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The Benefits of Waste Heat Recovery in New Energy Vehicles

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Abstract:

The rapid development of new energy vehicles (NEVs) has put forward higher requirements for energy utilization efficiency. The installation of a waste heat recovery system (WHRS) in NEVs can enhance their energy utilization efficiency and market competitiveness. This paper systematically analyzes the technical feasibility of waste heat recovery technology in the field of NEVs and the economic benefits it brings. The study shows that the application of waste heat recovery can significantly improve the low temperature performance of NEVs, with the coefficient of performance (COP) increasing by an average of 10% to 20%. It can reduce the dependence on fossil energy, increase the overall performance, mileage, and battery life of the vehicle, and enhance market competitiveness. Future research can focus on the development of small and efficient waste heat recovery devices and intelligent vehicle thermal management technologies to promote large scale application and contribute to the sustainable development of the NEV industry.

Keywords: Waste heat recovery; New energy vehicles; Electric energy; Economic benefits.

1. Introduction

With the intensification of the global energy crisis and environmental issues, NEVs, characterized by their cleanliness and high efficiency, have become an important direction for the transformation of the automotive industry structure. The development of NEVs can not only reduce the transportation industry's dependence on fossil fuels but also significantly decrease greenhouse gas emissions. During the operation of NEVs, excess heat is inevitably generated. If this heat can be effectively recovered and utilized, it will not only make full use of energy but also improve the performance and lifespan of fuel cells. Meanwhile, waste heat recovery technologies for traditional internal combustion engine vehicles and ships have made significant progress. For example, technologies such as thermoelectric conversion, organic Rankine cycle(ORC), and supercritical carbon dioxide cycle have been used to convert waste heat into electricity or other forms of usable energy [1]. These technologies have shown great potential in improving energy utilization efficiency and reducing carbon emissions. Thermoelectric conversion refers to the direct generation of voltage across the ends of a thermoelectric material when a temperature difference is formed, due to the Seebeck effect of the thermoelectric material, thus converting thermal energy into electrical energy.

Currently, the application of waste heat recovery technologies in NEVs mainly involves methods such as thermoelectric conversion, ORC, heat pump systems, and phase change heat storage. The integration of thermoelectric materials, which utilize the Seebeck effect to directly convert waste heat into electricity, and the application of ORC systems for recovering waste heat from engine exhaust are research focuses in this field. In addition, the combination of heat pump technology with air conditioning systems to utilize waste heat for passenger cabin heating, as well as the optimization of battery thermal management using phase change heat storage technology, are also research priorities [2][3]. Therefore, waste heat recovery can significantly improve the heating efficiency of NEVs in low temperature environments, reduce dependence on high energy consumption heating systems, and extend the driving mileage. Moreover, by recovering waste heat from batteries and electric motors, the overall system efficiency can be effectively enhanced [4][5].

This essay, based on the issue of the benefits of waste heat recovery in NEVs, first reviews the basic principles of waste heat recovery technology, then analyzes the technical feasibility and economic benefits, and finally puts forward relevant policy suggestions and outlooks for the future. This study aims to provide references for the future development of NEVs.

2. The Source of Waste Heat in NEVs

2.1 Waste Heat From the Motor System

The electric motors of NEVs generate a significant amount of heat during operation. The heat generated by the motor primarily comes from four sources. One is the Joule heat generated by the resistance when the current passes through the motor winding (copper wire). The second is the hysteresis loss (energy consumption) and eddy current loss (Joule heat) caused by the alternating magnetic field in the motor core. The third is mechanical loss, such as bearing friction, rotor wind resistance, brush friction and so on. The fourth is the stray loss, such as magnetic field distortion, local eddy current, etc., but this kind of loss accounts for a small proportion. These heat sources vary with environmental conditions, and some of the heat cannot be directly utilized and is typically considered waste heat. Through waste heat recovery technology, this waste heat can be effectively utilized.

2.2 Waste Heat From the Battery System

In daily life, mobile phone batteries will heat up due to the chemical reactions inside during charging and discharging. NEV batteries have a larger capacity and more intense chemical reactions, and thus generate a much larger amount of heat during charging and discharging. If this heat is not managed properly, it may lead to excessively high battery temperatures. Once the threshold is reached during high-speed driving, it will cause serious damage to the battery. There are three main sources of waste heat in the battery system. First, when the battery is charged and discharged, the current flowing through the internal materials (electrodes, electrolytes, etc.) generates joule heat due to the internal resistance of the materials. Second, electrochemical reactions occur, such as the process of lithium ion detachment from the electrode material, which is accompanied by exothermic reactions. Third, the polarization phenomenon caused by the lag in ion migration rate during battery operation will consume extra energy and convert it into heat.

