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Review

Review of Development Trend of Transportation Energy System and Energy Usages in China Considering Influences of Intelligent Technologies

Shaobo Liu [1,2], Kang He [1,2], Xiaofeng Pan [1,2,*] and Yangyang Hu [3]

1 National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan 430070, China; shaobo@whut.edu.cn (S.L.)
2 Intelligent Transportation Systems Research Center, Wuhan University of Technology, Wuhan 430070, China
3 China Ship Development and Design Center, Wuhan 430064, China
* Correspondence: x.pan@whut.edu.cn

Abstract: With the continuous development of intelligent transportation technologies, new ways of energy usage in transportation continue to emerge, which puts forward new requirements for the planning and design of energy systems. However, comprehensive analyses on the characteristics of transportation energy systems and the development trend of energy usage patterns brought by intelligent technologies have rarely been carried out so far. This paper explores this subject by reviewing the recent development and utilization of intelligent technologies in the transportation system and its impacts on energy usage. This review is carried out from three aspects, covering the representative intelligent transportation and energy technologies on vehicles, infrastructures and systems. The scope is limited within road, railway and water transport domains, with a focus on the recent developments in China as a representative. In terms of vehicles, the development trend of the power systems for new energy vehicles, the characteristics of energy usages in electric vehicles and the effects on energy saving and emission reduction are summarized. In terms of infrastructures, new technologies on smart road, smart port, intelligent railway energy system and the usage of clear energy on electric grid for transportation are reviewed, with the consideration of their potential influences on energy usages and the energy consumption characteristics of typical facilities also being analyzed. As for the transportation system, this review has focused on intelligent and connected transportation systems, train control and autonomous systems, and intelligent shipping system, with the emphasis on the energy saving and emission reduction effects of applying these intelligent technologies. The overall development trend of the transportation energy system is then analyzed based on the above materials, in particular, the future energy usage patterns in transportation system are given and the major challenges and obstacles approaching the future scenarios are also identified.

Keywords: intelligent transportation; green transportation; transportation energy system; energy usages for transportation; new energy; energy saving and emission reduction

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1. Introduction

The rapid development of heavy industry in human history has brought substantial life quality improvements, but people's living environment is also faced with a major challenge due to global warming rising from the massive burning of fossil fuels such as coal and oil [1]. As an important source of carbon dioxide, transportation is one of the largest sectors of greenhouse gas emission and energy consumption, making it crucial to develop clearer and greener transportation industry. In fact, the intelligence development and green development of transportation system are always complementing each other. On the one hand, the intelligence of transportation is able to promote the integration of information in transportation, continuously improve its efficiency, and thus reach an interconnected, information sharing and collaborative transportation environment [2]. On this basis, a new sustainable transport pattern could be formed by making full use of new energy, improving energy utilization efficiency, and reducing energy consumptions and pollution emissions. China, as one of the representative countries with very fast development in both intelligent transportation as well as its energy system and economic and social development, has transportation that as an important part of society is continuously expanding the scale of its energy consumption. After the strategic goals of carbon peaking and carbon neutrality ("dual carbon") being proposed by the government [3], the development of new transportation energy system with clean energy as the core has become particularly urgent.

Driven by the demand for sustainable development, the development of intelligent and green transportation system has been experiencing a vast transferring stage from its initial status to the upgrading development stage all around the world. In turn, the current transportation energy system is also about to experience an evolution. In recent years, the intelligent transportation planning strategies of those relevant departments of Chinese government and some major developed countries or regions are listed in Table 1. Since the focus of this paper is China, more referred documents of China have been given in Table 1 at the departmental level, while for other countries or regions, only the most important or relevant ones have been listed.

Table 1. Strategical development planning of intelligent transportation in China and other developed countries or regions.

Countries (Regions) or Departments	Release Date	Document Title
UK	2018 July 2021 February 2019	Digital Railway Strategy [4] Decarbonizing Transport, a Better Greener Britain [5] Maritime2050 [6]
Japan	February 2020	Smart Tokyo [7]
Germany	August 2016	German Federal Transport Infrastructure Plan 2030 [8]
USA	March 2020 2022	Intelligent transportation systems (its) joint program office: strategic plan 2020–2025 [9] U.S. DOT Strategic Plan [10]
EU	December 2020	Sustainable and intelligent transport strategies [11]
Ministry of Transport of the People's Republic of China	May 2018	Guidelines on the Development of Intelligent Shipping [12]
China State Council	September 2019	Outline on the Construction of a Strong Transportation Country [13]
China Railway Group Corporation	September 2019	Intelligence Development Trend of High-speed Railway [14]
China Development and Reform Commission	February 2020	Strategy for the Innovative Development of Intelligent Automobiles [15]
Ministry of Transport of the People's Republic of China	August 2020	Guidelines on Promoting the Construction of New Infrastructure in the Transportation Sector [16]
Ministry of Transport of the People's Republic of China	December 2020	Guidelines on Promoting the Development and Application of Road Transport Driving Technology [17]
China State Council	February 2021	Guidelines on Developing Comprehensive Transport Network [18]
Ministry of Industry and Information Technology	July 2021	Opinions on Strengthening the Management of Access to Intelligent Connected Vehicle Manufacturing Enterprises and Products [19]

From the above official documents of transportation development strategies released by China and other developed countries or regions, it can be seen that the transportation departments of various countries are actively exploring the application of intelligent technologies as well as new forms of energy usages in transportation system, aiming to form a sustainable intelligent transportation system. In addition, all countries have released the plan of key deadlines and tasks to be completed for achieving transportation intelligence, which generally present four characteristics: (1) To promote the integration of new technologies such as artificial intelligence (AI), big data and blockchain with the transportation industry; (2) intelligent driving technology is the most important direction of transportation intelligence; (3) intelligent facilities and infrastructures for transportation are becoming the hotspots of transportation intelligence research; (4) the integration of transportation and energy systems has become an inevitable trend.

With the continuous promotion of the transportation intelligence development, the current carbon emission structure of energy system in each sector in China is shown in Figure 1. The transportation sector currently accounts for 13% of carbon emissions from energy activities, second only to the energy supply and industrial production sectors. Profound adjustments will be made in terms of clean energy substitution, transportation restructuring, and transportation technology innovation [20].

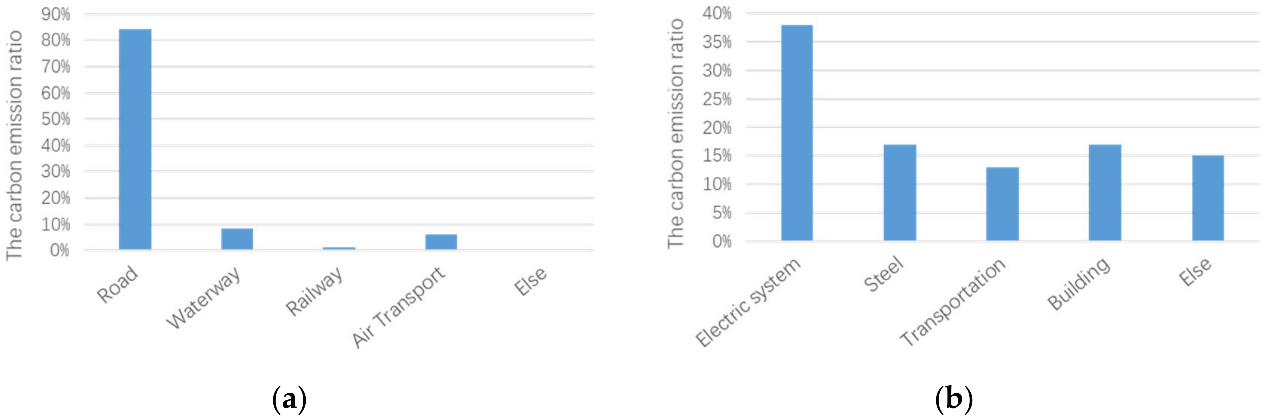

Figure 1. Carbon emission composition in China by industry sectors and transport modes. (**a**) The carbon emission ratio of each transport mode. (**b**) The carbon emission structure of each sector.

Considering the "dual carbon" strategical goal of the Chinese government, the transportation industry is under huge pressure to reduce carbon emissions. In order to minimize carbon emission, it is crucial to promote the development of new transportation energy systems based on clean energy and efficient energy utilization. As transportation electrification and usage of clean energy has prevailed, some inherent contradictions during the development of transportation energy system have emerged. It is important to further analyze the joint influences of factors that may influence the development trend of the current transportation energy system. These analyses can provide fundamental theories for the coupling development of clean energy system and transportation electrification. Potential benefits may include assessments of the efficiency of clean energy utilization with the existing transportation infrastructure, and the probable approaches of achieving energy usage self-consistency by exploring potentials of the transportation system itself.

At the same time, focus will be placed on new energy, intelligent connected vehicles (ICVs), new energy utilization of railway systems, new energy ships, intelligent shipping systems and other frontiers in the development of industries and equipment in order to achieve the organic combination of transportation intelligence and energy self-consistency and provide a reference direction for the planning and design of China's transportation energy system.

This paper aims to investigate the changes in the energy usage scenarios and the changes in the transportation energy system with the application of intelligent transportation technologies, through the analyses of the development trend of transportation intelligence and the characteristics of energy use, the efficiency of energy saving and emission reduction, etc., affected by the applications of new intelligent technologies. Considering the development demand of transportation intelligence and transportation energy self-consistency, the development trend of transportation energy system and transportation intelligence is analyzed through literature review and theoretical analysis from three aspects, namely vehicles, infrastructure and intelligent driving system, and in three types of transport modes, namely road transport, railway transport and water transport (covering inland waterway transport and maritime transport). The current situation and development trend of intelligent technology, new energy application technology and energy efficiency optimization technology in transportation system and corresponding energy system are summarized and analyzed. Focus will be placed on new energy vehicles, intelligent infrastructures, intelligent driving systems and technologies involved that may affect energy usage. The characteristics of the new technologies of intelligent transportation and the energy system including their influences on energy saving and emission reduction, the development trends of energy usage scenarios considering intelligent technologies, as well as the development trends of transportation energy system are analyzed and discussed.

2. Intelligent New Energy Vehicles

With the rapid development of new energy and intelligent vehicles, the ecological chain of the transportation system will be overturned in all aspects. The existence of vehicle changes from a manual controlled mechanical product to an intelligent product controlled by electronic information system. Meanwhile, with the release of the "carbon peaking" and "carbon neutrality" plans, the integrated development of transportation and energy systems becomes an inevitable trend in which the penetration rate of new energy usages in the total energy usages for transportation is an important indicator for the development of transportation energy systems. This section summarizes the characteristics of different power systems of new energy vehicles, reviews the current status of new technologies applied to these vehicles considering its energy saving and emission reduction abilities, and then analyzes the future development trend of new energy vehicles and the potential challenges.

2.1. Development Trend of Power Systems for New Energy Vehicles (NEVs)

According to the Ministry of Public Security of China [21], China National Railway Group Co., Ltd. (Beijing, China) [22] and the Ministry of Transport [23], by September 2022, national car ownership exceeded 315 million, and the ownership of NEVs was nearly 11.49 million, with the percentage of NEVs reaching 3.7%. China's national railway electrification rate is 75.4%, with 21,000 locomotives including 13,500 electric locomotives and 7400 internal combustion locomotives. As for the waterway, China has 125,900 water transport vessels, with a net carrying capacity of 284,326,300 tons and 857,800 passengers. It is obvious that the usage of new energy in the three modes of transport, namely road, railway and waterway, has huge development potential.

The relevant government departments also put emphasis and support the development of NEVs, and take "pure electric vehicles" as the development route of new energy vehicles, starting early from 2011 [24]. In terms of the road transportation, according to the latest data, the ownership of battery electric vehicles (BEVs) in China is 10.45 million, which has become the major type of NEVs, showing a high growth rate. In terms of water transportation, in December 2021, China's Ministry of Industry and Information Technology officially released the "14th Five-Year Plan" for Industrial Green Development [25], proposing to accelerate the development of green and intelligent ships and other strategic emerging industries to help the magnificent transformation of the ship industry. As for railway transportation, the electrified railway has always been the focus of railway development since Chinese government's 12th 5-Year Plan.

NEVs have the characteristics of low emissions, high energy efficiency, low maintenance costs and a comfortable ride experience. It is clear that developing NEVs is an inevitable trend and the percentages NEVs have become an important indicator for the development of vehicles. In addition, one of the core components of developing NEVs is the energy storage units [26]. Currently, the most commonly used energy storage unit for NEVs is power battery, in addition to ultra-capacitor (UC), flywheel and other energy storage devices. As an energy storage unit, a battery consists of one or more chemical cells that convert stored chemical energy into electrical energy for vehicles. The most common types of batteries on the market today are lead-acid batteries, lithium batteries and nickel-based batteries. Table 2 presents the characteristics of those three types of batteries such as service life, energy efficiency and manufacturing cost and energy density.

Table 2. Most commonly used energy storage battery types and their characteristics [27].

Battery Type	Service Life	Energy Efficiency (%)	Manufacturing Cost (USD/kWh)	Energy Density (Watt h/kg)
Lead-acid Battery	3–15 years	70–90	20–200	30–50
Nickel-based Battery	15–20 years	50–90	150–2400	30–70
Lithium-based Battery	~15 years	80–95	100–2000	90–190

2.1.1. Lithium Ion Battery Vehicles

Among the above three types of batteries, lithium-based batteries are the mainstream in the market. This type of batteries occupies a remarkable share in the booming vehicles market [28], and is still regarded as the most feasible solution in the battery industry considering its excellent power performance, high energy efficiency, long cycle life and feasible cost control, etc. [29,30]. Lithium-based batteries can be further divided into manganese acid lithium batteries, lithium iron phosphate batteries (LFP) and ternary lithium batteries (NCM) according to different anode materials. Currently, the ternary lithium and lithium iron phosphate batteries used in NEVs on the market in China are mainly manufactured by several new energy companies including LG New Energy, CATL, Panasonic, BYD and others.

In addition to the static charging mode of electric vehicle (EV), the dynamic charging mode while driving can completely solve the mileage concerns of static charging [31]. In fact, dynamic conduction power technology has been applied in electrified railway, which fully proves that the principle is technically feasible [32]. However, the application on road will undoubtedly cause huge cost problems. Therefore, in order to solve the cost problem of this charging method, Ali et al. [33] also proposed a way to charge the EVs by installing power collection units (PCUs) on the wheel hubs. In addition, Alstom [34], Honda [35], Siemens [36] and other companies have also carried out researches in this direction, and achieved promising results, but the current technological maturity is not enough to realize industrialization.

As for railway locomotives, the feasibility study [37,38] on chemical batteries as locomotive traction power proved that locomotives with chemical battery can be an alternative to internal combustion locomotives. Currently, applications of locomotives with chemical batteries are already available on the market. The most widely used locomotive batteries are lithium titanate (LTO) battery, lithium iron phosphate (LFP) battery and other lithium batteries. However, due to the long mileage and high load of railway locomotives, it is still difficult to meet the power demands for using batteries alone, so chemical battery-powered locomotives are currently serving for short-range rail transportation such as subways [39], while the long-range railway lines are mainly driven by hybrid locomotives with power batteries combined with internal combustion engines. As new energy storage components such as solid-state lithium batteries and sodium ion batteries continue to mature, the safety, power and energy density of energy storage units will be further advanced, leading to continuously improving of the traction of locomotives, range and other performance. In the near future, chemical battery-powered locomotives will step into our lives.

As for water transportation, although using batteries as the main power source for ships is also one of the development trends, the application in real scenarios is still rare due to reasons such as long charging time and low supported mileage range. The main application scenarios of using pure electric ships are short ranged inland waterway transport where the demand for power can be satisfied by batteries.

Additionally, of the outstanding performance of lithium ion batteries, other candidate ions batteries such as zinc ion, sodium ion, magnesium ion and aluminum ion are also undergoing active research and development, among which sodium ion's development [40] in the battery of automobiles may be faster. In order to solve the short battery life cycle problem, Yaïci W et al. [41] and González A et al. [42] proposed a hybrid energy storage system of ultra-capacitor and battery for application in NEVs.

2.1.2. Fuel Cell Battery Vehicles

A fuel cell power system uses materials such as hydrogen as the energy source and replaces the chemical cell with a fuel cell. Fuel cells are more efficient than internal combustion engines and therefore consume less energy [43]. Proton exchange membrane full cell (PEMFC) is the most widely used type of fuel cell batteries today. It is featured as zero emission, high power density and flexible mileage range and therefore is regarded as one of the most promising battery technologies besides lithium ion. However, its drawbacks such as complex hydrogen storage technology, high cost and safety problems have hindered the rapid development of fuel cell vehicles. The representative cars equipped with fuel cell batteries are Toyota Mirai II, Hyundai Nexo and Riversimple Rasa.

