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Pathway for Integrated Development of Waterway Transportation and Energy in China

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Abstract: Energy is vital for the survival and development of human society. Waterway transportation, as a significant component of the transportation industry, is one of major fields of energy consumption and greenhouse gas emissions. Therefore, the integrated development of waterway transportation and energy becomes a powerful measure against severe challenges such as resource shortage, climate change, and environmental pollution. This paper reviews the current energy consumption characteristics of waterway transportation in China in terms of ships and ports, and evaluates the evolution trend of energy demand of relevant main parts from the perspectives of energy supply, quality, and utilization mode. The technical assessment of the integrated development of waterway transportation and energy is conducted, including natural endowment analysis, energy application potential of infrastructure assets, and research and judgment on energy demand. Based on this, the development principles, ideas, and pathways of water way transportation and energy integration in China are proposed. Moreover, this paper proposes suggestions for promoting the integration of waterway transportation and energy in China from the aspects of policy, key technology, and personnel training, so as to provide a basic reference for cross-disciplinary research and high-quality development of the waterway transportation industry.

Keywords: waterway transportation; new energy; low-carbon fuel; zero-carbon fuel; energy utilization mode; transportation infrastructure

1 Introduction

Considering the rapid development of global integration and the intensification of market competition, the waterway transport industry has been pursuing high efficiency and low cost over the past few decades; however, the industry is one of the major contributors to the consumption of fossil fuels and greenhouse gas emissions [1]. The International Maritime Organization and other relevant agencies have issued a series of regulations on limiting ship emissions, and countries are also continuously promoting industrial restructuring to solve the problems of high energy consumption and low efficiency in the waterway transport industry [2]. Since the 1960s, the European Union,

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the United States, Japan, Australia and other countries and regions have begun to focus on the integrated development of waterway transport and energy, and related research has mainly revolved around the integration of ships and energy, ports and energy, and channels and energy [3]. New types of ships [4–7], using solar, wind, nuclear, hydrogen, and other sources of energy, have been actively developed, and the industry has been encouraged to use power sources such as purely electric ships as well as liquefied natural gas (LNG), ammonia, methanol, and hydrogen internal-combustion engines. For instance, in 2000, the world's first commercial wind /solar hybrid catamaran "Solar Sailer" was launched in Australia for sea trials. Furthermore, in 2009, the world's first fuel cell ship "Viking Lady", a marine engineering vessel, was refitted and equipped with a fuel cell power system with a power of 320 kW. However, research on ships using new forms of energy in China has only started recently. In 2022, the "Changhang Cargo 001", which is a demonstration ship from the Green and Smart Inland-River Ship Innovation Project launched by the Ministry of Industry and Information Technology of China, was officially delivered in Zhenjiang, China. It was the first green and smart ship to be used on Chinese inland rivers, and is equipped with a hybrid propulsion system integrating a diesel main engine, shaft motor, LNG gas fuel generator group, and lithium batteri. Additionally, related research and demonstration applications such as new-energy port machinery [8] and new-energy beacon lights are also advancing gradually.

The energy consumption of the waterway transport industry is dominated by the consumption of fuel, coal, and electricity. In particular, the proportion of fuel consumption is still rather high. Considering the current energy structure of the waterway transport industry in China, to cope with the rising global temperature and energy crisis, the energy supply of waterway transport should change from conventional to renewable energy. In addition, necessary adjustments should be made to the energy supply of the inland-river and coastal waterway transport infrastructure and carrying equipment in China to better adapt to the transformation. It is worth noticing that the greening of waterway transport is inseparable from the greening of energy consumption entities in waterway transport and the deep integration of waterway transport and new forms of energy. To promote the greening and low-carbon transformation of the waterway transport industry in China, several challenges have to be faced, such as the layout of the inland-river and coastal green transport infrastructure, optimization of the infrastructure's energy demand, energy diversification of a ship's power system, and the development of core technologies for energy integration and related equipment. It is necessary to conduct systematic and in-depth research, taking into account planning, policy, technology, economy, and other aspects.

With the aim of resolving the above-mentioned problems encountered in industrial development, scholars have conducted various studies. On the basis of analyzing the overall pattern of energy transmissions in China, the development trend of energy transmissions has been clarified, and suggestions for promoting an energy transmission network and overall transport system integration were proposed [9]. For the land transport system, the development and operational framework and control methods of transport–energy integration have been discussed from a technical point of view, and the key technologies involved in the coordinated development of the energy and transport systems have been expounded [10]. An integration of the waterway transport and energy planning method, operational method, and evaluation index system, taking into account the operation management and technical application, has been proposed for a port's energy system in waterway transport [11]. In this paper, we mainly focus on the urgent needs of China and refine the research entry points, focusing on the country's waterway transport industry, analyzing the industry's energy consumption characteristics and energy demand trend, analyzing the natural endowments of inland rivers and coastal areas, and evaluating the potential of the corresponding energy application of the transport infrastructure assets. Based on this, the development path of the integration of waterway transport and energy is proposed, in order to drive the industrial development research of the effective integration of waterway transport and energy.

2 Energy consumption characteristics of waterway transport in China

2.1 Energy consumption characteristics of a ship

Table 1 shows the energy types and energy transfer modes of ships with different power forms. A diesel engine power system has the advantages of a high-power level and high safety factor. The "diesel engine – shafting – propeller" power system configuration dominates the many configuration forms of a ship's power system. For this reason, a waterway's carrying equipment still uses the light/heavy diesel fuel that is used in a ship's engines [12]. Taking into account factors such as environmental protection, market benefits, and technological maturity, a novel ship power system including diesel electric propulsion, diesel–LNG dual fuel power, and various clean energy hybrid forms can also be used to enhance the greening level of a ship [13]. With proper parameter settings and energy distribution, a multi-energy hybrid power system can effectively reduce the energy consumption and carbon emissions of a ship [14].

Table 1. Energy types and energy transfer methods for ships with different power forms.

