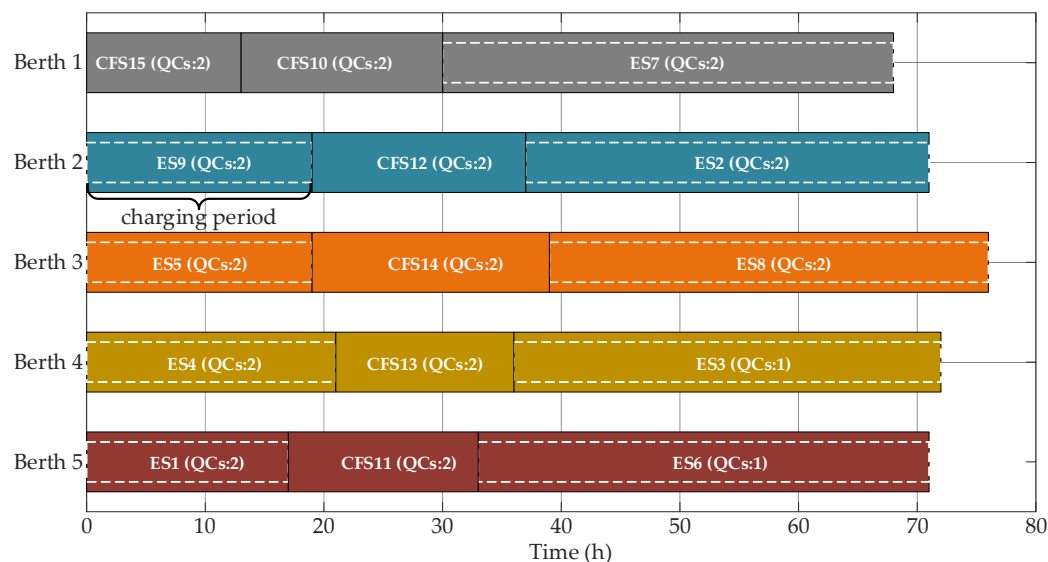


Figure 10. Gantt chart for port berth allocation under the traditional scheduling mode.

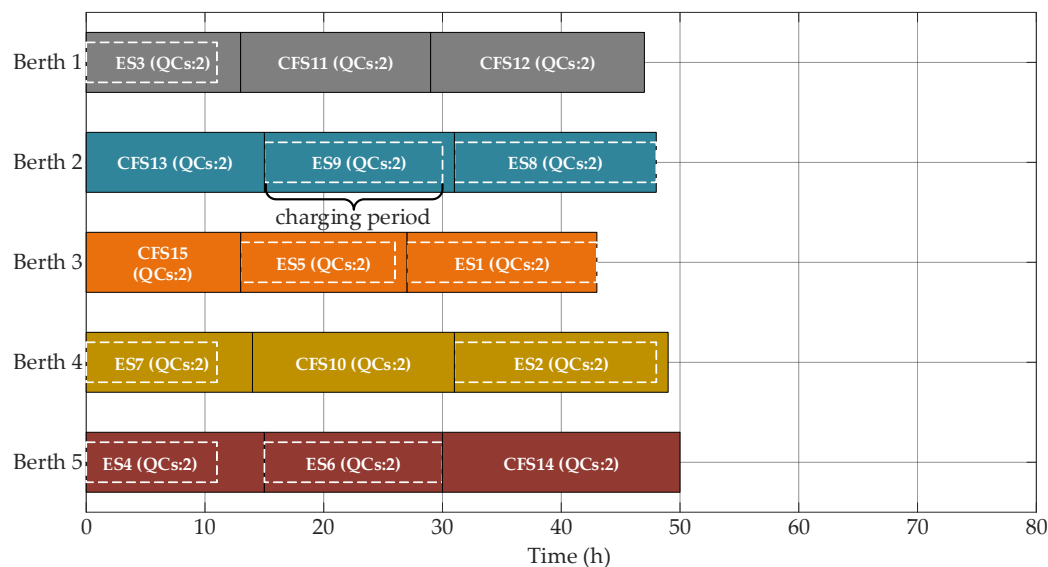


Figure 11. Gantt chart for port berth allocation under the coordinated scheduling mode.

The Gantt charts visually confirm these results: the maximum fleet turnaround time decreases from approximately 76 h in the traditional mode to 50 h in the coordinated mode, a reduction of 34.2%. In the coordinated scheduling mode, the charging time for ESs is significantly shortened, and the berth turnover efficiency is markedly improved. Multiple ships are able to depart earlier, which reduces the total occupancy duration of berth resources.