Among other metrics, when used as a locomotive power source, fuel cells can replace internal combustion locomotives for fulfilling transport tasks during non-electrified railway sections. Therefore, research on hydrogen fuel as locomotive power is currently a hot research topic, and it has been proven both in academia and in industry that it is feasible to use hydrogen gas directly into the engine as fuel or to use fuel cells to generate the electricity for locomotives. Different kinds of fuel cell locomotive power systems such as hydrogen fuel cell "extended-range" hybrid locomotives [44], internal combustion engines with hydrogen direct injection or injection ignition features [45], and fuel cell/ultra-capacitor hybrid trams [46], etc., have been studied and verified.

Adopting a fuel cell as the power system [47] of ships is still rare. Existing cases are mainly for small passenger ships and sightseeing ships, which usually use PEMFC together with a lithium battery, internal combustion engine or other renewable energy source in a hybrid power architecture. However, the overall trend is that projects on hydrogen fuel cell ships are still continuing worldwide, which indicates that hydrogen fuel cell ships are also a promising direction and will continue to spread in future.

2.1.3. Hybrid Electric Vehicles

Although battery electric vehicles are playing an important role in approaching "dual carbon", using batteries only also has significant technical disadvantages such as insufficient mileage range and long charging time, etc. Considering this, the hybrid electric power system is a perfect solution since hybrid electric vehicles (HEVs) are free from mileage range and charring time problems. HEVs are usually divided into Series Hybrid Electric Vehicle (SHEVs), Parallel Hybrid Electric Vehicle (PHEVs) and Combined Hybrid Electric Vehicle (CHEVs) [48], whose power transmission logics can be shown schematically in Figure 2.

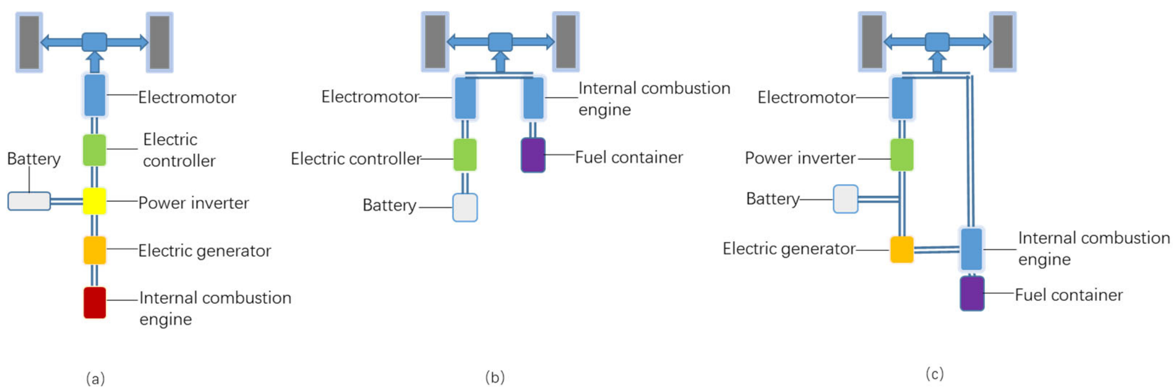

Figure 2. Schematic Diagrams of Power Transmission Logics of HEVs. (**a**) SHEVs. (**b**) PHEVs. (**c**) CHEVs.

As for railway locomotives, in addition to the power system configuration of battery + diesel unit, there are also hybrid power systems of hydrogen fuel, power battery and diesel unit. In addition to solving the above-mentioned mileage range and charging problems, the hybrid power system can also replace the internal combustion locomotive in the non-electrified railway sections. Additionally, the hybrid power system with battery and internal combustion engine can be directly transformed from the existing internal combustion locomotive. Therefore, the hybrid power locomotive is also one of the promising directions of future railway energy system development, and can also be seen as the transition product from the internal combustion locomotive to chemical power battery locomotive or hydrogen fuel cell locomotive.

At present, the power source of most of the ships are still carbon-based fossil fuel energies such as diesel, LNG, bioethanol, methanol, LPG and gasoline [49]. However, usage of many forms of new energy on ships are expanding very quickly including the forms of electric batteries and hydrogen fuel cells as the main power source, and also natural renewable energy such as solar and wind power as auxiliary power source. The characteristics of energy usages for different types of power sources on ships including battery electric power, hydrogen fuel cell, solar power, wind power and other alternative fuels of diesel (natural gas), etc., are summarized in Table 3 [50].

Table 3. The characteristics of energy usages for different types of power sources on ships.

Power Source Types	Characteristics of Energy Usages
Battery Electric Power	Zero emission, high energy efficiency, simple power system structure, rich raw materials, low energy storage density, high safety requirements, difficult for shore-based charging
Fuel Cell	Powerful battery, stable power supply, reliable battery safety, high energy efficiency compared to diesel engines, high technical difficulty, high cost and dangerous fuel storage
Solar Energy	Adequate energy, zero pollution, continuity of power supply, high energy storage requirements, low energy conversion efficiency and greatly influenced by environmental factors
Wind Energy	Adequate energy, zero pollution, continuity of power supply, high energy storage requirements, low energy conversion efficiency and greatly influenced by environmental factors
Alternative Fuels (LNG, biofuels)	Low carbon emission (compared to fossil fuels), and can be used as a transitional substitute for fossil fuels

It is easy to see from the energy-using characteristics of mainstream ships' power sources that battery electric power and fuel cell power are the main trends in the development of future ship power. However, due to the current technical defects, the lower energy density of these power sources has difficulty to meet the energy demand of heavy-duty ships if use batteries alone. Additionally, renewable energy sources such as solar energy and wind energy are also affected by the environment and can only serve as auxiliary power, so alternative fuels (LNG, biofuel, etc.) ships and hybrid electric ships are the main force in the transition period to completely clean energy ships.

2.2. Energy Usages Characteristics in Electric Vehicles and the Green Effects

Based on the above analyses of characteristics of power system for NEVs, it can be seen that the overall development trend of the current power system for vehicles is that the power sources of the current vehicles mainly include chemical batteries, hydrogen fuel cells and hybrid power systems, while alternative fuels such as LNG, biofuel and methanol can be used as the power sources for the transition stage from traditional vehicles to NEVs. Additionally, renewable energies can also be used as supplementary power sources. The utilization of multiple new energy sources achieves the effect of energy saving and emission reduction, and also promotes the integration of transportation and energy system, so the manufacturing and application of new energy products become a hot research topic. The following is a detailed summary on the application of new energy sources on three types of vehicles and an analysis on the energy saving and emission reduction effects of the application of new energy sources.

2.2.1. Chemical Battery Vehicles

As mentioned previously, the market share of ternary lithium battery and lithium iron phosphate battery for new energy vehicles worldwide are mainly held by companies such as LG New Energy, CATL, Panasonic and BYD etc. Table 4 lists the key parameters of the representative batteries from those companies and the vehicle models they have been applied on.

Table 4. Key parameters of representative lithium batteries and the corresponding vehicle models.

Battery Type	Battery Capacity (kW/h)	Energy Density (Wh/kg)	Mileage Range (km)	Vehicle Models Applied on
BYD Lithium Iron Phosphate Blade Battery	71.7–85.4	140–150	505–715	BYD Han, Song PLUS, etc.
LG Ternary Lithium Battery	78.4	168	660–675	Tesla model3, modelY, etc.
CATL Ternary Lithium Battery	84.8–120	165–206	605–849	Audi, BMW, Mercedes-Benz, VW, Red Flag HS9, etc.
CATL Kirin Cell	140	200	1032	ZEEKR 001
CALB	98–144.4	160–205	702–1008	XPEV G9, P7, AION LX, etc.
Panasonic Ternary Lithium Battery	100	–	664–715	Tesla modelS, modelX, etc.
CATL Ternary Lithium Battery	100	185.4	675–710	NIO ET7, ET5, etc.

Chemical battery-powered locomotives may be used as supplementary solutions for non-electrified railway sections, but are still very rare so far due to issues such as mileage range and charging. They are mainly used for subway or short-distance travel. In 2022, Alstom, Deutsche Bahn and the government of Baden-Württemberg and Bavarian states cooperated and successfully completed a trial run of a locomotive equipped with batteries [51]. Other applications of chemical battery-powered locomotives also include applications on the subway. However, the main power architecture for locomotives using batteries is still a hybrid power system. In 2011, CRRC Ziyang Co., Ltd. (Ziyang, China) in China completed research on a hybrid power locomotive model named CKD6E5000. The locomotive's power system is a combination of a 641 kW high-speed diesel engine and a 280 kW lithium iron phosphate battery pack. Since then, the research and development of hybrid electric locomotives has attracted more and more attention, among which some of the representatives have been presented in Table 5.

Table 5. Representative hybrid electric locomotive models and specifications [52].

Model Name	CKD6E5000	HXN6	FXN3B	CKD6E6000
Manufacturing Year	2011	2015	2018	2017
Manufacturer	CRRC Ziyang Co., Ltd.	CRRC Ziyang Co., Ltd.	CRRC Dalian Co., Ltd. (Dalian, China)	CRRC Ziyang Co., Ltd.
Battery Energy Capacity (kW·h)	400	1100	185	550
Battery Type	Lithium Iron Phosphate	Lithium Iron Phosphate	Lithium Titanate	Lithium Iron Phosphate
Initiating Traction Force/Kn	350	560	560	480
Maximum Speed(km/h)	80	100	100	80

In terms of pure electric ships, although the demand is less than that of automobiles, according to the report of "2015–2024 Global Market Report on Electric Ships, Small Submarines and Automated Underwater Ships" published by Research and Markets [53], the global electric ship market is expected to reach $7.3 billion by 2024. Therefore, major battery manufacturers have also launched one after another, and a number of companies have obtained the lithium battery product certification issued by CCS including CATL, CALB, EVE, Gotion High-tech, SUNWODA, REPT, Ganfeng Lithium, Lishen, Great Power, Xingying Tech, BYD, etc., of which the specifications of the representative models of power batteries for ships produced by each battery manufacturer is shown in Table 6.

Table 6. Specifications of representative models of power battery and applications on ships.

Ship Type	Ship Name	Battery Capacity (kW/h)	Battery Type	Battery Manufacturer
Cruise Ship	Greater Bay No.1 Junlv Cruise Dianjing Cruise	1885 3400 1200	Lithium Iron Phosphate Lithium Iron Phosphate Lithium Iron Phosphate	CATL [54] EVE [55] CALB
Towboar	Yungang Electric Towboat No.1	5000	Lithium Iron Phosphate	EVE [55]
Public Serice Vessel	Sea Patrol 12,909	2520	Lithium Iron Phosphate	CATL [54]
Cargo Boat	Puffer Boat	2400	Ultra Capacity+Lithium Battery	Guangzhou Development Ruihua New Energy Electric Boat Co., Ltd. (Guangzhou, China) [56]

2.2.2. Hybrid Electric Vehicles

The current market of HEVs in China is growing rapidly, with a cumulative growth of 45.7% in 2022 for HEV models and a year-on-year increase in penetration rate from 0.8% to 3.3%, among which plug-in hybrid electric models are growing at a much faster rate than other models [57].

In addition to HEVs, fuel cell electric vehicles (FCEVs) also occupy a certain market share. PEMFC, as the most widely used fuel cell, is popular for its zero emissions, high power density and flexible working range. However, due to the rapid development of EVs and the safety problem of hydrogen fuel, FCEVs has not been developed as much as that of BEVs and HEVs.

As for railway locomotives, in addition to the above-mentioned HEVs, with the rapid development of the whole industry chain of hydrogen energy, its role in the railway domain is becoming more and more important. More than a dozen countries have started research on hydrogen fuel cell locomotives, and research on hydrogen fuel cell hybrid power system for railway has become a hot spot. The Representative Research and Development Projects on hydrogen fuel cell locomotives around the world is shown in Table 7.

Table 7. Representative research and development projects of hydrogen fuel cell batteries worldwide.

Project Name	Institution	Highest Speed (km/h)	Delivery Date	Country
Flirt H2	Stadler US	130	2024	USA [58]
Fuel cell/ultra capacity locomotive	CRRC Tangshan Co., Ltd. (Tangshan, China)	70	2016	China [59]
CoradiaiLint	Alstom	140	2021	Germany [60]
Breeze	Alstom	140	2022	UK [51]
FV-E991	JR East	100	2024	Japan [61]
Mireo Plus H	Siemens	160	2024	Germany [62]

The current power sources used hybrid power system for ships may include various types including battery electric power, hydrogen fuel cells, solar, natural gas, wind energy, diesel or other alternative fuels. However, with the increasing capacity and energy density of power cell packs, the future trend is that it is still dominated by clean energy sources such as battery electricity and hydrogen. However, in the transition period to the development of battery electricity ships and fuel cell ships, hybrid electric ships and alternative fuel ships are the focus. Table 8 shows the current representative hybrid electric ships and their key information around the world.

Table 8. Representative hybrid electric ships and their key information worldwide.

Ship Type	Battery Type	Energy Type	Power/Kw	Country	Reference
Submarine	PEMFC PEMFC	Hydrogen Bioethanol	30 300	Germany/Italy Germany	[63,64] [65]
Warship	PEMFC	NATO-F76	25	Netherlands, Germany, etc.	[66]
Yacht	SOFC	Diesel, LPG	250	EU	[67]
	PEMFC/Lithium Battery	Hydrogen, Electricty	70 kw Hydrogen Fuel Cell and 86 kWh Lithium Battery	China	[68]
	PEMFC	Hydrogen, Solar Energy and Wind Power	126	Japan	[47]
	HT-PEMFC	(MeOH)	120	Germany	[69]
Inland Waterway Operating Vessel	MCFC	LNG	330	Norway	[70]
Research Vessel	PEMFC	Hydrogen	4	Japan	[63]
Cargo Boat	SOFC	MeOH	20	Italy	[71]

2.2.3. Energy Saving and Emission Reduction Effects of New Energy Vehicles

The role of NEVs in reducing energy consumption and carbon emissions has also attracted much attention in transportation energy system development. This is also an important factor that determines the future directions of NEV development. Jiang et al. analyzed the energy consumption and carbon emission impact of Evs [72]. The study showed that the energy consumption of conventional internal combustion engine automobiles is the largest over the whole life cycle with the same vehicle production technology, while the energy difference between BEVs and plug-in hybrid electric vehicles (PHEVs) is not significant. The total energy consumption of BEVs is 42% lower than that of conventional internal combustion engine automobiles, and the case of PHEVs is similar to that of BEVs.

Xia et al. [73] analyzed the relationship between the driving behavior of electric automobiles drivers and energy consumption. The study showed that driving behavior affects the energy consumption level of new energy automobiles, with smooth driving corresponding to lower energy consumption. At the same time, there are also studies that have explored the energy saving technology of EV. Based on passenger cars, commercial buses, light commercial buses and heavy commercial buses, Xia et al. [74]. evaluated the efficiency and cumulative cost of energy saving and emission reduction in NEVs in China as shown in Table 9.

Table 9. Unit emission reduction efficiency and cost of new energy vehicles in China [74].

Power System Type of Vehicles	Unit Cost of Emission Reduction (CNY)				Emission Reduction Rate (for Fuel Vehicle)/%
	Passenger Cars	Commercial Buses	Light Commercial Buses	Heavy Commercial Buses	
BEVs	1408	1028	1717	1538	100
PHEVs	2006	1210	2961	824	60–63
FCEVs	4223	2412	5887	948	100

By comparing the data in Table 9, it can be seen that the unit emission reduction cost of BEVs and PHEVs is much lower than that of FCEVs. Currently, the mainstream FCEVs are hydrogen FCEVs, so the manufacturing cost of fuel cells and the cost of producing and storage of hydrogen need to be reduced in the future. In addition, Du et al. [75] also constructed the marginal abatement cost (MAC) curves of various types of new energy automobiles using the TIMES model, and the results showed that the emission reduction effect of PHEV is lower than that of BEV and FCEV. Gopal et al. [76] constructed a full life-cycle MAC curve for new energy vehicles, and the results indicated that the emission reduction cost of HEVs and BEVs would reach negative numbers by 2030.

In terms of railway vehicles, the most widely used are electric locomotives and internal combustion locomotives. Electric locomotives are also zero-emission locomotives, but they need to be coupled with electrified railways. For non-electrified railway sections, only self-sufficient locomotives such as internal combustion locomotives can be used. Internal combustion locomotives have been known for their low energy conversion rate and high emissions, so the transformation of self-sufficient locomotives is particularly important. The development trend of self-sufficient locomotives is mainly represented by battery-powered locomotives and hydrogen fuel cell locomotives. Cipek et al. [77] used simulation software to simulate a conventional diesel and battery hybrid locomotive on a mountainous route and evaluated its energy cost (as shown in Table 10). Two tandem configurations corresponding to additional battery-based locomotive (denoted as DB1 and DB2 depending on the battery recharging regime). According to the given fuel saving results of the hybrid battery electric locomotives, it can be calculated that the battery locomotive can help the traditional locomotive reduce the fuel consumption by up to 30.93% and the cost by 22.27%, so the application of battery technology in railway locomotive is the trend of future development. With the continuous optimization of battery technologies, battery cost and renewable energy generation technologies, the manufacturing cost and energy cost of battery locomotive will be further reduced.

