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Research on the Green Development of Port Mechanical and Electrical Equipment under the "Dual Carbon" Strategy

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Abstract. After the goals of carbon peaking and carbon neutrality were put forward, the pressure of emission reduction in the shipping industry has been accelerated to transmit to ports, and the green and low-carbon transformation of mechanical and electrical equipment has thus become an important starting point for the implementation of emission reduction. This paper reviews the carbon reduction practices of typical ports at home and abroad, and examines the application effects and bottlenecks of core technologies from four directions: new energy power machinery, braking energy recovery, multi-energy complementary systems, and ship shore power. Analysis shows that port decarbonization is entering a new stage of multi-technology collaborative integration, and the supply side, the energy use side, and the management side need to exert force simultaneously; the policy dividends, market traction, and technology iteration during the transformation window period bring both opportunities and challenges. Based on this, the paper puts forward suggestions on connecting with policy tools, tackling core technologies, unifying standards and norms, and implementing whole-life-cycle digital management of equipment, for reference in the green upgrading of ports.

Keywords: Carbon peaking and carbon neutrality, port mechanical and electrical equipment, green transformation, new energy equipment, shore power system

1. Introduction

The maritime shipping industry carries an important share of global trade, and ports, as the core nodes in the shipping chain, with their loading and unloading equipment, horizontal transport vehicles, and auxiliary power devices, constitute an important source of emissions. Under the framework of the 15th Five-Year Plan, the state has explicitly put forward the binding targets of achieving carbon peaking on schedule and reducing carbon emissions per unit of GDP by 17%, which puts forward hard requirements for the port sector to accelerate the promotion of shore power application, expand the application scope of electric and hydrogen energy machinery, and build an intelligent energy management platform.

From the perspective of international regulatory trends, the European Union has included shipping into the carbon emission trading system at the beginning of 2024, and required ports of member states to equip large ships with shore power interfaces before 2030, and during port calls

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they must connect to the onshore power grid or adopt zero-emission schemes [1]. International hub ports such as Rotterdam and Singapore have successively launched their own zero-carbon terminal assessment standards. At the domestic policy level, the State Council released the plan for a dual-control system of carbon emissions in 2024, and multiple departments including the Ministry of Transport jointly issued the guidance on high-quality development of inland waterway shipping in 2025, clearly promoting the renewal and replacement of port working equipment toward green electricity, hydrogen energy, and LNG. The above policy signals indicate that the low-carbon transformation of port mechanical and electrical equipment is changing from advocacy requirements to mandatory constraints [2].

Around port decarbonization, research results have continued to accumulate in recent years. Alamoush et al. [3] systematically integrated the concepts, paths, barriers, and opportunities of port decarbonization; Karagkouni and Boile [4] classified and sorted out the green practices implemented in ports, and summarized the application genealogy of green technologies, tools, and strategies; Holder et al. [5] specifically evaluated the deployment opportunities of hydrogen energy technology in ports, and believed that hydrogen energy is expected to undertake heavy-load, high-intensity operation scenarios; Yu et al. [6] decomposed the driving factors of carbon emissions in Chinese ports, and pointed out that energy structure adjustment and operation efficiency improvement are the main sources of emission reduction. Overall, existing studies mostly focus on the overall emission reduction strategy of ports or the application of single technologies, and green research that takes mechanical and electrical equipment as an independent object and runs through the whole process of equipment selection and operation management still needs to be deepened.

The greening of port mechanical and electrical equipment involves multiple dimensions such as energy substitution, equipment upgrading, and operation optimization, and belongs to a typical system engineering. At present, the upfront capital expenditure of clean energy equipment remains high, the standard barriers between products of different manufacturers have not been broken through, and the infrastructure such as the port area distribution network and hydrogen refueling stations also has obvious shortcomings. How to achieve the dual goals of cost reduction and emission reduction within the policy opportunity window period urgently needs systematic theoretical analysis and path guidance. Acciaro et al. pointed out that port energy management involves the game coordination of multiple stakeholders, and port management agencies must play a new leading role in the energy transition [7].

2. Current status of green development of port mechanical and electrical equipment

2.1. Practices of green transformation in foreign ports

From the perspective of the evolution characteristics of the transformation path, foreign ports have shown three trends in the transformation process: the power source of port operations is shifting from diesel to electricity and hydrogen energy, the emission reduction strategy is shifting from passive compliance to active energy management, and the technical scheme is shifting from single-point application to system integration. The above practices show that greening is no longer limited to environmental compliance costs, but has become a strategic choice to reshape the global competitiveness of ports and cultivate sustainable development capabilities.