To further interpret these results from a system-level perspective and elucidate the trade-offs between energy and logistics, Figures 12 and 13 visualize the impact of the coordinated scheduling on shore power profiles and queuing dynamics, respectively.

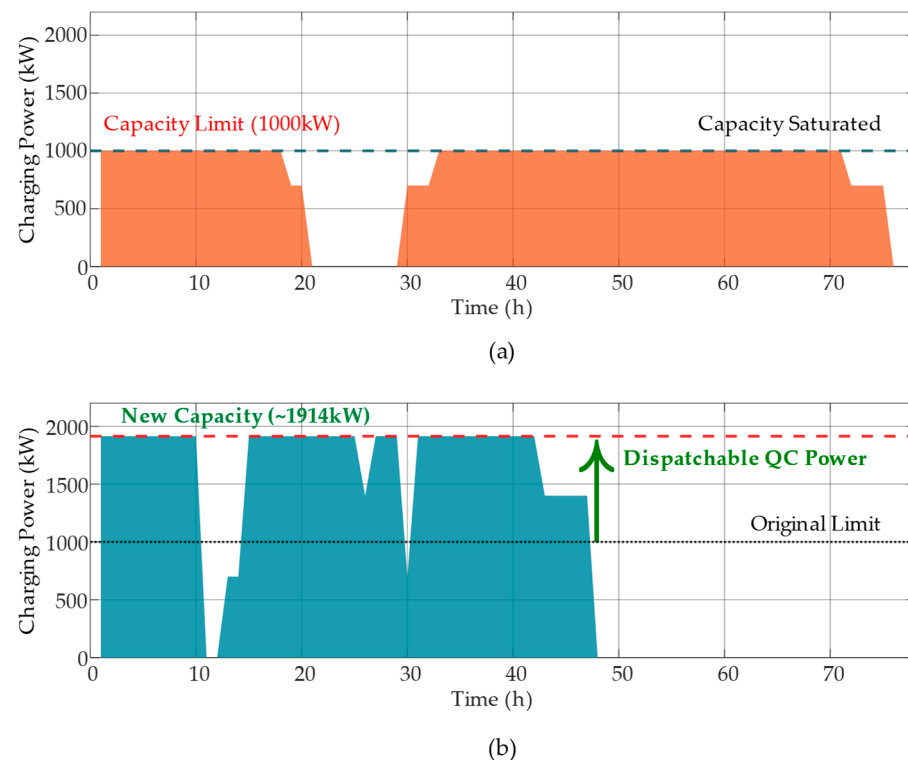


Figure 12. Shore power profile analysis under different operational modes. (a) Traditional scheduling mode; (b) Coordinated scheduling mode.

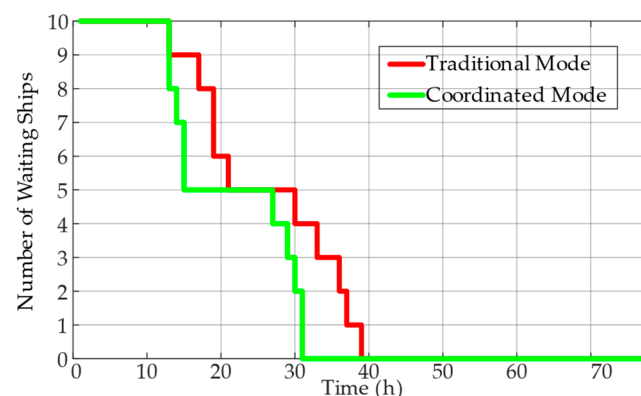


Figure 13. Comparison of queuing dynamics.

As illustrated in Figure 12a, under the traditional independent scheduling mode, the charging power is rigidly capped by the 1000 kW limit of the shore-side transformer. This creates a “charging bottleneck” even when charging demand is high, while simultaneously, the significant power margin on the QC side remains physically isolated and wasted. In

contrast, Figure 12b demonstrates that the proposed architecture successfully breaks this “energy silo.” By implementing the orderly peak-shaving strategy, the system smoothens the QC load volatility and releases a stable dispatchable power margin. Consequently, the available charging power dynamically peaks at nearly 2000 kW, representing a 91.39% increase in peak supply capability compared to the traditional mode.

This capacity expansion on the energy side directly translates into efficiency improvements on the logistics side. As shown in Figure 13, the number of waiting ships in the traditional mode (red line) remains high for an extended period due to the slow turnover rate caused by charging limitations. Conversely, the coordinated mode (green line) facilitates rapid queue clearance, significantly reducing the fleet’s total turnaround time.