In addition to battery locomotives, hydrogen fuel cell locomotives are also a major trend in energy saving and emission reduction in railway locomotives. Scott et al. [78] used simulation software to conduct simulation experiments of hybrid hydrogen fuel cell locomotives and conventional internal combustion locomotives, and compared the fuel consumption rate of the two. The comparison results are shown in Table 11.

Table 10. Estimated energy saving and cost hybrid battery electric locomotive [77].

Locomotive Power Type	Accumulated Consumption		Cost (Euro)
	Running for Once	Running for 2000 Times	
Conventional Fuel (Litres)	2751	5,502,000	6,894,006
Hybrid DB1/DB2 (Litres)	2233/1900	4,466,000/3,800,000	5,595,898/4,761,400
Hybrid DB1/DB2 (kWh)	1570/2889	3,140,000/5,778,000	324,676/597,445
Fuel Saving DB1/DB2 (Litres)	518/851	1,036,000/1,702,000	
Fuel Saving DB1/DB2 (%)	18.83%/30.93%		
Cost Saving DB1/DB2 (%)			14.12%/22.27%

Table 11. Estimated fuel consumption rate of diesel internal combustion locomotives and hybrid hydrogen fuel cell locomotives [78].

Engine No.	Diesel Internal Combustio Locomotive (1 m^3/h)	Hybrid Hydrogen Fuel Cell Locomotive (1 m^3/h)
Idle	30	6.63
1	47	10.39
2	175.14	38.73
3	292.30	64.64
4	401.74	88.84
5	555.00	122.74
6	763.36	162.84
7	1024.46	226.56
8	1186.25	262.34

The energy efficiency of hydrogen fuel cell locomotive is one of the metrics. Hydrogen, as a kind of clean energy, is of zero emission when used as a locomotive power source except for a small amount of carbon emission in the process of hydrogen production, so hydrogen fuel cell locomotive is an indispensable part of energy saving and emission reduction for railway vehicles.

As for ships, Soleyani et al. [79] compared the energy consumption of hybrid electric battery ships with that of conventional internal combustion ships. Manouchehriniac et al. [80] conducted a comparative analysis of the life cycle costs of hybrid electric ships and conventional internal combustion ships as shown in Table 12. The results all show that the use of chemical batteries effectively reduces the energy consumption and cost, and also meets the trend of energy saving and emission reduction due to the zero-emission characteristics of batteries. However, limited to the immaturity of battery technology, at present, battery electric ships are mainly used for short-range inland waterway transportation only.

Table 12. Comparison of energy consumption and life cycle cost between hybrid battery electric ships and conventional ships [79].

Ship Type	Conventional Ship	Hybrid Electric Ship	Power Battery Ship	Energy Consumption Reduction Rate (for Conventional Ship)
Fuel Consumption (litre/100 km)	92.6	61.8	-	33.3%
Full Life Cycle Cost	132,900 USD	226,150 USD	56,250 USD	-

Ye et al. [81] conducted a comparative analysis on the full life-cycle carbon emissions as well as the costs of fuels such as ammonia, hydrogen (PEMFC fuel cells) and distillate oil, as shown in Table 13. The results show that both hydrogen and ammonia PEMFC fuel cells can achieve almost zero emission standards, but considering the currently predicted high costs of fuel cell manufacturing and raw material prices, lower prices are necessary to make them more competitive.

Table 13. Emission factors and costs of different types of ammonia and hydrogen fuel cell batteries [81].

Fuel Type	ULSFO (Ultra-Low Sulfur Fuel Oil)	MGO(Marine Gas Oil)/LSMGO(Low-Sulfur Marine Gasoil)	Green Hydrogen	Green Ammonia
Full Life Cycle Carbon Emission Factor (kg CO_2/kg fuel)	3.613	2.677	0.967	0.605
Full Life Cycle Cost (£/103 kg)	380	420	4408	771

3. Intelligent Infrastructures and Energy Usages

Transportation infrastructure is the carrier and basis for developing transportation intelligence and is also the basic energy-using facility in the transportation energy system. This section summarizes on the development hotspots of intelligent transportation infrastructures and energy usages, by focusing on smart roads, intelligent railway energy systems, smart ports and clean energy on power grids for transportation. Energy usage characteristics, effects on energy saving and emission reduction in intelligent transportation energy infrastructures are analyzed.

3.1. Smart Road

Smart road is one of the hottest directions of intelligent transportation development all around the world. Development of smart roads in China can be traced back to the "digital highway" [17] in Fujian Province in 2002. In 2011, Zhejiang Province proposed a "smart city" project, in which the smart highway was one of the first demonstration projects launched. In 2018, China's Ministry of Transport issued an administrative document on "Accelerating the Pilot Project of New Generation National Transportation Control Network and Smart Highway" [82], which acknowledged nine smart highway pilot project locations and identified six priority themes of development in the pilot project. Although the fundamental exploration phase of smart road development has been completed, as of now, the concept of smart road has not been unified. As one of the examples, Zhejiang Province was the first to propose an overall architecture design of a smart road, which was composed of nine main parts [83].

In terms of energy usages, the characteristics of the energy-using facilities of smart roads is a direction worthy of attention. This paper summarizes the characteristics of energy consumption of the energy-using facilities of the smart roads, based on three information sources, including the following: the standard on "High-level Autonomous Driving Data Interaction Content Based on Intelligent Vehicle Infrastructure Cooperative Systems" [84] issued by the Chinese Society of Automotive Engineering; a representative smart highway project, namely the first smart highway project of Yu Yue Expressway [85] in Shaoxing City; information of the representative intelligent infrastructure products on the market. As observed from the intelligent facilities deployed along the Yu Yue Expressway, the energy consumption rates of roadside units fall in 10.6–13.8 kW/h, and the energy consumption of onboard units are between 28.5 and 40.5 W/h per vehicle. Details of this information are shown in Table 14.

In terms of energy saving and emission reduction, the Jiangxi Provincial Transportation Design and Research Institute has conducted a discussion on the construction of smart highways under the concept of carbon neutrality [86], in which five key findings were presented and their corresponding design ideas [87,88] were proposed. In addition, the intelligence of charging facilities for electric vehicles is also one of the research directions. The literature [89,90] discusses the optimization of energy saving for highway charging facilities in terms of optimizing the network layout of charging facilities according to traffic demand, intelligent management of highway electric grid architecture and intelligent monitoring and management of charging facilities. Additionally, there are also studies on intelligent control of infrastructures along the highway. Liu Gang et al. [91] proposed a smart lighting system based on KNX technology and measured the energy saving based on the statistics from the operations of highway in Sichuan Province. Wang Zhigang et al. [92] also proposed an intelligent control of lighting system for tunnels on highways which can achieve 64–75% power saving based on results from real applications.

Table 14. Energy consumption per unit of smart road energy-using facilities.

Facility Types	Energy Consumption	Product Model
HD Camera	10–20 W	AC7100HK-GF-02, SJ-688A
Electronic Police Camera	20 W	iDS-TCE300-B/12/16
Radar	2–2.5 W	MR76-Rayvision, TBR-310, W202
Positioning	1.5–2 W	YH-CZ-001, KS668GB
V2X Onboard Unit OBU	7–8 W	LB-LW10A, CB-LY15
V2X Roadside Unit RSU	7–8 W	LB-RW10, LB-RW30
Control Terminal Device	500 W	Intel

In addition, the massive land area occupied by roads in China has long been underdeveloped and underutilized; therefore, the development of clean energy usages considering distributions of nature clean energies is quite important for the cooperative development of road transportation and energy system. Renewable energy generation solutions along highways such as hybrid renewable energy systems using solar photovoltaic (PV) panels combined with vertical wind for street lighting [93], solar harvesting pavement modules [94], and supported new energy ecosystems independent of fossil fuels [95] etc., have achieved good energy saving effects. There are similar practices in this area in other countries around the world such as Lebanon. Hammoud et al. [96] used unconventional technologies to generate clean energy from PV panels and wind turbine systems on uninhabited roads. Based on the RETScreen software, the estimated capacity of the system is 39.9 GW/year. The system will achieve a reduction in CO_2 and GHG emissions of approximately 28.211 tons of CO_2/year.

3.2. Intelligent Railway Energy System

Railway power supply system is a major part of a railway energy system. It is composed of traction power supply system and electric power supply system. The intelligence of railway power supply system is manifested in the intelligent energy management of railway station building, intelligent traction power supply system and the development of nature clean energy along the railway.

3.2.1. Intelligent Energy Management of Railway Station Building

The intelligent energy management system of railway station may include the following: using intelligent sensors, video monitoring, intelligent controller and other equipment, with the help of 5G communication technology, Internet of Things, sensors, AI, big data and other technologies in order to achieve holographic perception of the status of mechanical and electrical equipment as well as environmental parameters in the station, and finally achieve the intelligent management and control of energy-using equipment so as to obtain better effects of energy saving and emission reduction as well as a higher intelligence level. Taking the intelligent energy management system upgrading project in Nanjing South Smart Station as an example [97], the main energy-using facilities of Nanjing South Station are the central air conditioning system, the lighting system and elevator, which consume 70%, 12% and 10% of the energy, respectively. In the upgrading project, the intelligent facilities to be added are 10 servers, 256 sets of network control appliance, 195 sets of on-site data collection devices, 1086 energy consumption measuring devices, 64 sets of on-site data DDC control cabinets, 30 sets of sub-system authorization docking, 685 sets of intelligent electric power allocation, HVAC and lighting supporting equipment, etc. The specific energy consumption power of each type of intelligent equipment is shown in Table 15, and the total energy consumption of intelligent equipment in Nanjing South Station is estimated to be 1241.48–1913.28 kW/h.

Table 15. Energy consumption parameters of intelligent equipment in intelligent station.

Facility Types	Energy Consumption Power	Product Model
Server	500 W	Intel
Ethernet Hub	396 W	TL-SG1452P
Network Bridge	17 W	SW8000-BV800
Exchanger	24–120 W	IES-2206GAT-SFP, TL-SG5412
Intelligent Gateway	3–14.4 W	WG783, WG793
HD Camera	5–10 W	DS-2CD5047EFWD, DS-2CD3T46WDV3-I3
Network Electric Instrument	5–15 W	APM810, ACR220E(L)
DDC Control Cabinet	5–15 kW	EC-BOX XL50A-UMMI-PC
Intelligent LV Power Distribution System	3.8 kW	VS-GPD2C
Intelligent Lighting Switch Module	144 W	DK2000-CSN1216M
Intelligent Control Module	1.2 W	SPGUI Electronic

Intelligent energy management systems for railway stations have been widely employed in China's railway system. In addition to the above cases, there are many other relevant representative cases. For example, the Shanghai Hongqiao Railway Passenger Station built an energy management system [98] that combines energy measurement and control layer, data network layer and system layer in one. The Kramer Station [99], on the other hand, realized humanized and precise management and control of station energyso as to achieve the purpose of energy saving and emission reduction. The Xiongan Station of Beijing-Xiongan Intercity Railway [100] used the "smart brain" to digitally monitor and control the energy-using facilities in the station building and realize intelligent energy usage control. Shi Jingyuan et al. [101] proposed to adopt the intelligent IOT framework in the design of Chongqing East Station and apply various intelligent technologies to the energy management so as to achieve multi-energy sources complementation in horizontal and "source-net-charge-storage" synergy in vertical, and form a new energy system with high degree of information integration including energy sources such as electric energy, solar energy and geothermal energy. Additionally, Feng Chen [102] proposed an electrified railway smart microgrid system (ERSMS) with integrated multi-energy system to reduce energy consumption and improve power quality of railway system.

3.2.2. Intelligent Traction Power Supply System

The intelligence of railway energy management is also reflected in the intelligent traction power supply system. The intelligent traction power supply system includes intelligent traction power supply facilities, intelligent power supply scheduling system and an intelligent power supply operation and maintenance system. These components work together to realize the resource optimization and data sharing of the traction power supply system [103]. From 2009 until now, China's intelligent substations have undergone the process from traditional substations, integrated automated substations, digital substations to the current intelligent substations [104,105]. With the wide usage of IEC61850 standard, it is obvious that the new generation of intelligent substations has reached a stable stage of development and has largely influenced the digitalization and intelligence of railway traction power substation system. However, there are still challenges in the standardization of technical characteristics in terms of interface standardization, and reliability of railway power supply equipment [106,107].

However, due to the special characteristics of railway transportation, the standard system of public electric power facilities cannot be copied for railway usage. Although the China Railway Corporation has issued a serial of documents including "General Technical Scheme of Intelligent Traction Power Supply System", "Technical Conditions of Key Equipment of Intelligent Traction Power Supply System", and "The Provisional Technical Standard of Railway Power Supply Safety Inspection and Monitoring System (6C)", China has not yet established a perfect standard for intelligent railway traction power supply system [108]. The equipment of intelligent traction power supply system includes intelligent primary equipment [109], wide-area measurement and control protection equipment and auxiliary monitoring equipment. The research on the application of intelligent traction power supply system started formally in 2015, as in this year the National Railway Group set up a project to study the "Key Technology of Intelligent Traction Power Supply System". In the following year of 2016, another project named "Research on Condition Monitoring and Fault Warning Technology of Intelligent Traction Power Supply Equipment" also started. During this period, a large amount of scientific research results on traction substations and their equipment have been developed and applied [110] in high-speed railways such as Beijing-Zhangjiakou [111], Beijing-Xiong'an and Beijing-Shenyang railway lines. Additionally, in order to better understand feature of intelligent railway energy system, the energy-using parameters of the intelligent traction power supply system are also worthy of investigation. This paper refers to Acrel's integrated automated substation system [112] and summarizes the energy consumption powers of the energy-using facilities of the intelligent traction power supply system, as shown in Table 16.

Table 16. Intelligent traction power supply system equipment energy consumption parameters.

Facility Types	Energy Consumption Power	Product Model
Microcomputer Protection Device	700 W	AM5-T 512112
Switchgear Integrated Measurement and Control Device	500 W	ASD200-T-H-WH2-C
Temperature Measurement Sensor	Battery Powered	ATE-200, ATE-100
Temperature Measurement Receiving Unit	8–15 W	ATC-450C, ATC-600C
Wireless Temperature Measurement Device	8 W	ARTM-Pn, ATP-007
Power Quality Online Monitoring Device		ANSVG-S-G 100-50/G
Microcomputer Protection Device	5–15W	AM5-T 512112
Power Monitoring Device	1–5 W	PZ72-E4/C, PZ72-DE/C
Communication Device	10 W	ANet Intelligent Communication Manager
Equipment Monitoring Server	500 W	Acrel-1000

3.2.3. Usage of Clean Energy along Railway and Intelligent Technologies of Railway Infrastructure

The construction of renewable energy infrastructure along the railway is also an important approach for the integration of railway transportation and energy system. Using clean energy such as solar and wind distributed inside the railway protection area as well as the stations as much as possible can provide auxiliary energy for the electrical facilities along the railway as well as the traction power supply of locomotives, and can also help solve the power quality problems such as traction network voltage fluctuation, negative sequence and harmonics, etc. Figure 3 shows the available mileage of high-speed railway with potential of solar energy development in different provinces of China.

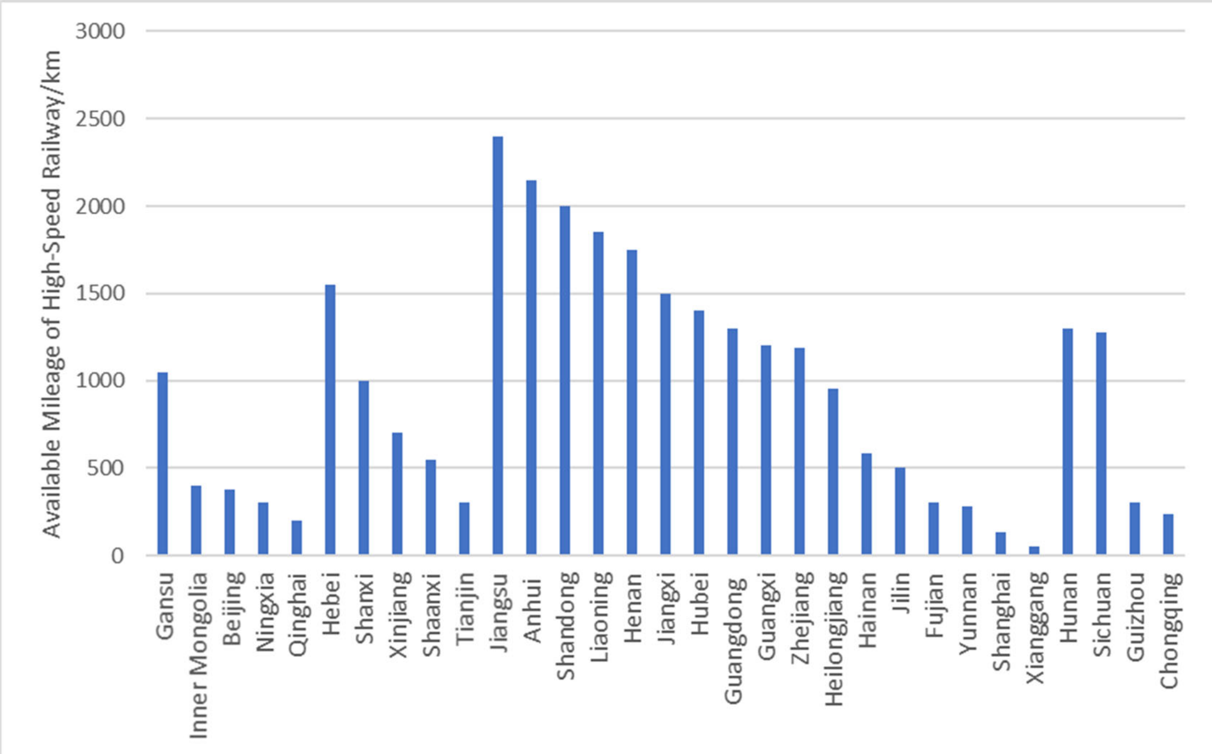

Figure 3. Available mileage of high-speed railway with potential of solar energy development in different provinces of China [113].