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Figure 1. H2 Barge 1, the world's first hydrogen-powered inland container ship

Ports in Europe and North America started early in decarbonization and generally adopted diversified means combining hydrogen energy, shore power, and renewable energy to advance transformation [8]. The world's first hydrogen-powered inland container ship, H2 Barge 1, relies on hydrogen fuel drive to achieve zero-carbon navigation throughout the journey (see Figure 1), sailing between Rotterdam in the Netherlands and Nike's European logistics park located in Belgium, with an annual emission reduction of about 2,000 tons per ship compared with traditional shipping. The UK's NatPower Marine has formulated a shore power deployment plan for dozens of ports in Asia, whose business model centers on charging operators and integrates shore-side substations, energy storage batteries, and smart grid interfaces as a whole. The three newly built automated yards at the Burchardkai terminal of the Port of Hamburg in Germany all use green electricity supply, and relying on renewable energy power supply significantly reduces energy consumption and carbon emissions. As the first port in Europe to provide shore power for container ships and cruise ships, the Port of Hamburg is advancing an all-round green energy transformation; from 2025, all large cruise ships and container terminals will be equipped with shore power connections to help reduce port emissions.

2.2. Current status of green development of domestic ports

The green work of ports in China takes the systematic optimization of energy structure and intelligent emission reduction as the main line. On the supply side, multiple ports actively build a micro-grid system with coordinated wind, solar, storage, and load — Tianjin Port took the lead in achieving complete self-sufficiency of green electricity in the port area, and the whole process of terminal operation reached net-zero emissions (see Figure 2); Rizhao Port laid out distributed wind power and photovoltaic projects (see Figure 3). On the energy use side, the large-scale deployment of electric container trucks and hydrogen fuel machinery combined with unmanned dispatching systems can effectively improve operation efficiency while significantly reducing carbon emissions. After Longgong Port put into use automated equipment such as unmanned container trucks, its efficiency increased by 30% compared with traditional methods; the all-category new energy port-working machinery demonstration launched by Tianjin Port covers seven major categories and twelve types of equipment, and these new energy equipment can meet the high-intensity operation requirements of the terminal site in terms of rated load and endurance, and greatly reduce carbon

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emissions compared with diesel equipment of the same level, while reducing maintenance costs by about 30%.



Figure 2. Tianjin Port's "Smart Zero-Carbon" terminal



Figure 3. Distributed wind power and photovoltaic power generation at Rizhao Port

In the field of dust control, the passive environmental protection unloading hopper developed by Yantai Port uses a gravity grille to achieve sealed dust control, and can suppress dust spillover without external power. Qinhuangdao Port introduced AI and big data into the whole process of bulk cargo operation, reducing the dust concentration in the dumping room to the order of 5 mg/m3. After the proportion of electric container trucks in Ningbo Beilun Port Area exceeded half, the annual carbon emission reduction exceeded 3,800 tons, and the energy cost saving exceeded 10 million yuan. The above data show that the green transformation of mechanical and electrical equipment not only produces environmental benefits, but also brings considerable economic returns.

2.3. Green technology system of mechanical and electrical equipment

The green technology system of port mechanical and electrical equipment takes low carbon and sustainability as the core goals, covering five directions: energy saving of drive systems,

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replacement of clean power equipment, multimodal transport integration, distributed energy utilization, and comprehensive dust control. In terms of drive systems, the variable frequency speed regulation technology realized by relying on frequency converters to adjust the power supply frequency and voltage, together with potential energy recovery technology, can reduce the energy consumption of lifting machinery by about 30%, which is consistent with the logic that frequency converters generally achieve energy consumption optimization by optimizing equipment operation status in the industrial field; in terms of clean power, electric and hydrogen energy machinery are accelerating the replacement of diesel equipment; in terms of distributed energy, photovoltaic and wind power combined with heat pump technology realize the low-carbonization of cold and heat supply in port areas; in terms of dust control, sealed corridors combined with dry mist dust suppression can control the dust concentration in operation areas within the environmental protection limits [9]. The integrated application of these green technologies enables port equipment to achieve emission reduction goals while also achieving the improvement of operation efficiency and safety.

3. Core technology paths for green transformation

3.1. New energy power equipment

The new energyization of port mobile machinery roughly advances along three technical routes: the first is the pure electric route, characterized by high energy density battery packs and high-power fast charging facilities; the second is the hydrogen fuel cell route, relying on high-pressure hydrogen storage and fuel cell stack technology; the third is the hybrid route, which takes into account both endurance and emission reduction through intelligent diesel-electric switching. All three schemes can achieve zero emissions in the operation process, and the energy use cost is reduced by more than 40% compared with traditional fuel equipment; the traffic-energy coupling modeling for port tractors also shows that the hydrogen fuel cell scheme has application potential in high-intensity operation scenarios. From the perspective of equipment types, the pure electric route has taken the lead in achieving large-scale application on small and medium-sized mobile machinery such as container trucks, reach stackers, and stackers, with battery pack capacity usually in the range of 200–400 kWh, and combined with dual-gun fast charging can complete energy replenishment in a short time; the hybrid route provides a flexible scheme for the transformation of old equipment during the transition period, and the intelligent switching between its diesel unit and motor can be realized through energy management strategies, significantly reducing idle fuel consumption and exhaust emissions while ensuring endurance.