Power form	Energy type	Energy transfer method
Diesel engine power	Fuel	Diesel engine–shafting–propeller
Electric propulsion	Fuel	Diesel generator–frequency converter–electric motor–propeller
LNG/diesel dual fuel power	Diesel /LNG	LNG/diesel dual fuel engine–shafting–propeller
Multi-energy hybrid	Fuel and clean energy	Diesel engine/solar energy/hydrogen energy/wind energy/electrochemical energy storage–inverter–electric motor–propeller Diesel engine–shafting + solar energy/hydrogen energy/wind energy/electrochemical energy storage–inverter–electric motor–propeller

2.2 Energy consumption characteristics of ports

The main energy consumers of the waterway transport infrastructure include the port's equipment and transport, and a ship's energy consumption whilst in port, which includes that used by the port's machinery and when berthing a ship [15], as shown in Fig. 1. The energy consumed by the infrastructure includes mainly electricity and fuel. Out of these, electricity accounts for the main part of the overall energy demand; this is mainly used for the electric loading and unloading equipment. Fuel is mainly used for transportation and operational vehicles. The early energy demands of berthing ships were mainly met by the berthing generators that consumed fuel to generate electricity. In recent years, berthing ships have mainly used shore power systems, and used shore power facilities to provide relatively cheap, high-quality, stable-frequency electricity to meet a ship's energy demands, thereby reducing the use of diesel generator groups and a ship's fuel consumption and operating costs, optimizing the atmospheric environment of the port area, and improving the competitiveness of the port/wharf.

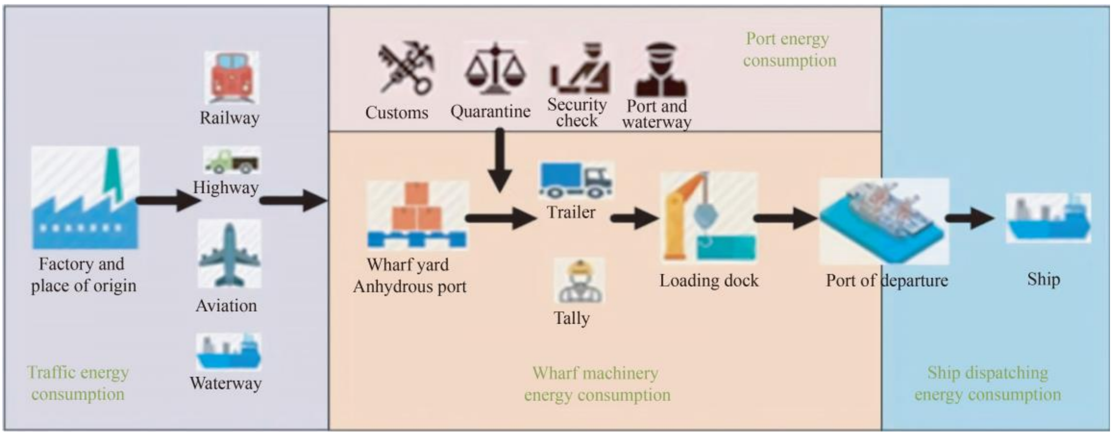

Fig. 1. Energy consumption mode of water transport infrastructure.

The energy demand of infrastructure is mainly provided by electricity, fuel, coal, LNG, and other energy sources. Out of these, electricity, coal, and fuel meet most of the demand. Electricity is mainly used for loading and unloading transportation machinery, storage security, and maintenance and management; diesel is mainly used for loading and unloading transportation machinery; and gasoline is mainly used for the official commuting and maintenance of vehicles.

In this study, the Tianjin Port was used as an example. As the largest comprehensive foreign trade port in northern China, the Tianjin Port has complete production and logistics facilities and sufficient statistical data. The energy consumption of Tianjin Port in 2018 was as follows [16]. (1) Electricity, fuel, and coal consumption accounted for approximately 36.08%, 37.90%, and 26.02% of the total energy consumption, respectively, where the energy consumption composition was relatively average. (2) The production energy consumption accounted for approximately 40.69%, and the non-production energy consumption accounted for approximately 59.31%, where the non-production energy consumption accounted for a relatively high proportion. (3) When the port handling capacity increased by 22%, the total energy consumption increased by 10.42% month-on-month, and the electricity consumption increased by approximately 32.11%, which exceeded the increase in handling capacity.

According to the functional positioning of different areas of the port, combined with the actual development planning of the port, the port's energy consumption loads mainly include the port/wharf's industrial load, public service load, commercial load, and living load, as shown in Fig. 2 [17]. Out of these, the port/wharf's industrial load has a continuous operation around the clock, has a large energy demand, and requires a high reliability. The energy consumption includes electricity, heat, and cold. With the upgrading of the related equipment, an increasing amount of the port's industrial equipment has been electrified in recent years (Table 2). The public service load and commercial load mainly take place in the daytime, and account for a small proportion of the port's load; hence, the requirements for the reliability of their energy supply are not high, and the type of energy used is mainly electricity. The main point of a living load is that its energy consumption sequence is opposite to that of other types of loads. The load's peak is generally at night, and the types of energy consumed mainly include electricity, heat, and gas.