Research on methodologies and technologies to better use the clean energy along the railway line has also been carried out by many researchers. Hu et al. [114], Xu et al. [115] and Zhong et al. [116], respectively, proposed the joint control strategies based on "energy–network–vehicle–storage" architecture, the portable photovoltaic power generation system based on foldable mechanism, the optimization planning of distributed photovoltaic power generation and energy storage system for high-speed railway traction power supply system. All these technologies have passed the simulation verification. For practical applications, Alam et al. [117] designed a solar piezoelectric hybrid power system for railway station that could theoretically drive a 10 kW load for 10 h per day. Kameya et al. [118] proposed an energy storage and fast charging system for a solar light rail, where the auxiliary EDLC on board would be fast charged by the main EDLC. Nurmanova et al. [119] studied the feasibility of implementing a wind energy collector on the roof of a locomotive, and although wind resistance would increase fuel consumption, the results were still positive. This study was also supported by Thadani's [120] experiments with wind turbines in both high-speed tunnels and high-speed tracks, with similar results. Wei et al. [121] designed an auxiliary power supply system for railway trains after considering photovoltaic panel installation, MPPT algorithm and system energy management. Additionally, there is also research on technologies of railway intelligent energy systems, whose major purpose is to save energy and reduce the emissions of electrified railways from any possible aspects including railway stations, infrastructures along the railroad or traction power system, etc. Some of the representative research and the energy saving rates achieved in the research are presented in Table 17.

Table 17. Representative research on technologies of railway intelligent energy system and the energy saving rate achieved.

Name of the Proposed Technology	Energy Saving Rate	Reference
Integrated Energy Efficiency Control System	16.18%	[122]
Optimization of Distributed Power Generation for High-speed Railway Traction Power Supply System	32.5%	[116]
AI High-speed Railway Station Lighting System	12%	[123]
Beijing Chaoyang Station Energy Management System	10–25%	[124]

3.3. Smart Port

As mentioned in the " The Fourteenth Five-Year Development Plan of Transportation Standardization" [125] jointly issued by China's Ministry of Transport and several other important departments, the government is promoting the application of 5G, IOT and other new information technology in port industries in order to achieve a high level of smart port with intelligent technologies such as intelligent vertical transport control at ports, unmanned horizontal transport, intelligent ship operations for move in and out of the port, automatic cargo handling, autonomous driving of container trucks, etc. Applications of these technologies are expected to advance the unmanned port operations and improve the efficiency and quality of port loading and unloading. The research and technology developments on this direction can be roughly categorized into the following three aspects:

3.3.1. Automation Equipment for Port Infrastructure

At present, the automatic loading and unloading port infrastructure consists of two parts, namely automatic loading and unloading of containers and automatic mooring of ships. The automatic loading and unloading of containers includes the automation of port loading and unloading and yard loading and unloading, in which the key intelligent technologies include the remote control automation of quay crane and yard crane, the automation of container crane and the intelligent management of port energy system [126]. Automatic mooring is an important step after automatic ship berthing, which can also achieve emission reduction while improving safety and efficiency. Although there is relevant research and technology in China, the automatic mooring device is basically from foreign companies. Foreign manufacturers of related equipment mainly include Cavotec, Trelleborg, Mampaey, MacGregor and others. One example of using this type of smart port technology and its effect on energy usage is that since 1996 when the M200D automatic mooring products has been put into use at the No.7 berth of Geraldton Port [127] in Australia, nearly 8000 tons of carbon dioxide emissions are reduced per year, demonstrating remarkable energy saving and emission reduction benefits.

3.3.2. New Energy "Unmanned" Container Truck Technology

At present, Automatic Guided Vehicles (AGVs) and Automatic Straddle Carrier(ASCs) are widely used in automated ports, while container trucks are mainly adopted in non-automated ports. The "unmanned container truck" refers to the container trucks adopting autonomous driving technology, which is one of the important development trends of intelligent ports. At present, it can be divided into three types: "shore bridge + AGV + automated rail mounted container gantry crane (ARMG)", "shore bridge + straddle carrier + ARMG" and "shore bridge + container truck + ARMG" [128]. The first one is mostly used, which had been adopted in many automated container ports built from 2015 to 2021 including Qingdao Port, Shanghai Port, Xiamen Ocean Gate Terminal, Shanghai Port Yangshan Phase IV Port and Tianjin Port [129]. The automation of horizontal transportation system involves a large number of intelligent issues covering random routing decisions, transport planning, etc. The application of intelligent driving technology in AGVs and ASCs will bring the horizontal transport of automated port to higher efficiency and lower cost of operation on the existing basis. Intelligent driving technology will bring new development opportunities to automated container ports [130].

3.3.3. Usage of Clean Energy in Ports

On the basis of the existing port energy supply system, studies on the planning and application of clean energy and electric energy substitution have been conducted mainly from the following two aspects:

- Adopt photovoltaic, wind, ocean, tidal and other renewable energy to generate electric to meet the port's power demand, thus achieving the sustainable development of the port. The following are successful cases and representative studies of clean energy usage technologies in ports. The Ribadeo port [131] in Spain meets the port's power demand by using ocean energy to generate electricity. The Genoa Port Authority [132] has also promoted the use of new energy sources in the port area by developing a renewable energy environmental plan to reduce fossil energy consumption. Seddiek et al. [133] explored the energy saving performance of fuel cells and offshore wind turbines in the port, and the results showed that their method would reduce 32,176 t CO_2, 53.2 t NOx and 8.3 t CO per year. Gutierrez–Romero et al. [134] used the Monte Carlo procedure to evaluate the prospects of solar and offshore wind energy applications in the Cartagena port as an example, and concluded that more than 1.0×10^4 t of CO_2 emissions can be reduced per year. Ahamad et al. [135] used the HOMER simulation software to design a hybrid wind/PV/storage/grid/converter energy system for Copenhagen port in Denmark. Misra et al. [136] designed a renewable energy port microgrid that can meet 60% of the total power of the port. Fang et al. [137] constructed a set of synergistic model of port energy dispatching and equipment energy use planning considering wind/solar complementarity as the main component, and verified that the model is effective in improving port energy usage.
- Another important direction on clean energy usage in ports is the usage of "shore power system". Supporting the development of the shore power system has been included in most recent strategic plans for smart port development in China. It is believed that further development and application of shore power system, together with the electrification of port vehicles and equipment, is the way that must be passed to realize the clean replacement of port energy [138]. Chinese government is vigorously promoting the development of shore power through many approaches including making regulations, providing financial stimulus, promoting academic research, aiming at energy saving and emission reduction through replacing fossil fuels with electric while ensuring the economic benefits of shore power projects, etc. [139]. Additionally, it is another relevant direction of the development of the intelligent power management system, which can also realize the effects of energy saving and emission reduction [140].

Based on the research on the above two directions of smart port development, the energy consumption parameters of intelligent equipment of port infrastructure can be summarized in order to facilitate the planning and design of these systems. The main intelligent energy-using equipment in smart port lies in the infrastructure perception layer, communication layer and decision surface. Taking Huawei's shore bridge RTG remote control system and the smart port of Tianjin Port [141] as examples, the energy consumption parameters of intelligent equipment are summarized in Table 18, and the total energy consumption of the port's intelligent equipment can be estimated as 351.198–809.530 kW/h.

The research on energy saving intelligent technologies for smart ports have mainly focused on the shore power energy saving of ships in port, RTG energy saving strategy, alternative fuel for container trucks, emission reduction strategy based on autonomous driving and intelligent management of port energy system. Some of the representative studies from on these topics and the corresponding energy saving and emission reduction effects are presented in Table 19.

Table 18. Energy consumption powers of intelligent equipment for smart port.

Facilities	Energy Consumption Power	Product Model
HD Camera	10–20 W	AC7100HK-GF-02, SJ-688A
Radar	2–2.5 W	MR76-Rayvision, TBR-310, W202
Positioning	1.5–2 W	YH-CZ-001, KS668GB
V2X Mobile Data Center MDC	7–8 W	LB-LW10A, CB-LY15
V2X Roadside Unit RSU	7–8 W	LB-RW10, LB-RW30
Control Terminal Device	500 W	Intel
Substation Optical Network Access	55–140 W	EA5801E-GP16, OptiXaccess EA5801E-GP04, etc.
Optical Network Unit ONU	7–15 W	OptiXstar P871E, OptiXstar W826P
Optical Distribution Node ODN	70–154 W	OptiXtrans E6600 Series
Network Electric Instrument	5–15 W	APM810, ACR220E(L)
DDC Control Cabinet	5–15 kW	EC-BOX XL50A-UMMI-PC
Intelligent LV Power Distribution System	3.8 kW	VS-GPD2C

Table 19. Representative research on energy saving intelligent technologies for smart ports and the corresponding energy saving and emission reduction effects.

Name of Technologies	Energy Saving Status	Carbon Emission Reduction Status	Reference
Full Life-cycle Benefits of Shore Power for Ships in Port	-	48–70%	[142]
Energy Savings from Shore Power in Lianyungang	437 t	-	[143]
MM200D Automatic Mooring Product under MoorMasterTM Series	-	8000 t/year	[144]
Energy Savings of Port AGV (Automated Guided Vehicle)	13%	13.6%	[145]
New Energy Container Truck	86.6%	67.8%	[145]
Energy Efficiency Assessment of Intelligent Control Distribution Systems in Power Grids	5.69–16.03%	-	[146]

3.4. Clean Energy on Electric Grid for Transportation

Most of the energy in the transportation energy system comes from the urban electric grid, which is supplied with electricity from various power plants. As of September 2022, according to the Ministry of Ecology and Environment of China [147], the share of non-fossil energy consumption in China has increased by 6.9%and reached 16.6% in the past decade. The non-fossil energy is mostly from nature and clean energy sources such as solar, wind or hydroelectric. Therefore, it is necessary to take a look at the typical renewable energy electric generator parameters and investigate the potential energy saving or carbon emission reduction effect of using these renewable energies. This paper summarized the capacity of power generation for the typical solar, wind and hydroelectric power generators, based on the representative leading power generator manufactures in the world (as shown in Table 20).

Table 20. Typical capacities of renewable energy power generation facilities of the world leading manufacturers.

Facility Types	Power Generation Capacity	Manufacturer or Brand	Product Model
Solar Energy PV Panel	375–460 W	LONGi Green Energy Technology Co., Ltd. (Beijing, China)	LR4-60HPH-375M, LR4-72HPH-460M, etc.
	420–700 W	TW Solar	TWMBIT-132-D, TWMAP-108-H, etc.
Wind Turbine	1–12 MW	Goldwind	GWH191-4.0MW, GWH191-6.7MW, etc.
	2–10 MW	Dongfang Electric Wind Power Co., Ltd. (Beijing, China)	D10000-185, D7000-186
	850 kW–2.0 MW	Vestas	V90-1.8/2.0MW, V80-2.0MW, etc.
Hydroelectric Generator	0.8–1000 MW	Harbin Electric Machinery	
	10–1000 MW	Dongfang Electric Machinery	

Additionally, reference [148] compared the carbon footprint savings of renewable energy generation (hydroelectric, solar, wind, and biomass) of licensed power plants in Kahlaman City, Turkey, from 2019 to April 2021 (as shown in Table 21).

Table 21. Annual carbon footprint reductions for licensed power plants in Kahlaman City [148].

Time Period	Total Renewable Energy Generation (MWh)	Carbon Footprint Reduction Compared to Coal (tCO_2)	Carbon Footprint Reduction Compared to Electricity Generation (tCO_2)	Carbon Footprint Reduction Compared to Nature Gas (tCO_2)	Average Carbon Footprint Savings Compared to All Fossil Energy (tCO_2)
2019	4,884,829	4,884,829	3,175,139	2,442,414	3,500,794
2020	4,219,702	4,219,702	2,742,806	2,109,851	3,024,120
2021 (by April)	1,497,264	1,497,264	973,222	748,632	1,073,039

According to Table 21, the total amount of renewable energy generation is 10,601,795 MWh from 2019 to April 2021, and the amount of carbon footprint achieved each year is more than 3,000,000 tCO_2. Additionally, the reference also pointed out that the share of renewable energy from the licensed power plants in Kahraman City has reached 47.4%. In addition, Bayazıt [149] investigated that the Gökçekaya Dam hydro power plant in Turkey achieved carbon footprint savings of 408,534 tons of CO_2 per year. Liu et al. [150] used the full life cycle assessment method to evaluate the advantages of grassland wind power generation with the example of grassland wind power plant in Inner Mongolia, which is found with the great potential for clean energy development. The International Renewable Energy Agency (IRENA) claims that PV power will cost less than carbon and that replacing 500 GW of high-cost coal power plants with solar or wind power will reduce carbon emissions by about 1.8 Gt (equivalent to 5% of 2019 carbon emissions) [151]. Therefore, it is very necessary to integrate renewable energy into the transportation energy system, which include not only increasing renewable energy generation in the power grid, but also increasing renewable energy usage along the road, railway and waterway or even on the vehicles.

4. Intelligent Driving System and Energy Usage

In addition to vehicles and infrastructures, this paper also tries to explore the development of intelligent technologies of transportation from the system perspective with the emphasis on technologies that may affect energy usage including the intelligent and connected transport system in road transportation domain, the train control and autonomous driving system in railway transportation domain and intelligent shipping system in water transportation domain.

4.1. Intelligent and Connected Transportation System

Intelligent and connected transportation system take advantages of advanced wireless communication and new generation Internet and aims at achieving dynamic real-time information interactions between vehicle–to–vehicle, vehicle–to–road and vehicle–to–people. Based on the dynamic and integrated transportation information, the system is able to achieve active safety control for vehicles and cooperative traffic management, thus increasing the safety, efficiency and energy saving transportation system.

The typical architecture of the intelligent and connected transportation system is shown in Figure 4.

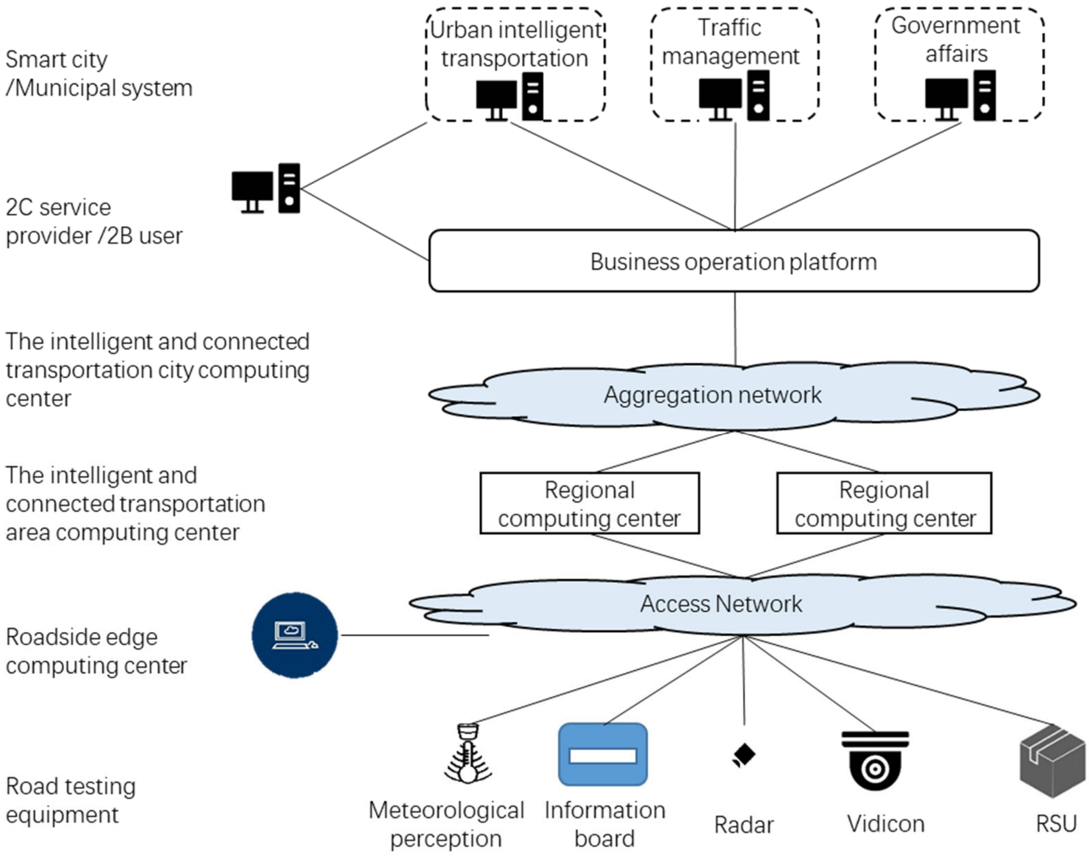

Figure 4. Network architecture of intelligent and connected transportation system [152].