3.2. Energy feedback and energy-saving drive

The basic principle of energy recovery technology is to recover the energy originally dissipated during the operation of equipment and reuse it, with a typical scenario being the potential energy recovery when a container crane lowers a load. Frequency conversion drive achieves smooth speed regulation and precise torque control by adjusting the motor frequency in real time, and has a significant energy-saving effect in port lifting equipment. According to the practice of frequency conversion technology application transformation of portal cranes, the energy consumption per ton of loading and unloading decreased significantly after the transformation; relevant research and engineering cases also show that the power consumption of cranes after installing frequency converters can be significantly reduced, and the energy expenditure also has a considerable saving.

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The four-quadrant converter feeds the electric energy generated in the braking process back to the grid, effectively improving the comprehensive energy utilization efficiency of the system. The DC drive scheme uses thyristor rectification to provide high-precision torque control, and is especially suitable for loading and unloading machinery that requires precise positioning. The above technologies jointly constitute the energy-saving technology base of port lifting equipment.

3.3. Multi-energy complementarity and shore power system

The renewable energy system in port areas takes multi-energy complementarity as the basic architecture: photovoltaic modules use high-efficiency monocrystalline silicon products, wind turbines are adapted to low wind speed environments, and heat pump systems adopt ground-source, seawater-source, or air-source schemes according to local conditions. The smart micro-grid gives priority to consuming clean energy through source-storage-load coordination control. The shore power system is another important path for port emission reduction. After a berthing ship is connected to shore power, it can shut down the auxiliary engine, thereby cutting the emissions of particulate matter, nitrogen oxides, and sulfur oxides. At the technical level of shore power, ports need to build high-voltage frequency conversion power supply devices and shipboard interface conversion equipment as supporting facilities, among which the high-voltage shore power system adopts the power supply standard of 6.6 kV/60 Hz or 450 V/60 Hz, and supplies power to ships through cable reels or shore-connecting trolleys. At present, the coverage rate of shore power facilities in major ports in China has reached more than 80%, but the actual power connection rate is still constrained by the ship modification progress and the convenience of power connection operations; the shore power promotion experience of European ports also shows that the cost-sharing mechanism and the convenience of operation process can determine the power connection rate more than the technology itself. From the perspective of the overall greening of port mechanical and electrical equipment, the multi-energy complementary system provides a clean power base for port areas, while the shore power system cuts off the emission source of ship auxiliary engines; the two cooperate to form a low-carbon closed loop on the energy use side and supply side of ports, laying a technical foundation for ports to achieve zero-carbon operation in all scenarios.

4. Opportunities, challenges and countermeasures for green development

4.1. Development opportunities

The "Dual Carbon" goal superimposed on the national large-scale equipment renewal policy has released a huge market space for the replacement of existing old equipment in ports. Both the Outline for Building a Leading Country in Transportation and the Planning Outline for the National Comprehensive Three-Dimensional Transportation Network list the promotion of shore power and the application of new energy equipment as key tasks, and clearly state that the on-site equipment of major coastal ports will basically complete the new energy power replacement by 2030. At present, the number of heavy trucks in operation in major ports in China is about 200,000 to 300,000, but the new energy penetration rate is only about 5%. With the dual drive of the policy side and the demand side, this market is welcoming an explosive window, and the operation scheduling of electric tractors and the layout of charging facilities have also been included in joint optimization research. From 2025, Ningbo Zhoushan Port, Tianjin Port, Shenzhen Yantian Port, etc. have banned the entry of vehicles of National IV and below into ports, requiring the electrification of new container trucks. These policy orientations have formed a strong demand-pulling effect.

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In terms of technology evolution, the innovation activity in directions such as hydrogen energy machinery, high-power fast charging, and intelligent energy management continues to increase, and equipment performance and energy efficiency indicators continue to be optimized and improved. Ports and equipment enterprises that took the lead in completing green transformation have accumulated replicable experience and set a benchmark for later entrants. Overall, the green transformation has shifted from the single-wheel drive of policy to a new stage of dual-wheel drive of market and policy.