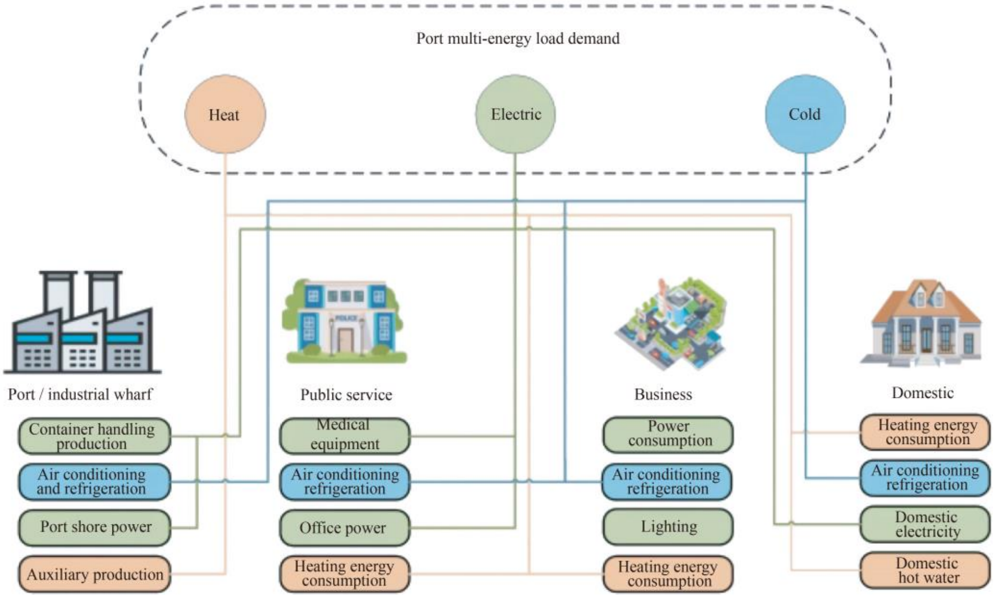

Fig. 2. Energy consumption of multi-energy loads in ports

Table 2. Clean energy alternatives for a port's industrial equipment.

Power system	Wharf crane	Orbital gantry crane	Tire-type gantry crane	Hoist	Yard truck	Straddle carrier	Automated guided vehicle	Automatic stacking crane
Diesel engine	√		√	√	√	√	√	
Electricity	√	√	√	√	√	√	√	√
LNG			√	√	√	√		
Hydrogen					√			

3 Development of the energy demand of waterway transport in China

3.1 Development of energy demand from the perspective of carbon emissions

To reduce greenhouse gas emissions, major countries and regions worldwide have actively formulated greenhouse gas emission reduction targets and action plans at different time points. Under the global climate change policy framework established by the United Nations, China and the European Union have taken the lead in proposing a roadmap for the reduction of carbon emissions [18].

From the perspective of carbon emissions, to achieve carbon peaking and carbon neutralization goals, ships' energy demand will gradually evolve from marine heavy oil and light oil to low-carbon fuels such as LNG, and finally to zero-carbon fuels, as shown in Fig. 3. The main forms of zero-carbon energy are hydrogen and ammonia. In the future, hydrogen and ammonia will gradually develop from gray hydrogen/gray ammonia, to blue hydrogen/blue ammonia and then to green hydrogen/green ammonia; that is, hydrogen and ammonia will be produced through renewable energy, which can actually achieve zero carbon emissions [19]. It can be seen that, based on the carbon emission aspect, the energy demand of waterway transport will evolve from high-carbon fuel to low-carbon fuel and eventually zero-carbon fuel.

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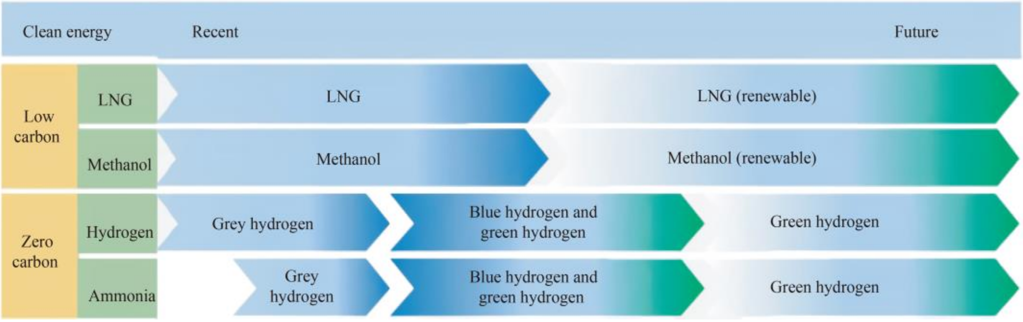

Fig. 3. Energy evolution from the perspective of carbon emission.

3.2 Development of energy demand from the perspective of energy supply

From the perspective of energy supply, the waterway transport's energy supply begins at the carrying tools' own energy, transforms to shore-based energy, and finally evolves into the partially self-consistent carrying tools' clean energy. In other words, the carrying tool is equipped with a hybrid power system or is supplemented by solar energy and wind energy and can use these to produce hydrogen/ammonia to provide energy for a ship, as shown in Fig. 4. (1) When the carrying tool (ship) provides power for itself through the carried energy, a special fuel oil tank needs to be set up to reduce the ship's cargo space, thereby affecting the operating economy of the carrying tool. The forms of energy carried by the carrying tool (ship) include fuel oil, LNG, hydrogen energy, and ammonia energy [20]. Out of these, the fuel oil can be filled through the berth and anchorage, meaning that it is transported to the berthing or anchored ship via the land tanker and oil supply ship, respectively. (2) Considering that the conventional internal-combustion engine-based power form will produce pollution and affect the air and water quality, the proportion of shore-based clean energy will be gradually increased. For ports, the available energy includes solar, wind, and tidal energies, which supply shore power to the ship when it is reaching port. Some small battery-powered ships can also be recharged with shore-based electricity to provide sailing power. (3) To achieve the carbon peaking and carbon neutralization goals, the application of clean energy including solar, wind, and wave energies to ships has become the key development direction of the carrying tool energy consumption model. The development and utilization of green energy can effectively reduce the energy loss caused by the ship's generator group or host and improve the energy utilization efficiency. Therefore, the self-consistent development model of clean energy has broad development prospects.

3.3 Development of energy demand from the perspective of energy quality

Currently, low-grade fossil fuels are mostly used in the waterway transport field. To enhance fuel utilization efficiency, technologies such as efficient utilization of clean energy, multi-energy complementary energy utilization, and waste heat recovery and utilization are booming. In the future, high-grade energy with high cleaning and conversion efficiency will be increasingly chosen as the first choice for waterway transportation. Therefore, from the perspective of energy quality, the waterway transport's energy demand will evolve from low-grade energy to high-quality energy.