The intelligent and connected transportation system is usually consist of the following four layers: system perception layer, network communication layer, platform layer, and application layer [153]. The key technologies of the system perception layer are used for collecting various information of vehicle status, vehicle location, road environment with visual, radar or other sensors [153]. The key technologies of the network communication layer include various on-board wireless communication technologies such as LTE-V, WIFI, DSRC, Zigbee, 4G/5G, Bluetooth technology, etc. [154], as well as roadside communication technologies include LTE-V, 4G/5G, eMTC, NB-IoT etc. [155]. The key technologies of the platform layer generally covers the major supporting system architectures [153] such as cloud management service platform (IaaS), application support platform (PaaS), and application platform (SaaS). The key technologies in the application layer generally include integrated monitoring and traffic control, cooperative control of transport safety, and autonomous driving, etc.

Among the above-mentioned system architecture, autonomous driving technology is the core of future intelligent and connected transportation system. The autonomous driving classification [156] method defined by SAE International classified it into six different levels from L0–L5. According to the evaluation of a consulting firm Guidehouse Insights [157], although there have already been leading autonomous driving companies successfully tested L4 autonomous driving cars, there are still many technical barriers to make the real application of autonomous driving publicly available including the uncertainties of sensing and decision-making under rare and complicated cases, high costs, low level standardization of the industry, incomplete legal and administrative support, etc.

In terms of energy consumption and carbon emission, technologies such as intelligent vehicle infrastructure cooperative systems (IVICS), intelligent and connected transportation system connection and autonomous driving bring digital sensing monitoring and intelligent control to road transportation, and also provide monitoring data for autonomous driving of vehicles. Some of the representative research on these topics that discuss the linkages between those intelligent technologies and energy usages are shown in Table 22. Energy saving control of autonomous driving, path planning of intelligent connected vehicles, congestion control at intersections and regenerative braking energy are the main ways to achieve energy saving and emission reduction under IVICS conditions from the intelligent system perspective.

Table 22. Data on energy saving and emission reduction rates of highway intelligent technologies.

Technical Topic of the Research	Energy Saving Rate	Carbon Emission Reduction Rate	Reference
Hill Information Economic Cruise Control Method	7–13%	7–13%	[158]
Following Controller for Heavy Trucks	18%	15%	[159]
Speed Control Method of Non-signalized Intersection Under Connected Vehicle Environment	21.6%	40%	[160]
Vehicle Trajectory Planning by Dynamic Planning Algorithm	8%	8%	[161]
Energy-efficient Driving Control for Autonomous Driving Vehicles	4.9%	10.4%	[162]
Regenerative Braking Energy Based on Dynamic Planning	41.59%		[163]

4.2. Train Control and Autonomous Driving System

For the railway transportation system, the train control system is one of the most basic components, and is usually involved in autonomous driving of railway trains. The development of train control system in China was first proposed in the Ninth Five-Year Plan. Through continuous development, a new type of train control system with on-board signals as the main body has been formed. The China Train Control System (CTCS) is composed of onboard subsystems and ground subsystems, and is divided into application levels 0–4 according to function requirements and equipment configuration [164].

As early as 2004, China's Ministry of Railways issued the CTCS Technical Specification General Provisions, in which the definition and basic framework of CTCS are specified according to foreign standards such as ETCS and in accordance with the basic national conditions of China [165]. Through 3 stages of development in 10 years, the number of CTCS standard technical documents reached 44 from 2004 to 2013 [166]. By the end of 2015, railway interoperability under CTCS-4 was widely used [167]. In 2019, China National Railways Group Ltd. proposed a general technical solution for the train control system of CTCS-4 and listed its main features [168].

In terms of autonomous train driving, it relies on the automatic train control system (ATC) and systematically combines various modern industrial control technologies including computer technology, signal control technology, sensor technology, data collection, communication, etc., and applies them to the intelligent control of the entire train [169].

In addition to automatic and intelligent driving itself, energy saving and emission reduction are also important directions for automatic driving development. The problem of energy-efficient optimal control of trains was first proposed by Ichikawa in 1968 [170]. Li et al. transformed the problem of energy efficient optimal driving of trains into a conventional optimization problem, using genetic algorithms to find the optimal solution and verifying the proposed method through simulations [171]. Meanwhile, regenerative braking energy management is also used as an important technology for energy saving and emission reduction. Li Minglin et al. proposed an integrated energy management strategy for traction load status with the introduction of energy storage devices of lithium batteries and ultra-capacitors, and verified its feasibility by simulation [172]. Table 23 shows several of the representative studies on railway intelligent technologies and the corresponding energy saving effect. It can be concluded that although the energy saving effects of energy saving control technologies are not as good as using clean energy directly, it still has considerable potential and can be an effective approach to achieve self-consistent transportation energy system.

Table 23. Representative studies on railway intelligent technologies and the corresponding energy saving rate achieved.

Name of the Technologies	Energy Saving Rate Achieved	Reference
Train Control Energy Saving Optimization based on Genetic Algorithm	7%	[173]
Optimal Model for Regenerative Braking Energy Savings under Timing Constraints	17.44%	[174]
Energy Savings of Regenerative Braking System with Inverter Feed-back Device	45.45%	[175]
Automatic Train Control Based on Machine Learning	7%	[176]
Feasibility of Distributed Regenerative Braking Device	10–24%	[177]

4.3. Intelligent Shipping System

The Ministry of Transport of China issued an administrative document in 2020 entitled "Guidance on Promoting the Construction of New Transportation Infrastructure", in which the following was pointed out regarding intelligent shipping: to build infrastructure such as geographic information mapping of waterways and meteorological and hydrological monitoring of navigation waters and improve electronic charts of high-grade waterways in order to support intelligent navigation of ships in all types of complex environments; to construct high-grade waterway sensing network, and realize remote, real-time fully covered supervision and service for ships through AIS, VHF, GMDSS, CCTV and other systems, as well as big data, ship networking and cloud computing technologies [129]. With the support of this development plan, the efficiency and safety of the shipping system would be improved significantly, including better connectivity and cooperation between intelligent shipping facilities such as waterways and locks, and intelligent shipping such as autonomous navigation, docking and de-docking, and automatic loading and unloading, etc. [16].

As one of the major components of the intelligent shipping system, intelligent waterways are usually regarded as a pair of "eyes" for inland shipping, and thus its development has attracted attention from both the industrial side as well as the academic side. The European Union proposed the concept of European inland shipping information service as early as 1990s, with the aim to develop inland waterway shipping in EU countries. This system provides users with static information such as electronic waterway map, laws and regulations and ship registration as well as dynamic information such as ship position, cargo information and expected arrival time, etc. [178]. Chinese scholars have also conducted much research on the development of the Yangtze River intelligent waterway, and reference [179] argues that the realization of intelligent waterway technologies such as waterway shift monitoring and dynamic sensing, intelligent simulation of waterway integration and evolution, intelligent information service and application of waterway relies largely on the support of modern information technology and theory.

As for intelligent shipping on oceans, the relevant references usually refer to it as the key technologies for "intelligent maritime" or "smart maritime", which are interchangeable under most of the cases. In recent years, scholars around the world have much research on the architecture design and intelligent decision making related to smart maritime. Reference [180] proposed a distributed "smart maritime cloud" architecture based on a service-oriented structure. Reference [181] proposed an ambiguous C-Mean method to realize the classification and identification of target types by radar mapper, which effectively reduced the difficulty recognition of ships. Reference [182] proposed a new weather information and decision support system for high-speed maritime transportation based on intelligent workplace. Reference [183] developed a ship collision risk assessment system as an intelligent solution based on an ambiguous inference system to help managers use this information for intelligent decision making.

In addition, intelligent ship navigation technology, as a core element of intelligent shipping, has also been paid much attention regarding its development, and has been a research hotspot in water transportation. In the past few years, remarkable scientific findings and applications have been revealed on this topic, but there are still many challenges. One of the representative achievements in Europe is the ship named Yara Birkeland [184], the world's first pure electric smart container ship jointly developed by Norway's YARA and Kongsberg, which completed its first voyage in November 2021, with remote piloting and automatic navigation systems, and which can achieve fully autonomous navigation. Japan's representative work comes from The Nippon Foundation, which officially launched the development of smart ship and navigation project in June 2020 and completed the real-ship test in early 2022, and achieved several technological breakthroughs [185]. Russia's demonstrative intelligent ships including Robochaya dredger, Pola Anfisa, and the ice-breaking tanker Mikhail Ulyanov began experimental automatic navigation at sea in 2021 [186]. South Korea's mega gas carrier Prism Courage completed its first intelligent voyage in June 2022 [187]. China also has many cases of intelligent navigation achievements including the world's largest intelligent navigation container ship "Zhifei" and the world's first intelligent unmanned system mother ship "Zhuhaiyun", which was officially launched in May 2022 [188].

5. Discussions and Conclusions

The development trend of using new energy for vehicles has shown that chemical batteries, hydrogen fuel cells and a hybrid power system for vehicles have become the common energy sources for road, railway and water transportation, among which batteries for locomotives and renewable energy for ships are still used as auxiliary energy sources only in near future. Therefore, energy sources such as electricity and hydrogen have become the main form of energy for future vehicles, but there are still many problems in new energy technologies for transportation. Mileage range is one of the major concerns. Although the energy density of the batteries has exceeded 200 Mh/kg for chemical batteries and 350 Wh/kg for hydrogen fuel cell, the supported mileage range can marginally meet the demand of road transportation, but in the face of heavy-duty and long-distance transportation by railway and waterway, it is still impossible to complete the work by using batteries alone.

Therefore, before batteries reach the capacity to fulfill these transport demands, the transportation energy usage mode during this transition period would be the following: for railways, its mainly about traction power system and hybrid power system (internal combustion + chemical batteries/fuel cells); for waterways, the main energy source would be chemical batteries, internal combustion engines, hydrogen fuel cells and renewable energy source hybrid power system, and the alternative fuels with lower carbon emissions such as methanol, LNG, ammonia and biofuels are available as power sources for the transition period. Additionally, the development of power system technologies, the technical standard system for new energy vehicles need to be improved as soon as possible, and more efforts should be made to address the research of key technologies such as energy management of batteries, battery energy density, energy saving technologies, planning of charging facilities, safety management of energy storage devices and components of the power system, etc.

The intelligence of transportation infrastructure and driving system is manifested in smart road, intelligent railway stations, intelligent traction power supply and smart port, intelligent and connected transportation system, autonomous driving and intelligent shipping etc. Energy-related development directions mainly include energy consumption of intelligent infrastructure, clean energy usage at ports, stations and along transportation corridors, energy saving and optimization control of intelligent driving, regenerative braking energy technology, transportation efficiency optimization under intelligent and connected environment and intelligent power distribution of electrified energy-using facilities. These are all key technologies and research hotspots for the integration of transportation and energy systems. Among them, in terms of energy saving and emission reduction, there are two different approach paradigms: direct generation and usage of clean energy for transportation infrastructures or vehicles and energy saving through applying other intelligent technologies such as sensor technology, computer technology and IOT, etc.

In general, the effect of the second approach (namely energy saving through applying other intelligent technologies) will be slightly insufficient in being compared with that of the first (namely direct generation and usage of clean energy), but it is still an important development trend of future transportation energy system. One of the problems for the current development of intelligent technologies is that the standards of many intelligent technologies such as intelligent driving system, intelligent power distribution of transportation infrastructure, etc., have not been improved, and the interfaces between infrastructures, facilities and vehicles has not been standardized, thus leading to the inability to achieve large-scale intelligent control. Therefore, the improvement of the standard system for various intelligent technologies is the top priority for future development. In addition, as the fast development of renewable energy usage along the traffic corridors, the unstable power quality during on-grid renewable energy generation also becomes a problem that needs to be solved.

With the continuous application of intelligent technologies in transportation systems, the development trend of future energy usage patterns has been revealed. Based on the previous review, the following is the summary and analysis on the energy usage patterns of the three transportation domains, namely road, railway and waterway. The future development trend of integrated transportation energy system is analyzed based on the "source–network–charge–storage" architecture.

For road transportation, the future energy usage pattern can be shown schematically as Figure 5. First of all, it can be seen from the above analysis that renewable energy power plants and renewable energy generation facilities along the highway are necessary links of the future highway energy consumption scenario since clean energy would be the main source of energy in the future. Additionally, as seen from the energy saving and emission reduction effects of vehicles with different power sources, the future popular power supply systems of vehicles are mainly BEVs, PHEVs and new energy such as hydrogen fuel cell system instead of internal combustion, which not only reduce the consumption of fossil energy and carbon dioxide emission, but also let the intelligent technology function better in vehicles. Although the cost of hydrogen fuel cells is high at present, with the continuous improvement of hydrogen energy technology and fuel cell technology, the potential of hydrogen fuel cells cannot be ignored. In addition, intelligent energy saving technologies, IVICS, autonomous driving and intelligent power distribution technologies are also playing positive roles in supporting or promoting energy saving and emission reduction.

As for railway transportation, the future energy usage patterns are shown schematically in Figure 6, in which the usage of new energy for locomotives consists of three different types including traction electric power locomotives, chemical battery electric locomotives and hydrogen fuel cell locomotives. For all these energy usage patterns, new energy supply facilities are necessary components including renewable power plants and electric grids, which can provide energy for energy-using facilities along railroad, chemical battery electric locomotives, traction power system, etc., as well as hydrogen plants, which can provide energy source for hydrogen fuel cell locomotives. The railway lines, together with its protective areas, cover a vast area with remarkable usable space for clean energy generation, so the development of renewable energy infrastructure along the railway line is also a key direction for railway energy saving and emission reduction. Additionally, intelligent technologies such as intelligent stations, automatic train driving systems, intelligent traction power supply systems, and intelligent power supply and distribution system, etc., are all important means for energy saving and emission reduction.

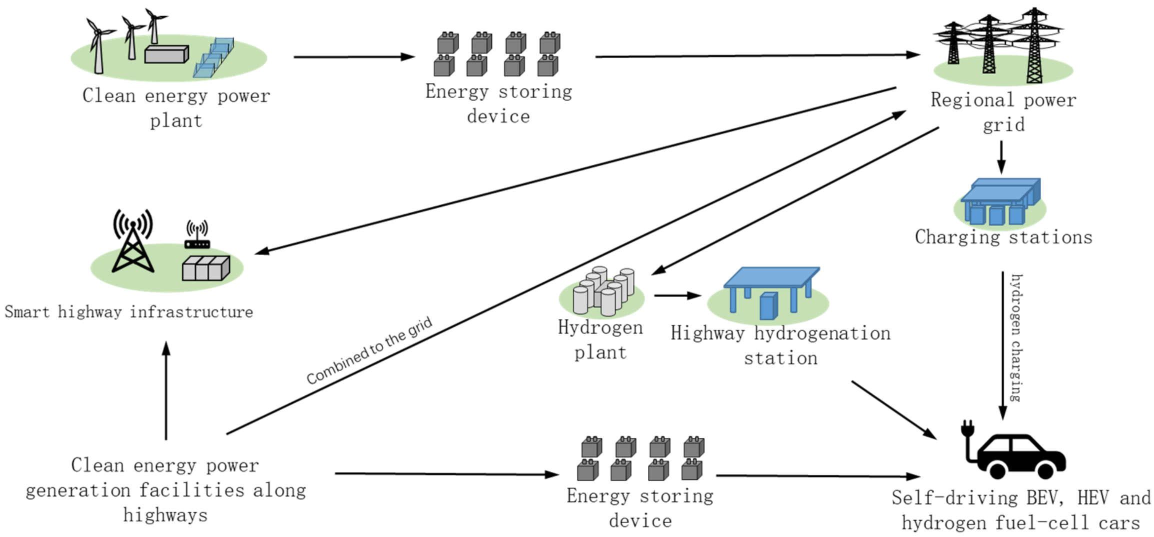

Figure 5. Schematic illustration of future transportation energy system and energy usage pattern of road transportation system.