From a broader engineering perspective, this improvement stems from a “Time-Energy Displacement” mechanism. By imposing millisecond-level orderly delays on QC start-ups, the stochastic peak loads are flattened. This operation effectively converts the “temporal flexibility” of QCs into “instantaneous power capacity” for ESs, significantly improving the Asset Utilization Rate of the port’s grid infrastructure. This mechanism validates the feasibility of mitigating grid congestion and logistical delays through software-defined coordination rather than expensive hardware expansion.

4.3. Sensitivity Analysis of ES Penetration

To validate the robustness of the proposed model and evaluate its scalability under varying operational intensities, a sensitivity analysis regarding the penetration rate of electric ships (ESs) is conducted. Specifically, the fleet composition is systematically varied by increasing the number of ESs within the 15-vessel fleet from 0 to 15. Figure 14 illustrates the correlation between ES penetration levels and the percentage of operational cost reductions achieved by the coordinated scheduling mode compared to the traditional mode.

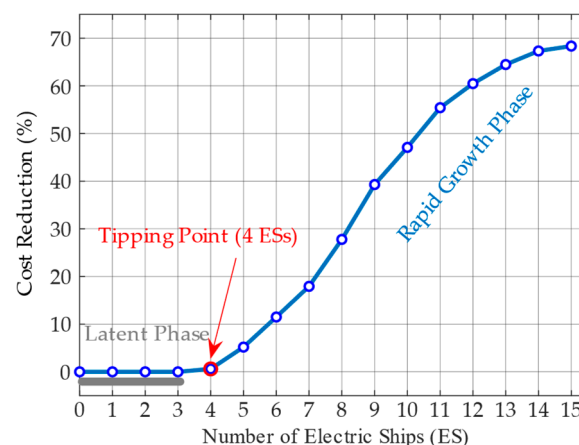


Figure 14. Cost reduction percentage under different ES penetration levels.

The simulation results reveal three distinct phases regarding the system’s performance:

- (1) The Latent Phase (0–3 ESs): When ES penetration remains below 20%, the cost reduction is negligible (approaching 0%). This observation suggests that at low electrification densities, the baseline transformer capacity (1000 kW) of the port is sufficient to accommodate charging demands, rendering coordinated scheduling unnecessary for capacity alleviation.
- (2) The Tipping Point (4–5 ESs): A critical inflection point emerges at an ES penetration rate of approximately 26.7% (4 ESs). At this threshold, the cost reduction initially rises to 0.62% before accelerating to 5.19% with 5 ESs. This transition signals the onset of

- the “charging bottleneck” within the traditional power architecture, indicating that the physical grid capacity is no longer adequate to support independent operations.
- (3) The Rapid Growth Phase (6–15 ESs): As penetration exceeds 40%, the marginal benefit of the coordinated scheme amplifies significantly. In the fully electrified scenario (15 ESs), the proposed method yields a 68.34% reduction in total operational costs. This trajectory demonstrates that the efficacy of logistics–energy coordination scales positively with the industry’s electrification progress, offering a “future-proof” solution that mitigates the need for capital-intensive infrastructure expansion.

5. Conclusions

To address the severe challenges posed to ports by the high-power charging demand of battery-powered ships, this paper proposes a bi-level coordinated optimization scheduling method for ship–shore logistics and energy flow, based on a SIU interconnection architecture. The core of this method lies in proactively tapping into and releasing the port’s latent and underutilized power capacity by implementing an orderly peak-shifting schedule for QC cluster operations. To enable the effective utilization of this surplus capacity, a hybrid AC/DC ship–shore interconnection architecture featuring a flexible power dispatching capability is designed.

The case study shows that the orderly peak-shifting strategy reduces the aggregated peak active power of the QC cluster by 49.9%, which releases 913.9 kW of dispatchable charging power. As a result, the available charging supply capability increases from 1000 kW to 1913.9 kW. From a power-grid perspective, this coordinated use of existing transformer margins mitigates local congestion during charging peaks and improves the utilization of port electrical assets.

At the operational level, the coordinated scheduling mode reduces the total port berthing operational cost by 39.29% and shortens the maximum fleet turnaround time by 34.2%. The sensitivity analysis indicates that the benefit becomes significant when ES penetration exceeds about 25% in the tested setting, suggesting that the proposed scheme is suitable for ports in the electrification transition stage.

To manage the increasing charging demands from ESs during the industry’s electrification transition, this research targets day-ahead tactical planning and offers a cost-effective pathway for ports. The proposed architecture also assumes that standard converter protections and feeder protection coordination are in place for fail-safe operations. Future work will focus on large-scale validation with different port sizes and on incorporating uncertainties, such as ship arrival times and workloads, into the model by developing a stochastic or robust optimization framework to enhance the practical applicability of the proposed solution.

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