The high-quality energy can usually be evaluated from the perspectives of thermodynamics and economics. In addition to the value of the fuel itself, the volume of the cabin occupied by the fuel will affect a ship's operating cost, and different types of fuel have little effect on a ship's dynamic performance. Therefore, different types of fuel can be analyzed from the perspective of energy density. In Fig. 5 there is a comparison of the volumetric energy density of marine fuel. An inland river voyage is relatively short, the frequency of its port calls is relatively high, and its fuel supply is relatively convenient. In addition to low-carbon fuels such as LNG and methanol, energy with a relatively low density can also be used. For ships with battery power, the use of lithium iron phosphate batteries is currently a relatively balanced technical route, and ternary lithium batteries will play a key role in the application of ships with high density demand [21]. For international ships, the voyage is longer, and the frequency of port calls is low; hence, the fuel supply is inconvenient for these ships and a fuel with a high energy density is required, resulting in the application of low-carbon fuel or ammonia fuel.

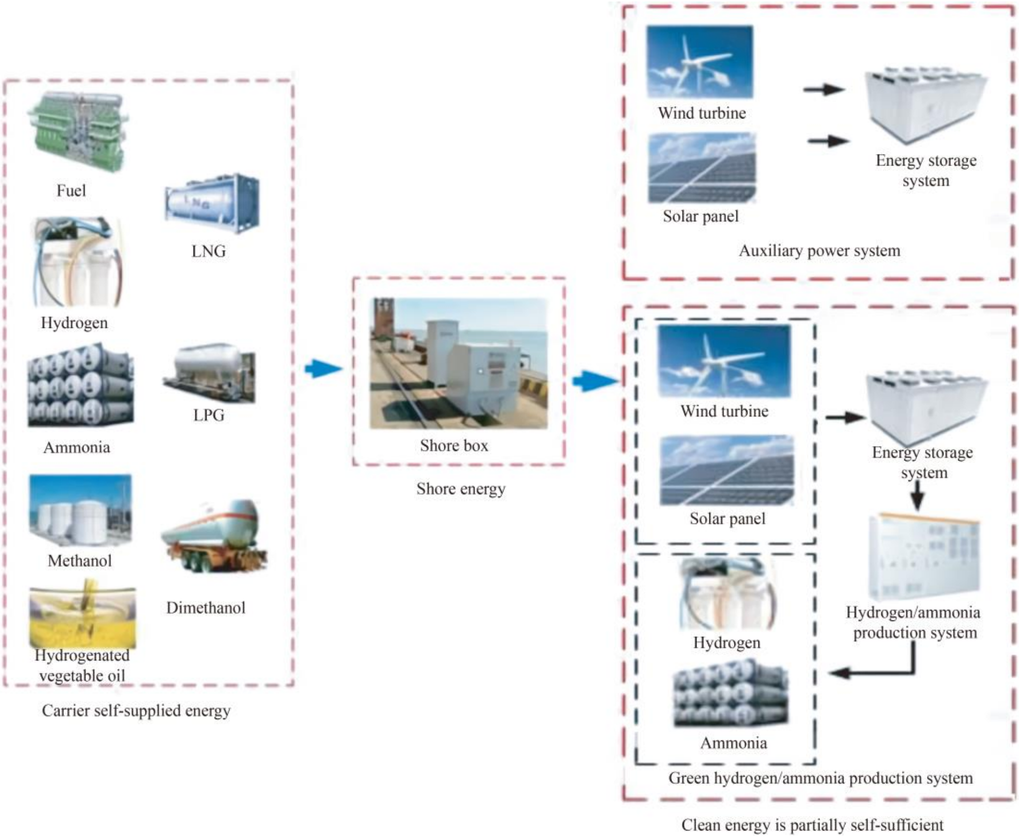

Fig. 4. Changing trend of water transportation energy supply.

Note: LPG is the abbreviation of liquefied petroleum gas.

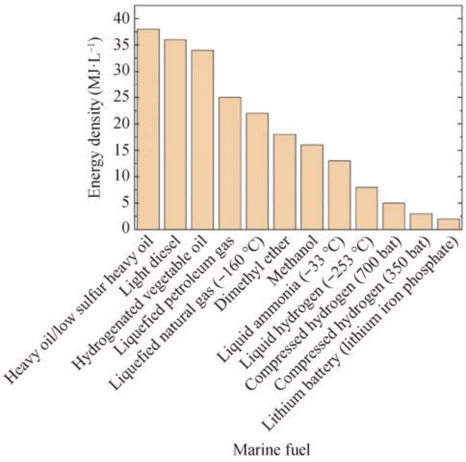

Fig. 5. Comparison of energy contained in unit volume of marine fuel.

3.4 Development of energy demand from the perspective of the energy utilization mode

The existing form of energy utilization is too singular, and the interaction and recycling between different types of energy have not been fully realized. Hence, future forms of energy utilization will evolve toward multi-energy comprehensive utilization.

Fig. 6 shows the development of energy demand from the perspective of the energy utilization mode. According to the conditions of the port hub, a “power generation + energy storage” energy development model of the integration of green energy and a grid power supply can be used to reduce the load of a city’s power supply system. The mechanical potential energy can be recovered by utilizing the characteristics of the port’s large-scale equipment operations and used in a nearby machine. By using green energy to electrolyze water to produce hydrogen, the fuel cell of a port’s mobile equipment can be supplemented with hydrogen energy. By using shore power technology, berthing ships can be provided with clean power. By using the space and resources of a ship to collect solar energy, wind energy and wave energy, a multi-energy integrated system can be formed to provide it with electricity. The excess electricity is used to produce hydrogen, which is used in the hydrogen power facility for ships. The comprehensive utilization of multi-energy can be realized by collecting vibration energy to provide power for sensing equipment.