2.3 Residual Heat

While passengers are turning on and off the air conditioning and the vehicular audio system, these electronic components also generate a small amount of heat. This heat primarily originates from the energy loss of power electronic devices during the processes of high-frequency switching, current conversion, and signal processing.

During the vehicle braking process, the friction between the brake disc and pad generates a large amount of heat. This heat is usually dissipated into the air through the cooling fins of the brake disc. However, it can produce a high temperature in a short time, leading to overheating of the braking system and affecting braking performance.

Vehicles exposed to the sun are often very stuffy inside. This means that the body and interior materials of the car are also absorbing solar radiation, which also generates afterheat.

3. Overview of Waste Heat Recovery Technology

Waste heat recovery technology refers to the conversion of low-grade waste heat generated in industrial production, power generation, transportation and other processes into usable energy through means such as heat exchange, thermoelectric conversion, and thermochemical storage. This process improves energy utilization efficiency and reduces carbon emissions. At present, common waste heat recovery technologies include heat exchangers (such as plate and shell-and-tube heat exchangers), ORC, thermo-

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electric materials, and phase change heat storage technologies. The technology has evolved from simple heat exchange to complex energy conversion systems.In traditional industrial sectors, waste heat recovery technology has already developed relatively maturely and has been widely applied. In industries such as steel and chemicals, high temperature waste gases generated during the production process are recovered to preheat raw materials or to generate electricity through thermoelectric conversion.

Waste heat recovery technology mainly targets the various waste heat generated during vehicle operation. It converts this waste heat into usable thermal or electrical energy through special devices or systems, such as heat pumps, heat exchangers, and thermoelectric conversion devices. Heat pumps can be driven by a small amount of high-grade energy (such as electricity) to upgrade heat from a low-temperature heat source to a high-temperature level for heating the vehicle's interior air or battery pack. This enhances the battery's adaptability in cold environments. Heat exchangers can transfer heat from high-temperature components to a medium that requires heating, such as coolant or air. Thermoelectric conversion devices can directly convert thermal energy into electrical energy to provide additional power for the vehicle's electrical system.

In recent years, with the full development of materials science, thermodynamic optimization and intelligent control technologies, the efficiency and cost effectiveness of waste heat recovery system (WHRS) have been significantly improved. Especially with the rise of NEVs, the application of this technology in the automotive field has gradually attracted attention. Although large scale application still faces challenges such as large temperature fluctuations of waste heat sources, low heat conversion efficiency and complex system integration, with the advancement of the "dual-carbon" goals and the increasing demand for green manufacturing, waste heat recovery technology will provide key technological support for achieving efficient energy utilization and sustainable development. It is an inevitable trend to apply waste heat recovery technology in various industries.

4. Technical Feasibility Analysis

4.1 Technical Principle and System Design

The core of waste heat recovery technology is converting the waste heat generated during system operation into usable energy. In NEVs, the main sources of waste heat are the heat generated by the motor system, battery system, and electronic components during operation. These types of heat are usually emitted into the environment in the form of waste heat. The waste heat recovery system collects this waste heat through devices such as heat exchangers and then converts it into usable thermal or electrical energy using technologies such as heat pump systems, ORC, and supercritical carbon dioxide. The waste heat generated by the motor can be recovered through a heat exchanger and used for passenger cabin heating and battery system preheating, which reduces battery power consumption and enhances the vehicle's mileage. The waste heat generated by the battery can also be recovered through a heat exchanger and used for passenger cabin heating or preheating other systems. In addition, battery waste heat can be upgraded through a heat pump system to drive other devices.

The design of the waste heat recovery system in NEVs needs to take into account factors such as the vehicle's space layout, heat source distribution, and energy conversion efficiency in a comprehensive manner. A typical waste heat recovery system consists of the following four main parts. There are the heat source collection part, the heat exchange part, the energy conversion part, and the control system part. The heat source collection part is responsible for collecting the waste heat that escapes from the components; the heat exchange part transfers the waste heat to the working medium; the energy conversion part converts thermal energy into electrical or thermal energy; and the control system part monitors the operating status in real time to ensure the efficiency and stability of the process.