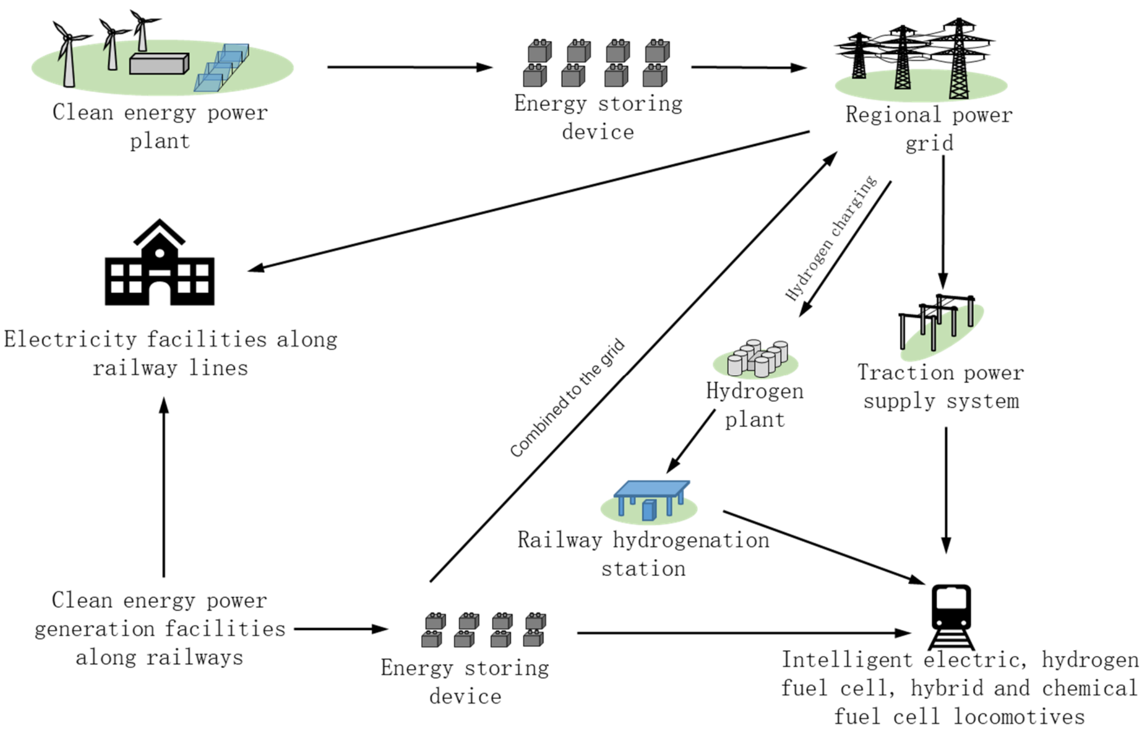

Figure 6. Schematic illustration of future transportation energy system and energy usage pattern of railway transportation system.

As for water transportation, considering the continuous development of smart port and new energy technologies for shipping, the energy usage pattern of water transportation can be considered dominated by the multi-energy powered ships and the intelligent facilities at ports as shown in Figure 7. In this figure, the energy usage patterns can be classified by the different navigation mileage supported by each type of technologies. For inland shipping with short navigation mileage, chemical battery ships and hydrogen fuel cell ships will be the development trend. For ocean voyages, hybrid power systems composed of chemical batteries, diesel engine, hydrogen PEFMC, solar energy, wind energy, etc., and can be used for power supply. In addition to fuels, the energy consumption structure of ports has also changed dramatically, and many new energy-using technologies have already been deployed including shore power system, automatic ship mooring, new energy container trucks with automatic driving and intelligent port power grids.

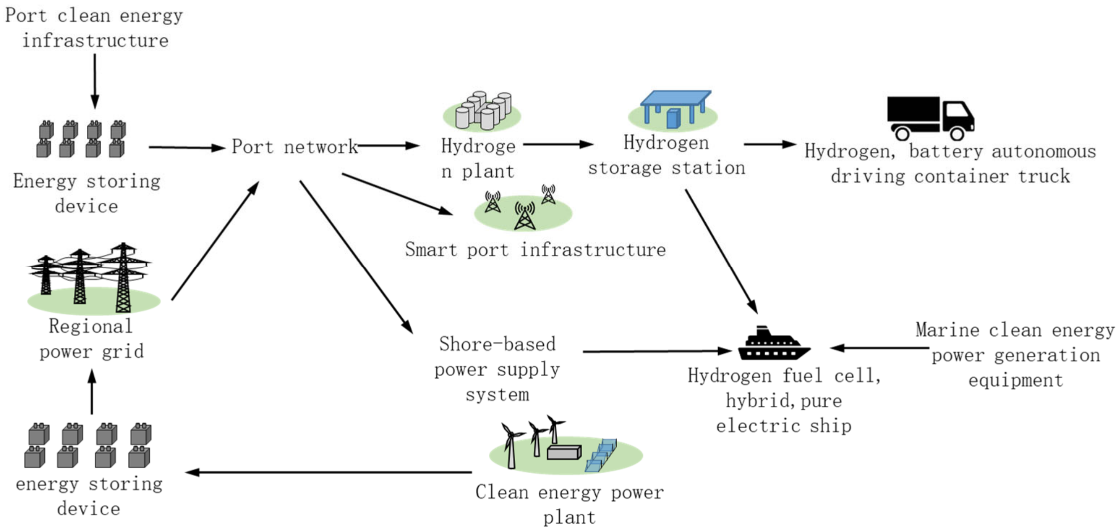

Figure 7. Schematic illustration of future transportation energy system and energy usage pattern of water transportation system.

To sum up, from the perspective of the whole transportation energy system, in order to achieve the goal of high efficiency, clean and intelligence of the transportation energy system at all levels, there must be an overall planning and design of the complete "source-net-charge-storage" transportation energy system structure as shown in Figure 8.

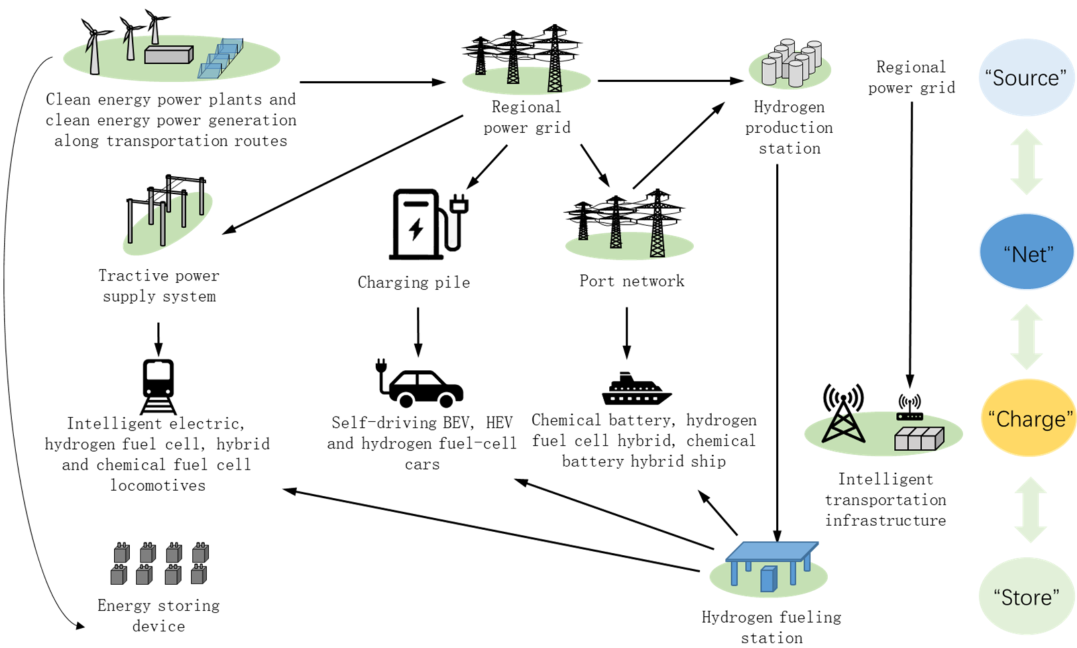

Figure 8. "Source–net–charge–storage" integrated transportation energy system architecture.

From the "source" level, wind, solar, hydro and other renewable energy without carbon emissions will become the main source of the future power system, with the continuous maturity of power generation, distribution and energy storage technologies. As clean energy is limited by local natural conditions, the full usage of different clean energy sources in different regions and the complementary and mutually reinforcing of various energy sources are the development trend of future transportation energy system.

From the perspective of "net", with the development of intelligent transportation technologies, various new energy networks are formed. On the one hand, the existing electric grid network structures are changing because of merging intelligent technologies such as intelligent traction power electric system for railway, intelligent electric network for smart port, etc. On the other hand, the intelligent technologies also lead to various new type of electric grids covering intelligent and connected facilities and large number of charging piles, etc. The future network of energy transmission requires not only electric supplies with high stability, reliability and quality, but also adequate and safe new energy fuel supplies. At the same time, promoted by the continuous development of intelligent power supply and distribution technology, integrated intelligent electric grid control technology is also the development trend of future transportation energy system.

From the perspective of "charge", with the wide applications of new energy vehicles and intelligent transportation technologies, the energy usages of transportation system have changed from traditional internal combustion engines to chemical batteries, fuel cells and hybrid power systems, and the energy sources have also changed from fossil energies to clean energies in the forms of electric, hydrogen fuel, green ammonia, solar energy and wind energy. Intelligent technologies such as automatic driving, regenerative braking, intelligent power distribution, intelligent traction power supply, intelligent and connected transportation system, smart port, etc., have also produced new energy usage loads.

As for "storage", with the continuous development of renewable energy generation technologies, the single on-grid solution of direct integrating into the regional power grid will cause power losses. Therefore, future direction of using renewable energies more efficiently would be the usage of various type of energy storage facilities such as chemical batteries, flywheel energy storage and ultra-capacitors, etc., but with the premise of ensuring power quality and solving the problems of large voltage fluctuations, low frequency oscillation and harmonic resonance, etc. At the same time, optimal energy resource allocation and cooperative control could be achieved through technologies such as an intelligent energy information system and intelligent control with the support of intelligent infrastructures.

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References

1. Jebeile, J. Values and Objectivity in the Intergovernmental Panel on Climate Change. *Soc. Epistemol.* **2020**, *34*, 453–468. [CrossRef]
2. Verma, S.; Mishra, S.; Gaur, A.; Chowdhury, S.; Mohapatra, S.; Dwivedi, G.; Verma, P. A comprehensive review on energy storage in hybrid electric vehicle. *J. Traffic Transp. Eng.* **2021**, *8*, 621–637. [CrossRef]

3. Xi, J. Building on Past Achievements and Launching a New Journey for Global Climate Actions—Statement at the Climate Ambition Summit. In *Gazette of the State Council of the People's Republic of China*; The State Council of the People's Republic of China: Beijing, China, 2020; Volume 7. (In Chinese)
4. Digital Railway Strategy. Available online: https://cdn.networkrail.co.uk/wp-content/uploads/2018/05/Digital-Railway-Strategy.pdf (accessed on 4 November 2018).
5. Yu, L. Carbon Neutrality Strategies and Pathways of Urban Transportation from a Global Perspective. *Urban Transp. China* **2021**, *19*, 19–25,81. (In Chinese)
6. *UK Government Pushes on with Maritime 2050*; The Department for Transport: London, UK, 2019. Available online: https://www.gov.uk/government/publications/maritime-2050-navigating-the-future (accessed on 1 May 2023).
7. Veselitskaya, N.; Karasev, O.; Beloshitskiy, A. Drivers and barriers for smart cities development. *Theor. Empir. Res. Urban Manag.* **2019**, *14*, 85–110.
8. Feng, M.; He, J. Introduction of the 2030 German Federal Transport Infrastructure Plan. *China Transp. Rev.* **2018**, *40*, 116–121. (In Chinese)
9. Chan-Edmiston, S.; Fischer, S.; Sloan, S.; Wong, M. *Intelligent Transportation Systems (ITS) Joint Program Office: Strategic Plan 2020–2025. United States. Department of Transportation*; Intelligent Transportation Systems Joint Program Office: Washington, DC, USA, 2020. Available online: https://rosap.ntl.bts.gov/view/dot/63263 (accessed on 15 May 2023).
10. Department of Transportation Strategic Plan FY 2022–2026. Available online: https://www.transportation.gov/sites/dot.gov/files/2022-04/US_DOT_FY2022-26_Strategic_Plan.pdf (accessed on 28 March 2022).
11. Gkoumas, K.; Santos, F.L.M.; Stepniak, M.; Pekár, F.U.S. Department of Education Fiscal Years 2022–2026 Strategic Plan Research and Innovation Supporting the European Sustainable and Smart Mobility Strategy: A Technology Perspective from Recent European Union Projects. *Appl. Sci.* **2022**, *11*, 11981. [CrossRef]
12. Xie, Z. Seven ministries, including the Ministry of Transport, jointly issue guidelines on the development of smart Shipping. *Transp. Guangdong* **2019**, 52. (In Chinese)
13. State Council prints Outline for Building China into a transportation Power. *Archit. Technol.* **2019**, *50*, 1159. (In Chinese)
14. Wang, T. Study on the development strategy of China intelligent high speed railway. *China Railw.* **2019**, *1*, 9–14. (In Chinese)
15. Tian, Y. 11 Ministries Jointly Issued the Intelligent Car Innovation and Development Strategies. *Intell. Connect. Veh.* **2020**, 6–7. (In Chinese)
16. Liu, H. The Ministry of Transport issued a guideline to promote the transformation and upgrading of "new infrastructure" in the transport sector. *Zhongguo Zhiliang Wanlixing* **2020**, 31–32. (In Chinese)
17. Department of Science and Technology; Ministry of Transport. Interpretation of the Guidelines on Promoting the Development and Application of Road Traffic Autonomous Driving Technology. *Commer. Veh.* **2021**, *9*. (In Chinese)
18. The CPC Central Committee and the State Council Print and Issue the Outline Development Plan for National Comprehensive Three-dimensional Transport Network. *Gazette of the State Council of the People's Republic of China*; The State Council of the People's Republic of China: Beijing, China, 2021; pp. 25–37. (In Chinese)
19. Opinions of the Ministry of Industry and Information Technology on Strengthening the Management of Intelligent Connected Automobile Production Enterprises and Product Access (No.103 of the Ministry of Industry and Information Technology). *Technol. Inf.* **2021**, 6–8. (In Chinese)
20. Zhang, J.; Xue, Y.; Zhao, J.; He, J.; Li, B.; Zhang, H.; Yuan, S.; Li, B.; Huang, Z.; Weng, H.; et al. Evaluation of Cost and Economic Impact of China's Carbon Peak Pathway on Key Industries. *Res. Environ. Sci.* **2022**, *35*, 414–423. (In Chinese)
21. The Average Monthly Increase of New Vehicles in the Third Quarter Was Significantly Higher than That in the First Half of the Year, Which Maintained a Rapid Growth for Three Consecutive Months. Available online: https://app.mps.gov.cn/gdnps/pc/content.jsp?id=8719816 (accessed on 8 October 2022). (In Chinese)
22. China State Railway Group Co. Ltd. *2021 Statistical Bulletin*; People's Railway Newspaper Society: Beijing, China, 2022. (In Chinese)
23. Transport Industry Development Statistical Bulletin. Available online: https://xxgk.mot.gov.cn/2020/jigou/zhghs/202205/t20220524_3656659.html (accessed on 25 May 2022).
24. The Total Number of New Energy Vehicles in Our Country Is 13.1 Million, Showing a Rapid Growth. Available online: http://www.gov.cn/xinwen/2023-01/11/content_5736281.htm (accessed on 11 January 2023). (In Chinese)
25. Notice of the Ministry of Industry and Information Technology on Printing and Distributing the 14th Five-Year Plan for Industrial Green Development. Available online: https://www.miit.gov.cn/cms_files/filemanager/1226211233/attach/20224/99a5c254cd5a45c9896b0cb0b675ed03.pdf (accessed on 15 November 2021). (In Chinese)
26. Hadjipaschalis, I.; Poullikkas, A.; Efthimiou, V. *Overview of Current and Future Energy Storage Technologies for Electric Power Applications (Review)*; Electricity Authority of Cyprus: Nicosia, Cyprus, 2009; Volume 13, pp. 1513–1522.
27. Lemian, D.; Bode, F. Battery-Supercapacitor Energy Storage Systems for Electrical Vehicles: A Review. *Energies* **2022**, *15*, 5683. [CrossRef]
28. Lukic, S.M.; Cao, J.; Bansal, R.C.; Rodriguez, F.; Emadi, A. Energy Storage Systems for Automotive Applications. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2258–2267. [CrossRef]
29. Schmuch, R.; Wagner, R.; Hörpel, G.; Placke, T.; Winter, M. Performance and cost of materials for lithium-based rechargeable automotive batteries. *Nat. Energy* **2018**, *3*, 267–278. [CrossRef]