In the future, the waterway transport industry will be committed to forming a multi-energy synergistic energy network, realizing the capture, conversion, and control of different energies, providing energy for carrying tools and infrastructure, and greatly improving energy savings and the reduction of emissions.

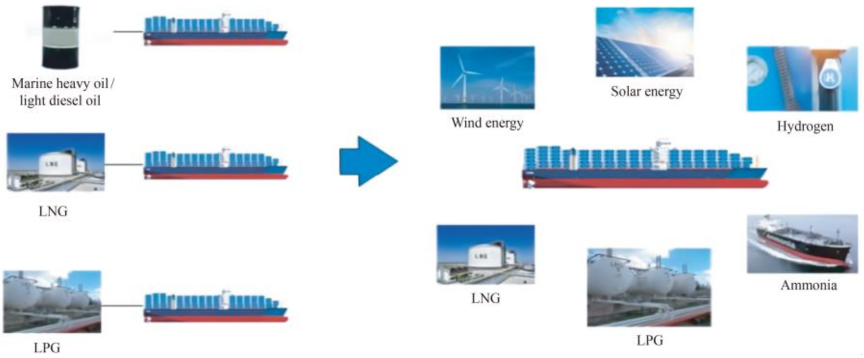

Fig. 6. Evolution trend of ship energy demand from the perspective of energy utilization mode.

4 Technical assessments of the integration of waterway transport and energy development

4.1 Natural endowments of waterway transport in China

According to the way wind resources are categorized in China, combined with the layout of ports and the high-level waterway network in the national three-dimensional transport network, it can be seen from a superposition analysis of the geographic information system that most inland river and coastal ports in China are located in one of the four types of wind resource areas. With regard to inland river high-level waterways, approximately 95% (~2.5×10^4 km) are located in the wind resource class IV area, approximately 3% (~740 km) are located in the wind resource class III area, and approximately 2% (~459 km) are located in the wind resource class II area. The wind resource partitions in which the high-level waterway network in China is located are shown in Table 3.

Table 3. Wind resource partitions where high-level waterway network in China is located.

Wind resource partition	Waterway
Class II zone	Lancangjiang–Mekong River waterway
	Jinshajiang–Yangtze River waterway
Class III zone	Part watershed of the Heilongjiang waterway
	Part watershed of Songhuajiang waterway
Class IV zone	Most of Songhuajiang waterway
	Yangtze River waterway
	Jialingjiang waterway
	Minjiang waterway
	Beipan River–Hongshui River waterway
	Youjiang–Xijiang Shipping Line
	Ganjiang waterway
	Minjiang waterway
	Hanjiang waterway
	Xiangjiang waterway
	Beijing–Hangzhou Grand Canal
	Shayinghe waterway
	Xinjiang waterway

In terms of the solar resource distribution, approximately 82% (~2.2×10^4 km) of high-level inland river waterways in China are located in the solar resource class III area, approximately 17% (~ 4547 km) are located in the solar resource class II area, and 1% (~318 km) are located in the solar resource class I area. The solar resource partitions in which the high-level waterway network in China is located are shown in Table 4.

As shown in Table 3 and Table 4, the natural endowments of high-level waterways in China are reasonable. In most of the country's waterways, the port has certain wind and solar resources and can develop new energy power generation and application, and its infrastructure assets have the potential for energy applications.

Table 4. Solar resource partitions where high-level waterway network in China is located.

Wind resource partition	Waterway
Class I zone	Hutuohe waterway
	South canal waterway
Class II zone	Heilongjiang waterway
	Songhuajiang waterway
	Jialingjiang waterway
	Minjiang waterway
	Lancangjiang–Mekong River waterway
	Jinshajiang–Yangtze River waterway
Class III zone	Yangtze River waterway
	Beipan River–Hongshui River waterway
	Youjiang–Xijiang Shipping Line
	Ganjiang waterway
	Minjiang waterway
	Hanjiang waterway
	Xiangjiang waterway
	Beijing–Hangzhou Grand Canal
	Shayinghe waterway
	Xinjiang waterway

4.2 Evaluation of the potential of the energy application of the waterway transport infrastructure assets

To evaluate the potential of the energy application of the waterway transport infrastructure assets, two typical application scenarios in waterway transport are calculated: the power generation potential of ports and waterways.

4.2.1 Assessment of a port's power generation potential

Taking the main coastal and inland river ports in the comprehensive three-dimensional transport network in China (excluding the data of Hong Kong port) as the research object, the potential of solar energy and wind energy that can be used by photovoltaic equipment and wind turbines in the port area is analyzed, respectively. The area, shoreline length, and average tidal range data of the port zone are mainly obtained from the data of the port planning and environmental impact assessment. If the relevant data of the planning and environmental impact assessment are outdated or missing, the estimation is based on the data of the port unit's handling capacity (calculated separately for coastal and inland river ports), port zone area, shoreline length, and port's handling capacity.

The power generation potential of the port is evaluated according to two utilization methods. The first method is to measure under optimistic scenarios, that is, to install photovoltaic equipment or wind turbines within 30% of the total area of the port. The second method is calculated in general scenarios, that is, laying photovoltaics or wind turbines within 10% of the total area of the port.

The installable capacity of solar energy is caculated based on the *Land Control Index of Photovoltaic Power Station Engineering Projects* released in 2015 [22]. On the premise that the total output efficiency of solar energy converted to electricity by an optoelectronic device is 20%, the installable capacity of solar energy of the Chinese port area under optimistic scenarios is approximately 29 623 MW, and the annual power generation is 5.74×10^9 kW·h. The installable capacity of solar energy in general scenarios is approximately 14 760 MW, and the estimated annual power generation capacity is 1.913×10^9 kW·h.