4.2. Challenges faced

The high upfront capital investment is the primary challenge. The procurement price of electric and hydrogen energy equipment is significantly higher than that of diesel equipment; taking diesel generators as an example, the price of small units (≤75 kVA) is mostly 50,000–200,000 yuan, and the price of medium units (75–375 kVA) is 150,000–800,000 yuan, while the procurement cost of electric and hydrogen energy equipment far exceeds this range, and the supporting charging piles, hydrogen refueling stations, and energy storage systems also require a large amount of capital investment. Although the cost advantage is obvious from the perspective of the whole life cycle — for example, the domestic first 10,000-ton-class pure electric intelligent container ship "Ningyuan Diankun" has a single-voyage cost lower than that of fuel ships, saving 67 tons of fuel in the first month and an estimated 800 tons of fuel per year — the high upfront capital expenditure still constitutes a large financial pressure on small and medium-sized ports, and the existing subsidy policies cannot yet fully cover the funding gap; the putting into use of the first hydrogen energy auxiliary power system transformation reach stacker in Shandong Port also reflects the capital scale of such equipment investment from the side.

Non-uniform standards and lagging infrastructure are the other two main constraints. The new energy equipment currently applied in ports lacks unified norms in terms of charging interface protocols, hydrogen storage and transportation standards, and data interaction specifications; the interoperability between products of different manufacturers is poor, which increases the complexity of system integration and operation and maintenance. The capacity of the port area distribution network is often insufficient to support large-scale charging loads; according to the Guidance on the High-Quality Development of the Distribution Network under the New Situation issued by the National Development and Reform Commission and the National Energy Administration, the distribution network will have the access capacity of about 12 million charging piles by 2025, and the carrying pressure of the current distribution network can be seen from this. Wind and solar power generation has intermittency and requires large-capacity energy storage; the hydrogen energy supply chain is not yet mature, and the infrastructure construction in the production, storage, and transportation links is lagging, which pushes up the cost of hydrogen use and affects supply stability.

4.3. Countermeasures and suggestions

In terms of countermeasures, the first is to grasp the policy window. The national equipment renewal and new energy subsidy policies are in a period of intensive release, and ports and equipment enterprises should take the initiative to connect, make good use of policy tools such as fiscal subsidies and tax incentives, and lay out the product matrix in advance around green port equipment. The second is to tackle core technologies: the deep integration of new energy and intelligence is the main direction, and the integrated system integrating intelligent scheduling, energy management, and remote operation and maintenance functions needs to be developed, and frontier equipment such

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as hydrogen-energy-driven loading and unloading machinery should also strive for substantial breakthroughs. At the standard level, the unification of charging protocols, hydrogen storage and transportation standards, and data interface specifications requires the industry to promote jointly; enterprises that take the lead in participating in the formulation of industry and national standards are more likely to win first-mover advantages in the field of green smart ports; the Mechanical and Electrical Bureau of CCCC can rely on its full industry chain capability to provide ports with one-stop green solutions from planning and design, equipment complete sets, to operation and maintenance management. At the management level, the mechanical and electrical equipment should be included in digital control throughout the whole process from selection and design, installation and commissioning, condition monitoring, maintenance, to scrapping and disposal, so that the equipment operation evolves continuously along the efficient, intelligent, and green direction.

5. Conclusions

Focusing on the green transformation of port mechanical and electrical equipment under the background of the "Dual Carbon" strategy, this paper examines the development status, core technology paths, and countermeasures. The main understandings are as follows:

From the perspective of development trend, the greening of ports at home and abroad is accelerating: foreign pioneering ports advance emission reduction by taking hydrogen energy application, shore power deployment, and renewable energy utilization as starting points, while domestic ports take the coordinated wind-solar-storage-load system and new energy equipment replacement as the core path, and both emission reduction and economic returns have achieved remarkable results. Port decarbonization is moving from single-point technology breakthroughs to multi-technology collaborative integration, and the three dimensions of supply, use, and management need to be promoted simultaneously.

From the perspective of technology paths, new energy power equipment, energy recovery and energy-saving drive, multi-energy complementary systems, and shore power technology constitute the four main trunks of greening, and technology fusion drives port equipment to upgrade toward efficient, low-carbon, and intelligent directions. Among them, the emission reduction effect of hydrogen energy technology and shore power systems is the most direct, and for the ultimate scheme toward zero-carbon operation, the multi-energy fusion system has the most potential.

From the perspective of constraints, high initial investment, non-uniform standards, and lagging infrastructure are the three main thresholds; the corresponding strategies are to grasp policy opportunities, break through key technologies, build a standard system, and implement whole-life-cycle management, and these aspects need to be promoted in a coordinated manner.

This study also has limitations: the commercialization effect of frontier technologies such as hydrogen energy machinery still needs a longer cycle of practical testing; issues such as the economic evaluation model of port green transformation, the differentiated green transformation paths of different types of ports, and the whole-life-cycle carbon footprint accounting of new energy equipment all need to be deepened by follow-up research.

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