30. Winter, M.; Barnett, B.; Xu, K. Before Li Ion Batteries. *Chem. Rev.* **2018**, *118*, 11433–11456. [CrossRef]
31. Jon, A.S.; Giuseppe, G. *Technology for Dynamic on-Road Power Transfer to Electric Vehicles*; Sintef Energy Research: Trondheim, Norway, 2018. Available online: https://www.sintef.no/globalassets/project/elingo/18-0733-rapport-3-technology-for-dynamic-on-road-6-til-nett.pdf (accessed on 15 May 2023).
32. Song, Y.; Liu, Z.; Rønnquist, A.; Nåvik, P.; Liu, Z. Contact wire irregularity stochastics and effect on high-speed railway pantograph–catenary interactions. *IEEE Trans. Instrum. Meas.* **2020**, *69*, 8196–8206. [CrossRef]
33. Ali, S.A.; Pickert, V.; Alharbi, M.A.; Li, H.; Patsios, H. Wheel Hub Active Power Collection Unit for Dynamic Conductive Road Charging. *IEEE Trans. Transp. Electrif.* **2022**, *9*, 1927–1936. [CrossRef]
34. Veyrunes, P.; Duprat, P.; Hourtane, J.L. Ground-level feeding systems from rail to road. In Proceedings of the 2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), Harbin, China, 7–10 August 2017.
35. Tajima, T.; Noguchi, W.; Aruga, T. Study of a dynamic charging system for achievement of unlimited cruising range in EV. In Proceedings of the SAE 2015 World Congress and Exhibition, Detroit, MI, USA, 21–23 April 2015.
36. Bateman, D.; Leal, D.; Reeves, S.; Emre, M.; Stark, L.; Ognissanto, F.; Myers, R.; Lamb, M. *Electric Road Systems: A Solution for the Future?* TRL Limited: Wokingham, UK, 2018; p. 138.
37. Universities study battery traction. *Railw. Gaz. Int.* **2020**, *176*, 17.
38. Zhao, J. Design and Analysis of Electric Main Circuit of CHD2A1 Electric Battery Trailer. *Railw. Locomot. Car* **2021**, *41*, 40–44. (In Chinese)
39. Wen, Z.; Chen, F.; Song, F.; Wu, C. Improvement and Realization of Traction Function of Storage Batteries on Trains of Add-on Purchase for Shenzhen Metro No.3 Line. *Roll. Stock* **2020**, *58*, 29–32. (In Chinese)
40. Zhou, F. Properties and applications of new sodium battery materials and their influence on industrial development. *Chin. J. Appl. Chem.* **2022**, *39*, 349–350. (In Chinese)
41. Yaïci, W.; Kouchachvili, L.; Entchev, E.; Longo, M. Dynamic Simulation of Battery/Supercapacitor Hybrid Energy Storage System for the Electric Vehicles. In Proceedings of the 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov, Romania, 3–6 November 2019.
42. Gonzalez, A.; Goikolea, E.; Andoni Barrena, J. Review on supercapacitors: Technologies and materials. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1189–1206. [CrossRef]
43. El Fadil, H.; Giri, F.; Guerrero, J.M.; Tahri, A. Modeling and Nonlinear Control of a Fuel Cell/Supercapacitor Hybrid Energy Storage System for Electric Vehicles. *IEEE Trans. Veh. Technol.* **2014**, *63*, 3011–3018. [CrossRef]
44. Wang, X.; Qi, H.; Sun, F.; Zhao, Z. Powertrain system design of hydrogen fuel cell range-extended hybrid electric locomotive. *Electr. Drive Locomot.* **2022**, 110–115. (In Chinese)
45. Boretti, A. High-efficiency internal combustion engine for hybrid hydrogen-electric locomotives. *Int. J. Hydrogen Energy* **2022**, *48*, 1596–1601. [CrossRef]
46. Chen, W.; Bu, Q.; Liu, Z.; Li, Q.; Sun, B.; Li, M. Power system design for a fuel cell hybrid power tram. *J. Traffic Transp. Eng.* **2016**, *51*, 430–436. (In Chinese)
47. Xu, X.; Yang, R.; Ji, Y.; Zhang, X.; Jiang, L.; Li, K. Review on key technologies of hydrogen fuel cell powered vessels. *J. Traffic Transp. Eng.* **2022**, *22*, 47–67. (In Chinese)
48. Liu, W.; Placke, T.; Chau, K.T. Overview of batteries and battery management for electric vehicles. *Energy Rep.* **2022**, *8*, 4058–4084. [CrossRef]
49. Yang, F.; Li, S.; Shen, Q.; Yang, G. Development Trend of Green Shipping and Application Prospect of Fuel Cell Ships. *Ship Eng.* **2020**, *42*, 1–7. (In Chinese)
50. Fan, A.; He, Y.; Yan, X.; Wang, J. Concept and Key Technologies of Intelligent New Energy Ship. *Ship Eng.* **2020**, *42*, 9–14. (In Chinese)
51. Tian, R. Trains equipped with traction batteries began passenger service. *Foreign Railw. Locomot. Mot. Car* **2022**, 27. (In Chinese)
52. Li, L.; Zhu, B.; Ren, C. Development and Application Practice of Hybrid Locomotive at Home and Abroad. *Electr. Drive Locomot.* **2020**, *82*, 73–76. (In Chinese)
53. Cao, W. It is high time to develop pure electric boat sails. *Marit. China* **2022**, 64–66. (In Chinese)
54. Case Study of "Greater Bay Area One" Luxury Passenger Ship. Available online: https://www.catl.com/othercase/445.html (accessed on 14 August 2020). (In Chinese).
55. EVE Helps China's First Marine Pure Electric Tugboat Set Sail! Available online: https://www.evebattery.com/news-611 (accessed on 26 August 2021). (In Chinese).
56. The World's First Thousand-Ton New-Energy Electric Ship Has Received Its Ship in Nansha. Available online: http://www.gzns.gov.cn/zfxxgkml/gzsnsqkjgyhxxhj/zwdt/content/mpost_5349809.html (accessed on 28 January 2019). (In Chinese)
57. Sina Hybrid Automotive Industry Depth Report: Hybrid Market Emerging, Autonomous Vehicle Enterprises Such as Japan Rise. Available online: https://k.sina.com.cn/article_7426890874_1baad5c7a001015998.html (accessed on 6 March 2023). (In Chinese).
58. Flirt H2: Sbcta and Stadler Strengthen Sustainable Rail Transport in the USA. Available online: https://www.stadlerrail.com/en/media/article/flirt-h2-sbcta-and-stadler-strengthen-sustainable-rail-transport-in-the-usa/1134/ (accessed on 15 May 2023).
59. Zhu, Y. The world's first commercial fuel cell/ultracapacitor hybrid streetcar has rolled off the assembly line. *Electr. Drive Locomot.* **2016**, 105. (In Chinese)
60. Bruner, M. Germania: Il treno a idrogeno Coradia iLint vince il German Sustainability Award. *Ing. Ferrov.* **2022**, *77*, 65–67.

61. Takayuki, L. Development of fuel cell hybrid test railway vehicle. *Foreign Railw. Locomot. Mot. Car* **2021**, 1–4. (In Chinese)
62. Siemens, DB plan fuel cell Mireo Plus H train. *Fuel Cells Bull.* **2020**, *2020*, 6. [CrossRef]
63. McConnell, V.P. Now, voyager? The increasing marine use of fuel cells. *Fuel Cells Bull.* **2010**, *2010*, 12–17. [CrossRef]
64. Sattler, G. Fuel cells going on-board. *J. Power Sources* **2000**, *86*, 61–67. [CrossRef]
65. Liu, G. Research on fuel cell propulsion ships. *Mar. Electr. Electr. Technol.* **1994**, *21*, 49–57. (In Chinese)
66. Krummrich, S.; Tuinstra, B.; Kraaij, G.; Roes, J.; Olgun, H. Diesel fuel processing for fuel cells—DESIRE. *J. Power Sources* **2006**, *160*, 500–504. [CrossRef]
67. Tse, L.K.C.; Wilkins, S.; McGlashan, N.; Urban, B.; Martinez-Botas, R. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. *J. Power Sources* **2011**, *196*, 3149–3162. [CrossRef]
68. Shao, X. *The First Fuel Cell Yacht, the Lihu, Has Passed the Trial*; Wuxi Daily: Wuxi, China, 2021. (In Chinese)
69. sunfire 50 kW SOFC for ship-integrated fuel cell project in Germany. *Fuel Cells Bull.* **2015**, *2015*, 3–4. [CrossRef]
70. Fuel cell system on FellowSHIP supply vessel is hybridised. *Fuel Cells Bull.* **2012**, *2012*, 3–4.
71. Strazza, C.; Del Borghi, A.; Costamagna, P.; Traverso, A.; Santin, M. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. *Appl. Energy* **2010**, *87*, 1670–1678. [CrossRef]
72. Jiang, D.; Song, L.; Wang, L. Analysis on Impact of Energy Consumption and Carbon Emission of New Energy Vehicles Based on GREET Software. *Automob. Appl. Technol.* **2022**, *47*, 15–21. (In Chinese)
73. Wang, Q.; Wang, C.; Li, S. Energy-saving Technology for New Energy Vehicles based on Low-emission Orientation. *Auto Time* **2021**, 106–107. (In Chinese)
74. Xia, C.; Ma, D.; Cai, B.; Chen, B.; Liu, H.; Yang, L.; Lv, C. Analysis of carbon emissions abatement technology and cost in road transport sector of China. *Environ. Eng.* **2021**, *39*, 50–56. (In Chinese)
75. Du, H.; Li, Q.; Liu, X.; Peng, B.; Southworth, F. Costs and potentials of reducing CO_2 emissions in China's transport sector: Findings from an energy system analysis. *Energy* **2021**, *234*, 121163. [CrossRef]
76. Gopal, A.R.; Park, W.Y.; Witt, M.; Phadke, A. Hybrid- and battery-electric vehicles offer low-cost climate benefits in China(Article). *Transp. Res. Part D Transp. Environ.* **2018**, *62*, 362–371. [CrossRef]
77. Cipek, M.; Pavković, D.; Krznar, M.; Kljaić, Z.; Mlinarić, T.J. Comparative analysis of conventional diesel-electric and hypothetical battery-electric heavy haul locomotive operation in terms of fuel savings and emissions reduction potentials. *Energy* **2021**, *232*, 121097. [CrossRef]
78. Scott, D.S.; Steinberg, B.A. Hydrogen vs diesel fueled locomotives: A technoeconomic appraisal. *Int. J. Hydrogen Energy* **1984**, *9*, 101–107.
79. Soleymani, M.; Yoosofi, A.; Kandi-D, M. Sizing and energy management of a medium hybrid electric boat. *J. Mar. Sci. Technol.* **2015**, *20*, 739–751. [CrossRef]
80. Manouchehrinia, B.; Molloy, S.; Dong, Z.; Gulliver, A.; Gough, C. Emission and life_cycle cost analysis of hybrid and pure electric propulsion systems for fishing boats. *J. Ocean Technol.* **2018**, *13*, 66–87.
81. Ye, M.; Sharp, P.; Brandon, N.; Kucernak, A. System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping. *Int. J. Hydrogen Energy* **2022**, *47*, 8565–8584. [CrossRef]
82. Circular of the General Office of the Ministry of Transport on Accelerating the Pilot of the New-Generation National Traffic Control Network and Smart Highways. Available online: https://xxgk.mot.gov.cn/2020/jigou/zhghs/202006/t20200630_3320182.html (accessed on 27 February 2018). (In Chinese)
83. Meng, G. A practical study on the construction of "Intelligent Expressway" in Zhejiang. *Informatiz. Constr.* **2012**, 21–23. (In Chinese)
84. The Ministry of Industry and Information Technology. *High-Level Automatic Driving Data Interaction Content Based on Vehicle-Road Collaboration*; The Ministry of Industry and Information Technology, PRC: Beijing, China, 2021. (In Chinese)
85. Li, Y.; Zhang, T.; Wang, S.; Wang, J.; Chen, L. Research on intelligent high-speed energy saving and emission reduction based on vehicle-road collaboration scenario. *China ITS J.* **2022**, 95–97. (In Chinese)
86. Xie, L.; Zhu, L.; Zhu, F. Discussion on the construction of intelligent Expressway under the concept of carbon neutrality. *China ITS J.* **2022**, *104*, 44–45. (In Chinese)
87. Yang, L. Application of intelligent power supply in expressway. *ShuZiHua YongHu* **2019**, *25*, 182. (In Chinese)
88. Yu, L.; Yang, F. Design and application of intelligent highway tunnel energy-saving lighting system. *Digit. Technol. Appl.* **2022**, *40*, 190–193. (In Chinese)
89. Wang, H.; Yuan, J.; Chen, Z.; Ma, Y.; Dong, H.; Yuan, S.; Yang, J. Review and Prospect of Key Techniques for Vehicle-Station-Network Integrated Operation in Smart City. *Trans. China Electrotech. Soc.* **2022**, *37*, 112–132. (In Chinese)
90. He, F. Research on Intelligent Management System of Electric Vehicle Charging Station. *Sci. Technol. Vis.* **2018**, 139–140. (In Chinese)
91. Liu, G.; Zhu, L.; Jiang, G. Smart Lighting System of Highway Tunnels Based on KNX Technology. *Tunn. Constr.* **2021**, *41*, 281–287. (In Chinese)
92. Wang, Z. Study on Energy-Saving Technology of Highway Tunnel Lighting System. Master's Thesis, East China Jiaotong University, Nanchang, China, 2011. (In Chinese).

93. Zulkepele, S.A.S.; Al–Humairi, S.N.S.; Chandrasekaran, J.S.; Ahmad, A.S.; Daud, R.J. Towards A Clean Energy: Design A Wind-Solar Hybrid Power Generation System for Highway Streetlights. In Proceedings of the 2021 IEEE 9th Conference on Systems, Process and Control (ICSPC 2021), Malacca, Malaysia, 10–11 December 2021.
94. Ma, T.; Li, S.; Gu, W.; Weng, S.; Peng, J.; Xiao, G. Solar energy harvesting pavements on the road: Comparative study and performance assessment. *Sustain. Cities Soc.* **2022**, *81*, 103868. [CrossRef]
95. Yang, T.; Yan, D. Construction of the renewable energy eco-system: Strategic distributions along the chain of "photovoltaics-energy storage-electric vehicles". *J. Phys. Conf. Ser.* **2019**, *1347*, 012002. [CrossRef]
96. Hammoud, M.; Hallal, J.; Moussa, T.; Kassem, H. Techno-economic study of a hybrid power generation system at the Lebanese coastal highways. *Int. J. Appl. Power Eng.* **2021**, *10*, 373–382. [CrossRef]
97. Yin, S.; Liu, X.; Cao, B. Practice and Thoughts on the Application of Energy Performance Contracting in Large Railway Passenger Stations. *Shanghai Energy Conserv.* **2019**, 839–842. (In Chinese)
98. Qu, H.; Li, J. Introduction of the Energy Management System of Shanghai Hongqiao Railway Terminal Station. *Build. Electr.* **2011**, *30*, 31–35. (In Chinese)
99. Li, Z. Build Intelligent Passenger Station with Modular Distributed Control System. *Railw. Signal. Commun.* **2011**, *47*, 64–65. (In Chinese)
100. Guo, M.; Du, Z.; Meng, X. The entire Beijing-Xiong intercity railway line has been completed, and the Xiongan station has been put into use simultaneously. *Urban Mass Transit* **2021**, *24*, 36. (In Chinese)
101. Shi, J.; Li, Q. "Intelligent" Technical Guidelines for Chongqing East Railway Station Building and Supporting Hub Area. *Math. Probl. Eng.* **2021**, *2021*, 1–12. [CrossRef]
102. Feng, C.; Gao, Z.; Sun, Y.; Chen, P. Electric railway smart microgrid system with integration of multiple energy systems and power-quality improvement. *Electr. Power Syst. Res.* **2021**, *199*, 107459. (In Chinese) [CrossRef]
103. Jiang, X.; Chen, X. Current Situation and Development of Intelligent Traction Power Supply System. *China Railw.* **2019**, 14–21. (In Chinese)
104. Li, X. Research on Design Scheme of Intelligent Traction Substation. Master's Thesis, Southwest Jiaotong University, Chengdu, China, 2017. (In Chinese).
105. Editorial office of Electr. Power Inf. Commun. Technol. The first new-generation smart substation of State Grid Jiangxi Electric Power was put into operation. *Electr. Power Inf. Commun. Technol.* **2015**, *40*. (In Chinese)
106. Liu, Q. Application of IEC61850 Standard in Intelligent Substation. Master's Thesis, Dalian University of Technology, Dalian, China, 2019. (In Chinese).
107. Gao, Q.; Pang, L.; Teng, Q. Analysis of integrated Automation system of Chinese high-speed railway traction power supply. *Encyclopedia* **2018**, 717. (In Chinese)
108. Zhu, F. Study on Standard System for Intelligent Traction Power Supply System. *Electr. Railw.* **2018**, *29*, 6–8. (In Chinese)
109. Wang, H. Research on the Key Technology of Primary Equipment in Intelligent Traction Substation. *High Speed Railw. Technol.* **2017**, *8*, 68–71. (In Chinese)
110. Qiao, L. Research and Development Prospect of Railway Intelligent Traction Power Supply System Technologies. *Encyclopedia* **2020**, 1839. (In Chinese)
111. Yang, S.; Tian, L.; Guo, X.; Dong, W. Research on Safety Testing Technology of the Intelligent Traction Power Supply System of Beijing-Zhangjiakou High-Speed Railway. In Proceedings of the 5th International Conference on Electrical Engineering and Information Technologies for Rail Transportation (EITRT), Qingdao, China, 22–24 October 2021; Volume 864, pp. 459–467.
112. Chen, Y. Design of 35 kV Intelligent Substation Integrated Automation System Based on Acrel-1000. *Autom. Appl.* **2022**, 132–134. (In Chinese)
113. Ai, G.; Hao, X.; Liu, X.; Yan, D. Energy saving potential research of photovoltaic system installed over high-speed railway. *Acta Energ. Sol. Sin.* **2023**, *44*, 409–417. (In Chinese)
114. Hu, H.; Ge, Y.; Huang, Y.; Ai, L.; Zhou, Y.; He, Z.; Gao, S. "Source-network-train-storage" Integrated Power Supply System for Electric Railways. *Proc. CSEE* **2022**, *42*, 4374–4391. (In Chinese)
115. Xu, P.; Zhou, J.; Li, D.; Hao, D.; Wu, X.; Wei, F.; Kong, L.; Xu, Y.; Lv, X. Research on Self-Cleaning Portable Photovoltaic Power Generation System for Applications Along the Railway. *SSRN Electron. J.* **2022**, 31. [CrossRef]
116. Zhong, Z.; Zhang, Y.; Shen, H.; Li, X. Optimal planning of distributed photovoltaic generation for the traction power supply system of high-speed railway. *J. Clean. Prod.* **2020**, *263*, 121394. [CrossRef]
117. Alam, K.; Khan, T.; Azad, A.; Munasib, S.; Arif, K.; Hasan, A.; Kabir, M. Modeling and Computation of a Solar-Piezoelectric Hybrid Power Plant for Railway Stations. In Proceedings of the 2012 International Conference on Informatics, Electronics & Vision (ICIEV), Dhaka, Bangladesh, 18–19 May 2012; pp. 155–159.
118. Kameya, T.; Uddin, J.; Kezuka, H.; Suzuki, G.; Katsuma, H. Demonstration Experiment for Energy Storage and Rapid Charge System for the Solar Light Rail. *Energy Procedia* **2014**, *57*, 906. [CrossRef]
119. Nurmanova, V.; Bagheri, M.; Phung, T.; Panda, S.K. Feasibility study on wind energy harvesting system implementation in moving trains. *Electr. Eng.* **2018**, *100*, 1837–1845. [CrossRef]
120. Thadani, H.L.; Zaaba, F.D.; Shahrizal, M.R.M.; Jaj, A.S.J.A.J.S.; Go, Y.I. Design and performance evaluation of vertical axis wind turbine for wind energy harvesting at railway. *World J. Sci. Technol. Sustain. Dev.* **2021**, *18*, 190–217. [CrossRef]