The installable capacity of wind energy is measured based on the *Construction Land Index of Power Engineering Project (Wind Farm)* [23], and the land use index for a single unit is calculated according to 3000 kW. In addition to considering the basic land use index of the unit, those constructing the wind turbine station also need to consider the land use conditions of the substations, power collection lines, management centers, and traffic engineering. Hence, the overall land use index was calculated as two times that of the basic land use index of the unit. Under the assumption that the wind energy is converted into electricity by electromechanical equipment and the total output efficiency is 30%, the installable capacity of wind energy of Chinese ports under optimistic scenarios is 2.2×10^8 kW, and the annual power generation is 1.39×10^{10} kW·h. Moreover, the installable capacity of wind energy in general scenarios is 0.7×10^8 kW, and the annual power generation is 5.21×10^9 kW·h.

4.2.2 Assessment of a waterway's power generation potential

The power generation potential of an inland river waterway is evaluated according to two scenarios. Scenario 1 is an optimistic scenario, where photovoltaic equipment or wind turbines can be installed on both sides of 20% of the high-level waterway. Scenario 2 is a general scenario calculation, where 10% of the high-level waterway can be laid with photovoltaic equipment or wind turbines. The installed capacity is calculated when the photovoltaic equipment or wind turbine is laid within 5 m on each side of the waterway under the two scenarios, respectively.

The installable capacity of solar energy is calculated based on the *Control Index of Land Use of Photovoltaic Power Station Engineering Projects*, and the calculation method is the same as that of a port. Under the assumption that the total output efficiency of solar energy that is converted into electricity by an optoelectronic device is 20%, the installable capacity of solar energy of inland river waterways in China under optimistic scenarios is 2321 MW, and the annual power generation is 4.5×10^8 kW·h. Whereas, the installable capacity of solar energy in general scenarios is 1160 MW, and the annual power generation is 2.3×10^8 kW·h.

The installable capacity of the wind energy of a waterway is caclulated based on the *Construction Land Index of Power Engineering Project (Wind Farm)*, and the land use index for a single unit is calculated according to 3000 kW. Under the assumption that the wind energy is converted into electricity through electromechanical equipment and the total output efficiency is 30%, the installable capacity of wind energy of inland river waterways in China under optimistic scenarios is approximately 2×10^7 kW, and the annual power generation is 1.43×10^9 kW·h. Furthermore, the installable capacity of wind energy in general scenarios is approximately 9×10^6 kW, and the annual power generation is 6.4×10^8 kW·h.

4.3 Energy demand of the waterway transport system in China

The energy demand of the waterway transport system in China has been rapidly increasing and the total amount of its energy consumption is larger than other industries' energy consumption in the country. By forecasting the total freight volume and total cargo turnover, the total energy consumption of different types of waterway transport systems in China is now estimated.

According to the *China Statistical Yearbook 2021* [24], the total energy consumption of the transport, warehousing, and postal and telecommunication industries in China in 2019 was 4.391×10^8 tce (~1.752×10^{11} kW·h), of which the consumption of gasoline was 6.25×10^7 t, accounting for 45.82% of national gasoline consumption. Diesel consumption was 9.87×10^7 t, accounting for 66.14% of national diesel consumption. Kerosene consumption was 3.69×10^7 t, accounting for 93.39% of the national total consumption of kerosene.

In 2019, the waterway freight volume in China was 7.47×10^8 t, and the cargo turnover was 1.04×10^{13} t·km. The volume and cargo turnover of inland river transport, coastal transport, and ocean freight are shown in Table 5.

Table 5. The basic situation of waterway transport in China in 2019.

Waterway transport type	Total cargo ($\times 10^8$ t）	Total cargo turnover ($\times 10^8$ t·km)
Inland river transport	39.13	16 302.01
Coastal transport	27.27	33 603.56
Ocean transport	8.32	54 057.47
Total	74.72	103 963.04

In 2019, the statistics of 123 highway waterway transport enterprises showed that the unit consumption of ocean and coastal freight transport enterprises was 0.48 kgce per 100 ton nautical miles, and the unit consumption per 1000 tons of a port was 0.21 tce [25]. In 2019, the basic situation regarding the energy consumption of waterway transport in China was that the energy consumption of ocean and coastal freight was approximately 2.27×10^7 tce (~1.85×10^{11} kW·h) and the ports' energy consumption was approximately 2.93×10^6 tce (~2.38×10^{10} kW·h).

According to the basic situation of waterway transport in 2019 and past historical data, the development of waterway transport in 2025, 2030, and 2035 is forecasted, and the results are shown in Table 6. It is estimated that the national ports' handling capacity will reach 1.66×10^{10}, 1.74×10^{10}, and 1.78×10^{10} t in 2025, 2030, and 2035, respectively [26]. Similarly, according to historical statistics, the energy consumption of ports in China in 2025, 2030, and 2035 are predicted, and the results are 2.83×10^{10}, 2.97×10^{10}, and 3.04×10^{10} kW·h, respectively.

Table 6. The predicted sizes of waterway transport in China in 2025, 2030, and 2035.

Year	Waterway transport type	Total cargo (× 10^8 t)	Total cargo turnover (× 10^8 t·km)
2025	Inland river transport	43.3	19 080
	Coastal transport	30.8	38 409
	Ocean transport	—	10 569
2030	Inland river transport	46	21 710
	Coastal transport	32.9	40 989
	Ocean transport	—	11 108
2035	Inland river transport	46.3	23 000
	Coastal transport	34.2	42 571
	Ocean transport	—	11 108

5 Development ideas and paths for integrating waterway transport and energy in China

5.1 Development principles

According to the carbon peaking and carbon neutralization goal and the energy structure of the current waterway transport industry, the integrated development of waterway transport and energy can be divided into three steps, namely short-term (2021–2025), medium-term (2025–2030), and long-term strategies (2030–2035). The short-term strategy is to develop wind and solar energies according to the natural endowments of coastal ports, increase the power density of chemical energy storage equipment and fuel cells by waterway carrying tools, and form a low-carbon energy (such as LNG and methanol) or oil (gas)/electric hybrid mode, combing renewable energy with energy storage modes. The medium-term strategy is to further promote ports and anchorages, electrify their power equipment and carrying tools, and realize the production, storage, and transportation of hydrogen energy. The strategy is to increase the use ratio of clean energy, realize the self-consistency of clean energy, and form a self-sufficient mode of the micro-grid. On this basis, the long-term strategy is to advance to the areas where the natural endowments of the coastal and inland rivers are deficient, realize grid connection of surplus electricity, and build a multi-level hub system that integrates waterway transport and energy. Specific development principles are as follows:

(1) Accelerating the diversification of a ship’s power system energy. According to the characteristics of waterway transport—mainly domestic inland river shipping supplemented by international shipping, inland river and coastal ships will gradually transition from multi-mode diesel (gas)/electric hybrid ships, such as LNG, diesel engine, and battery (super capacitor), to purely electric ships. International ships are to be mainly powered by ammonia and hydrogen fuel, using an internal-combustion engine and fuel cells as the main power source, and clean energy such as solar and wind energies as an auxiliary power source.

(2) Accelerating the transition of energy demand forms of ports and anchorages. Considering the economic cost and operational mode, the natural endowment of the infrastructure will be used to phase out old equipment with high energy consumption, high emissions, and low efficiency represented by diesel engines, and form an energy integration system based on primary energies such as solar, wind, wave, and tidal energy. While satisfying the shore power energy consumption of ports, anchorages, and ships, surplus electricity will be connected to an energy storage system or a grid, and the green energy will be used to electrolyze water to produce hydrogen, thereby realizing a green–economy integrated port-ship energy network.

(3) Accelerating the research on the key technologies of energy integration and the development of core equipment. Zero-carbon fuel represented by ammonia and hydrogen will gradually replace conventional fuel. Considering the feasibility and economy of the technology, it will be necessary to assess many core technologies, such as ammonia ignition, nitrogen oxide emission reduction, and high-density hydrogen storage. It will also be necessary to develop an energy storage system with batteries and supercapacitors as the medium to further increase energy density and reduce costs. Achieving breakthroughs in key technologies such as lightweight carrying tools, ship wind-assisted navigation, photovoltaic power generation, and waste heat recovery and utilization will help achieve zero carbon emissions.

(4) Accelerating the formulation of relevant industry technical standards and regulatory systems. To implement the carbon peaking and carbon neutralization goals, special funds will be set to conduct pilot subsidies for new energy powered ships, and the technical threshold will be continuously raised. The integration of waterway transport and energy will be guided through the technical standards of the new energy industry, to form a complete technical standards system. The *New Energy Ship Subsidy Standards* should be formulated, the *Port and Ship Shore Power Management Measures* should be improved, and the use of shore power by ships in port should be promoted. Finally,

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carbon tax policies and incentives should be implemented.

For the integration of waterway transport and energy in China, it will be necessary to establish a new development model in terms of energy structure, infrastructure, technical route, laws and regulations. Only by promoting a highly mature and highly feasible energy system and building a low-carbon and zero-carbon fuel structure can the effective integration of waterway transport and energy be promoted, thereby realizing the green, intelligent, and efficient development of waterway transport.

5.2 Development ideas

Based on the facts that the energy supply of waterway transport in China will shift from a low-carbon mode to a zero-carbon mode and its energy system will shift from low-efficiency to high-efficiency, the transition of the energy structure can be achieved. By optimizing the energy configuration of the waterway transport system, the coverage can be expanded, and the freight volume and cargo turnover can be improved. Through the integration of the waterway transport's infrastructure and new energy, a clean, efficient and intelligent novel waterway transport energy system can be built from the aspects of source, grid, load, and storage.

At the source level, it is necessary to diversify the application of the waterway transport's energy and increase the proportion of renewable energy (e.g., wind and solar energy) in waterway transport systems such as ports, ships, waterways, and anchorages. For different natural endowments, the economic benefits and development potential are evaluated, and the self-consistent rate of energy consumption and new energy penetration rate is improved. According to different ship types, routes, and functions, various resources are fully utilized, forming a new development model.

At the grid level, the port is used as a hub to strengthen the connection between ports, anchorages, waterways, and ships in a certain space. Considering the dispersion and volatility of the waterway transport energy system, the solar, wind, wave, and tidal energies are integrated with the grid, to diversify energy consumption forms, optimize the energy structure, and build a distributed micro-grid through the multi-point interconnection of the waterway transport energy system and multi-energy complementarity, finally forming a safe, smart, economic, green, and integrated micro-grid system before 2035.

At the load level, the load energy demand is arranged in the distributed micro-grid. Owing to the dispersion and volatility of the grid, the controllability of the load side of the waterway transport energy system is realized through the source, grid, and storage levels. A novel waterway energy system based on substations, energy storage stations, and distribution stations is developed to realize the power balance of the waterway transport energy system and improve the economy and stability of the load side.

At the storage level, power-type and energy-type energy storage techniques are applied to the waterway transport's energy. The energy storage system can release energy in a short time, compensate for the energy fluctuation in the grid, improve the quality of electricity, increase the utilization rate of electricity, and improve the ability to absorb primary energy (e.g., wind and solar energy). Finally, the coordinated operation of the system source, grid, load, and storage will be achieved.

In summary, the integration of waterway transport and energy in China needs to put forward specific application scenarios, clarify research paths, provide policy support, develop related industries, establish demonstration projects, and form a waterway transport and energy integration system that fits with the country's natural endowments.

5.3 Development path

To realize the carbon peaking and carbon neutralization goal, guided by the *Outline for Building a Strong Transportation Country* and relevant policy documents, the waterway transport and energy integration will gradually change from windy/light-abundant areas to less load/light-abundant /windy areas and coastal and inland river areas with less light and less wind, and from coastal ports to inland river ports, according to the principles of reasonable promotion and gradual promotion.

According to the calculation of the energy application potential of waterway transport assets in China, if natural endowments of wind and solar resources are fully considered, the clean energy utilization rates of the three stages in 2021—2025, 2026—2030, and 2031—2035 are calculated to be 20%, 40%, and 60%, respectively. According to the electrical load demand of the waterway transport system, and without considering the energy consumption of the carrying equipment, the self-consistent rates under optimistic scenarios in different stages are now calculated.

2021–2025: the penetration rate of new energy in China is no less than 15%, and the self-consistent rate of energy consumption is expected to be 17.3%. An energy supply mode that combines renewable energy power generation and hybrid energy storage is adopted, and priority should be given to the development of coastal ports and offshore windy and light-abundant areas. At this stage, energy consumption is still mainly based on the grid's power supply, supplemented by renewable energy power generation. The effect on energy savings and reducing emissions is expected to be significant, and the energy utilization efficiency will be gradually improved.

2026–2030: the penetration rate of new energy in China is no less than 35%, and the self-consistent rate of energy consumption is expected to be 33.1%. The active power output provided by combing renewable energy power generation and hydrogen/hybrid energy storage is further increased, and the remaining output is supplemented by the grid, which will be utilized significantly in inland river waterways, ports, anchorages, and water service areas with superior natural endowments and a smaller energy consumption load. Substantial progress in energy savings and emission reductions is expected to be achieved, and energy efficiency will be further improved.

2031–2035: the penetration rate of new energy in China is no less than 55%, and the self-consistent rate of energy consumption is expected to be 48.5%. By adopting the micro-grid mode and the mode that combines renewable energy power generation with hydrogen/hybrid energy storage, approximately 50% of the active power output can be provided, and grid connection of surplus power can be realized in a low energy consumption period. This mode can be gradually applied to the coastal and inland river waterways and ports with less wind and light. Great strides will be made toward realizing intelligent, green, highly efficient, and environmentally friendly power sources for waterway transport.

6 Recommendations for the integration of waterway transport and energy in China

6.1 Policy level

It is necessary to specify strategic positioning and strengthen the top-level design. The positioning of the waterway transport and energy integration should be clarified, the waterway transport and energy integration should be incorporated into the development strategy of national waterway transport, and research and top-level design of the integration should be conducted.

It is imperative to implement the integration concept and accelerate related construction. The idea and concept of waterway transport and energy integration should be promoted, renewable energy systems such as solar energy, wind energy, and hydrogen energy should be incorporated into the greening upgrades of waterways, anchorages, and ports and synchronized to relevant plans.

It is also necessary to strengthen demonstrations and guidance to achieve precise support. The waterway transport and energy integration should be promoted, and R&D enterprises, design units, shipbuilding enterprises, and ship owners should be encouraged to cooperate. The scope of any support should be studied and optimized, subsidy standards improved, and policy time limits extended. In addition, management regulations and standards should be improved to stimulate the enthusiasm of all parties.

6.2 Technical level

It is imperative to strengthen independent research and development and promote technological innovation. The independent innovation of the waterway transport and energy integration should be strongly promoted, comprehensively improving the performance of renewable energy systems, gradually developing key technologies in typical application scenarios such as waterways, anchorages, and ports, and promoting the development of the entire industry chain. The key technologies involved in the integration of waterway transport and energy are as follows.

6.2.1 Wind, solar, storage, and hydrogen multi-energy system integration mode and matching method

Different waterways have different natural endowments at their ports, ways of realizing the energy application of their transport assets, energy integration modes, and renewable energy penetration rates. Meanwhile, any port area has a large amount of equipment that consumes energy, with various electromechanical systems being coupled. The energy consumption is large and unpredictable, and the port areas' energy demand is random and different. Wind, solar, storage, and hydrogen energies have different operating characteristics and capacities. It is difficult to match the various energy sub-systems, and it is difficult to achieve an optimized overall efficiency. Hence, in the future, the wind, solar, storage, and hydrogen multi-energy system integration mode and matching method should be developed to provide technical support for the integration of waterway transport and energy.

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6.2.2 Energy capture and stability control of the multi-energy system

The capture and energy application of wind and solar resources of waterways and ports are the basis of the waterway transport and energy integration. Meanwhile, the different loads of port areas and the wide range of loads impose new requirements for the soft interconnection of source, load, and storage, power transformation, and a stable operation. Therefore, realizing the soft interconnection and stable control of the waterway–port–ship multi-energy system is a key problem to be solved in the development of the integration of waterway transport and energy.

6.2.3 Operational control and security technology of integrated large-capacity hydrogen production, injection, storage, supply, and utilization

Waterways and port areas have abundant natural endowments of renewable energy such as wind, solar, and hydro energy, but the uncertainty and randomness of these sources are large. Meanwhile, the operation of hydrogen-using equipment in the port area has a certain periodicity. Conducting “production–injection–storage–supply–utilization” full-chain hydrogen energy management and deployment under fluctuating hydrogen production conditions in a reasonable manner, and quickly realizing early warnings about safety and emergency responses under complex conditions are the key to ensuring the safe and efficient utilization of hydrogen energy.

6.2.4 Optimized operational control technology for a multi-energy accessed local grid for port areas

For the multi-energy system in port area where the grid is connected to large-capacity multi-type integrated energy, some multi-energy flow power supplies exhibit low damping or negative impedance characteristics, which will make the entire local grid system exhibit low inertia and weak damping characteristics, resulting in the deterioration of the anti-disturbance ability of the grid system. Therefore, it is necessary to study the control strategy for the stable operation of the multi-energy integrated system for the connection of the multi-energy system to the port area’s grid.

6.3 Talent training level

It is necessary to establish a distinct discipline system to promote the continuous development of the industry. With the sustainable development of the discipline as the goal, the national energy transport development plan and strategic requirements should be integrated, the characteristics of multiple disciplines must be synchronized, and the coordinated development of transport, electrical, and other power sources should be accelerated to facilitate the integration of waterway transport and energy, as well as production–education–research–application integration, thus establishing a comprehensive, distinctive discipline system.

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