121. Ma, W.; Wei, W.; Hu, R.; Wang, Z. Auxiliary power supply system of passenger train based on photovoltaic and energy storage. In Proceedings of the 2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA), Hefei, China, 5–7 June 2016.
122. Feng, T.; Li, W.; Bai, J. Design and Application of Energy Efficiency Management and Control Integrated System in Large Railway Station Building. *Electr. Technol. Intell. Build.* **2018**, *12*, 65–70. (In Chinese)
123. Zhang, G.; Dong, J.; Qin, J.; Li, W. Research on energy-saving technology of high-speed railway station lighting system based on artificial intelligence. *Manuf. Autom.* **2021**, *43*, 127–130. (In Chinese)
124. Liu, H. Research and Application of Intelligent Power Saving Technology in Railway Passenger Stations. *Railw. Tech. Innov.* **2020**, 124–128. (In Chinese)
125. The five departments jointly issued the 14th Five-Year Development Plan for Standardization of Transportation. *China Highw.* **2021**, *64*, 18–19. (In Chinese)
126. Yang, R.; Yi, Y. Design of dismantling and assembling process of new type twistlock in automatic container terminal. *Containerization* **2014**, *25*, 33–36. (In Chinese)
127. Gao, F.; Tang, Y.; Nie, X.; Yu, B.; Hu, K. Review of research and application on automatic mooring system of ships in ports. *China Harb. Eng.* **2022**, *42*, 11–15. (In Chinese)
128. Li, J. Development and challenge of automated container terminals in China. *Port Econ.* **2016**, 29–32. (In Chinese)
129. Yan, X.; Liu, J.; Zhang, Y.; Li, S.; Wang, T. State-of-the-art and prospect of intelligent shipping. *Mod. Metall.* **2022**, *2*, 7–18. (In Chinese)
130. He, J. Application and development trend of handling process system in automated container terminal. *Port Waterw. Eng.* **2018**, 199–203. (In Chinese)
131. Li, X.; Peng, Y.; Wang, W.; Huang, J.; Liu, H.; Song, X.; Bing, X. A method for optimizing installation capacity and operation strategy of a hybrid renewable energy system with offshore wind energy for a green container terminal. *Ocean Eng.* **2019**, *186*, 106125. [CrossRef]
132. Acciaro, M.; Ghiara, H.; Cusano, M.I. Energy management in seaports: A new role for port authorities. *Energy Policy* **2014**, *71*, 4–12. [CrossRef]
133. Seddiek, I.S. Application of renewable energy technologies for eco-friendly sea ports. *Ships Offshore Struct.* **2020**, *15*, 953–962. [CrossRef]
134. Gutierrez-Romero, J.E.; Esteve-Pérez, J.; Zamora, B. Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* **2019**, *255*, 113883. [CrossRef]
135. Ahamad, N.; Othman, M.; Vazquez, J.C.; Guerrero, J.M.; Su, C.-L. Optimal sizing and performance evaluation of a renewable energy based microgrid in future seaports (Conference Paper). In Proceedings of the IEEE International Conference on Industrial Technology, Lyon, France, 20–22 February 2018; pp. 1043–1048.
136. Misra, A.; Venkataramani, G.; Gowrishankar, S.; Ayyasam, E.; Ramalingam, V. Renewable Energy Based Smart Microgrids—A Pathway to Green Port Development. *Strateg. Plan. Energy Environ.* **2018**, *37*, 17–32. [CrossRef]
137. Fang, S.; Wang, C.; Liao, R.; Zhao, C. Optimal power scheduling of seaport microgrids with flexible logistic loads. *IET Renew. Power Gener.* **2022**, *16*, 2711–2720. [CrossRef]
138. Chen, H.; Zhu, X.; Sun, R.; Wang, B. Thoughts on the construction and application of port intelligent energy system. *Mar. Equip./Mater. Mark.* **2019**, 101–102. (In Chinese)
139. Sciberras, E.A.; Zahawi, B.; Atkinson, D.J.; Juandó, A.; Sarasquete, A. Cold ironing and onshore generation for airborne emission reductions in ports. *Proc. Inst. Mech. Eng. Part M-J. Eng. Marit. Environ.* **2016**, *230*, 67–82. [CrossRef]
140. Yigit, K.; Acarkan, B. A new electrical energy management approach for ships using mixed energy sources to ensure sustainable port cities. *Sustain. Cities Soc.* **2018**, *40*, 126–135. [CrossRef]
141. HUAWEI Smart Tianjin Port, A Best Practice in Smart Port Operations. Available online: https://e.huawei.com/en/material/enterprise/570aadd8e1a445f1a955db461e6e8ca5 (accessed on 17 October 2021). (In Chinese).
142. Zis, T.; North, R.J.; Angeloudis, P.; Ochieng, W.Y.; Bell, M.G.H. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports(Article). *Marit. Econ. Logist.* **2014**, *16*, 371–398. [CrossRef]
143. Peng, C. Application of Shore Power for Ocean Going Vessels at Berth in China. In Proceedings of the 2016 International Conference on Sustainable Energy, Environment and Information Engineering (SEEIE 2016), Bangkok, Thailand, 20–21 March 2016.
144. Peng, Y.; Wang, W.; Liu, K.; Li, X.; Tian, Q. The Impact of the Allocation of Facilities on Reducing Carbon Emissions from a Green Container Terminal Perspective. *Sustainability* **2018**, *10*, 1–19. [CrossRef]
145. Yang, Y.; Chang, W. Impacts of electric rubber-tired gantries on green port performance. *Res. Transp. Bus. Manag.* **2013**, *8*, 67–76. [CrossRef]
146. Satsangi, S.; Kumbhar, G.B. Energy savings estimation of a distribution system in presence of intelligent volt-VAr control based on IEEE Std. 1547-2018. *CSEE J. Power Energy Syst.* **2022**, *8*, 1–10.
147. The 2022 Global Energy Transition Forum Was Held in Beijing. Available online: http://www.nea.gov.cn/2022-09/23/c_1310665286.htm (accessed on 23 September 2022). (In Chinese)
148. Kerem, A. Investigation of carbon footprint effect of renewable power plants regarding energy production: A case study of a city in Turkey. *J. Air Waste Manag. Assoc.* **2022**, *72*, 294–307. [CrossRef]
149. Bayazıt, Y. The effect of hydroelectric power plants on the carbon emission: An example of Gokcekaya dam, Turkey. *Renew. Energy* **2021**, *170*, 181–187. [CrossRef]

150. Liu, P.; Liu, L.; Xu, X.; Zhao, Y.; Niu, J.; Zhang, Q. Carbon footprint and carbon emission intensity of grassland wind farms in Inner Mongolia. *J. Clean. Prod.* **2021**, *313*, 127878. [CrossRef]
151. Editorial office of Sino-Glob. Energy. Photovoltaic power will cost less than coal. *Sino-Glob. Energy* **2020**, 102. (In Chinese)
152. Song, J. The Solution and Architecture of Edge Computing Network of Cooperative Vehicle Infrastructure System in Smart City. *Autom. Panor.* **2022**, *39*, 38–41. (In Chinese)
153. Lin, Y. Discussion on the application of vehicle-road collaboration technology in intelligent expressway. *East China Sci. Technol.* **2019**, 16–17. (In Chinese)
154. Hong, W.; Chen, J. Industry segmentation and market space of vehicle and road collaboration business. *C-Enterp. Manag.* **2021**, 61–63. (In Chinese)
155. Chen, L. Exploration of intelligent transportation based on 5G Internet of Everything. *Intell. City* **2019**, *5*, 88–89. (In Chinese)
156. SAE updated driving automation classification Standard. *Intell. Connect. Veh.* **2021**, 17. (In Chinese)
157. John, A.S. Follow the leaders: Waymo on top among automated driving systems companies, Guidehouse report finds. *Automot. News* **2021**, *95*, 18.
158. Guo, L. Real-Tine Optimal Automotive Control for Intilligent Energy Conservation an Road Test. Ph.D. Dissertation, Jilin University, Jilin, China, 2019. (In Chinese).
159. Zhang, J.; Ioannou, P.A. Longitudinal control of heavy trucks in mixed traffic: Environmental and fuel economy considerations(Article). *IEEE Trans. Intell. Transp. Syst.* **2006**, *7*, 92–104. [CrossRef]
160. Chang, Y.; Zhang, C.; Zhang, P.; Sun, C. A Speed Control Method of Non-signalized Intersection Based on Gap Optimization Under Connected Vehicle Environment. *J. Chongqing Univ. Technol. (Nat. Sci.)* **2021**, *35*, 10–17. (In Chinese)
161. Jin, H.; Ding, F. A Study on Economic Speed in Lane-change Maneuvers of Intelligent Vehicles. *Automot. Eng.* **2018**, *40*, 542–546, 553. (In Chinese)
162. Xiong, S. Research on Eco-Driving Control Strategies for Autonomous Driving Vehicle. Ph.D. Dissertation, Tianjin University, Tianjin, China, 2020. (In Chinese).
163. He, H.; Shi, M.; Cao, J.; Han, M. Regenerative Braking Energy Management Strategy Based on Dynamic Programming. *J. Chongqing Univ. Technol. (Nat. Sci.)* **2021**, *35*, 74–80. (In Chinese)
164. Xiong, W.; He, T.; Kuang, W. Design and implementation on section simulation system of CTCS-2. *Appl. Electron. Tech.* **2017**, *43*, 128–131. (In Chinese)
165. Fan, M. Conversation on Technical Development of Chinese Train Control System. *Railw. Signal. Commun.* **2019**, *55*, 41–48. (In Chinese)
166. The Ministry of Railways of the People's Republic of China. *Technical Specification for CCTS-3 Class Train Control Vehicle-Mounted Equipment of the Ministry of Railways of the People's Republic of China (Interim)*; China Railway Publishing House Co., Ltd.: Beijing, China, 2012; p. 116. (In Chinese)
167. Ning, B.; Liu, C. Technology and Application of Train Operation Control System for China Rail Transit System. *J. China Railw. Soc.* **2017**, *39*, 1–9. (In Chinese)
168. Mo, Z. Overall Technical Solution of CTCS-4 Level Train Control System. *Railw. Signal. Commun.* **2019**, *55*, 34–40. (In Chinese)
169. Clark, S. *A History of Railway Signalling (from the Bobby to the Balise)*; Lloyds Register Rail: London, UK, 2012.
170. Kunihiko, I. Application of Optimization Theory for Bounded State Variable Problems to the Operation of Train. *Bull. JSME* **1968**, *11*, 857–865.
171. Li, Y.; Hou, Z. Study on energy-saving control for train based on genetic algorithm. *J. Syst. Simul.* **2007**, *19*, 1–4.
172. Li, M.; Zhou, F.; Wu, L.; Hou, P. Research on Management and Control System of Locomotive Regenerative Braking Energy. *J. Power Supply* **2021**, *19*, 108–116. (In Chinese)
173. Lechelle, S.A.; Mouneimne, Z.S. OptiDrive: A practical approach for the calculation of energy-optimised operating speed profiles. *IET Semin. Dig.* **2010**, *2010*, 1–8.
174. Li, G.; Lin, J.; Zhuang, Z.; He, L. A Research on Energy-Saving Train Control of Urban Mass Transit based on Regenerative Brake. *Railw. Transp. Econ.* **2019**, *41*, 121–126. (In Chinese)
175. Li, Y.; Zhang, H.; Bu, L.; Liu, W.; Zhang, J.; Wu, T. Discussion of the energy-saving effect of inverter feedback devices from energy consumption of traveling trains. *J. Railw. Sci. Eng.* **2020**, *17*, 2381–2386. (In Chinese)
176. Li, G.; Liu, Y.; Huang, J.; Liu, Y. Study on Train Energy-efficient Automatic Driving from Learning Human Driver Patterns. *J. Hunan Univ. (Nat. Sci.)* **2019**, *46*, 128–140. (In Chinese)
177. Pyper, A.; Heyns, P.S. Evaluating a distributed regenerative braking system for freight trains. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **2019**, *233*, 844–856. [CrossRef]
178. Liu, H.; Liu, Q.; Cai, D.; Li, X.; Xuan, H.; Zeng, X. Study on division method of inland waterway development stage. In Proceedings of the 2nd International Conference on Transportation Information and Safety: Improving Multimodal Transportation Systems—Information, Safety, and Integration, ICTIS 2013, Wuhan, China, 29 June–2 July 2013.
179. Guo, T.; Liu, H.; Wan, D.; Chu, X.; Lei, G. System architecture and key technology research of Yangtze River intelligent waterway. *Port Waterw. Eng.* **2012**, *6*, 140–145. (In Chinese)
180. Li, S. Thinking on the practice and development trend of intelligent maritime supervision. *China Water Transp.* **2013**, 61–62. (In Chinese)

181. Ma, F.; Wu, Q.; Yan, X.; Chu, X.; Zhang, D. Classification of Automatic Radar Plotting Aid targets based on improved Fuzzy C-Means. *Transp. Res. Part C Emerg. Technol.* **2015**, *51*, 180–195. [CrossRef]
182. Gourgoulis, D.; Yakinthos, C. An Intelligent Maritime Workplace using IT technologies. In Proceedings of the 2008 Third International Conference on Dependability of Computer Systems DepCoS-RELCOMEX, Szklarska Poreba, Poland, 26–28 June 2008.
183. Tusseyeva, I.; Bukhari, A.C.; Lee, B.-G.; Kim, Y.-G. An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system. *Expert Syst. Appl.* **2013**, *40*, 1220–1230.
184. Lu, Y.; Zhan, H.; Liu, Q.; Jin, J. The world's first fully automatic, zero emission container ship has flown in. *Navigation* **2022**, 8–11. (In Chinese)
185. Feng, S. Smart Ship Development: How Do Japan and Europe share the same path? *China Ship Surv.* **2021**, 16–19. (In Chinese)
186. Li, Y.; Wang, Y. Development and prospect of ship intelligent navigation technology. *China Water Transp.* **2022**, 53–55. (In Chinese)
187. Zhang, B.; Geng, X.; Li, Y.; Wen, J.; Yu, Q.; Feng, H. Development status and trend of intelligent navigation technology. *Sci. Technol. Rev.* **2022**, *40*, 51–56. (In Chinese)
188. Geng, X.; Luo, J.; Wang, Y.; Li, C. Governance of intelligent sailing ships. *Ship Eng.* **2021**, *43*, 26–30. (In Chinese)