Some studies have built a simulation model of the thermal management system of pure electric passenger vehicles based on AMESim software, which includes the heat pump air conditioning subsystem and the motor thermal management subsystem. By reasonably distributing the refrigerant flow, the total heat absorbed by the thermal management system from the electric drive system and the environment is significantly increased, thereby significantly improving the heating power of the passenger cabin. For example, when the vehicle speed is 60 kilometers per hour, the passenger cabin heating power can be increased by 100.37% [6]. There are also studies that have proposed a waste heat recovery control strategy for fuel cells based on fuzzy control. A large amount of waste heat is generated during the operation of fuel cells. In order to maintain a stable stack temperature and effectively utilize this waste heat, the rotation speed of the cooling fan or tap water pump is adjusted through a fuzzy controller to achieve a reasonable switch between cooling and heat exchange modes. This improves energy utilization efficiency, enhances system temperature adaptability, and stabilizes the stack temperature [7]. These studies have demonstrated that under the current technological conditions, the design and implementation of the motor waste heat recovery system are feasible and can bring benefits.

4.2 Technological Superiority

In traditional NEVs, a large amount of heat is wasted during operation as it dissipates into the environment. WHRS can convert this heat into usable thermal or electrical energy and reintroduce it into the vehicle for reuse. Nowadays, waste heat recovery technology has become relatively mature, and the foundation for its application is in place. Song J et al. have provided theoretical support and optimization directions for the development of WHRS in NEVs by combining the supercritical carbon dioxide (S-CO_2) cycle with the ORC. Through simulation, they concluded that by properly selecting the working fluid, optimizing system parameters and configurations, the efficiency of the waste heat recovery system can be significantly improved, thereby enhancing the energy utilization efficiency and cost-effectiveness of NEVs [1].

There are also studies on waste heat recovery related to fuel cells. Li R, Wu Z et al. have conducted a detailed study of a 200 kW proton exchange membrane (PEM) fuel cell system and proposed a waste heat recovery strategy based on phase change materials (PCMs) to improve the thermal management performance of the fuel cell system, especially under cold boot conditions. They have also verified the advantages of PCMs: improving thermal management efficiency, reducing cold boot time, lowering energy consumption, and enhancing system reliability [8]. This means that NEVs can also adopt corresponding battery systems to reduce the starting time of electric vehicles in winter and improve the driving experience for drivers.

4.3 Existing Cases of Waste Heat Recovery Technology Application

The application of waste heat recovery technology in various fields has achieved significant results and has made important contributions to the efficient use of energy and the reduction of energy consumption and emissions. Although the technology is relatively mature, its application in NEVs is still in the development stage and needs to learn from fields that have already utilized this technology.

Lianbo M et al. mainly studied the waste heat recovery potential of flue gas generated by hydrogen enriched natural gas (HENG) combustion and the performance of the flue gas condensing heat exchanger (FGCHE) [9]. The university campus energy system mentioned in the article by Tariq H A et al. is a typical application case in the field of architecture. By optimizing the energy system, they achieved effective utilization of electrical and thermal energy, improved energy utilization efficiency, and reduced carbon emissions [10]. Noorbakhsh H et al. proposed a ship multi-generation system that combines various technologies such as internal combustion engines and supercritical carbon dioxide Brayton cycles. They conducted energy, exergy, exergy economic, and exergy environmental (4E) analyses. Through one-dimensional and two-dimensional sensitivity analyses and partial algorithm optimization, they determined the optimal operating conditions of the system [11].

Heat pump technology is a widely applied waste heat recovery technology in NEVs at present. Through the heat pump system, the battery pack can be heated, the battery life can be extended, and the battery performance in low temperature environments can be improved. It can also provide heating for the passenger cabin, reducing the consumption of battery power for temperature regulation and extending the vehicle's mileage. Some new energy vehicle manufacturers have introduced WHRS in some models. For example, Tesla has equipped the Model Y and Model 3 with heat pump systems to recover waste heat from the battery and electric motor, improving winter endurance. The "Octovalve" eight-way valve integrated thermal management system efficiently distributes heat to the passenger cabin or battery. BYD's Han EV (high-end version) is equipped with a wide temperature range heat pump system that can recover waste heat from the electric drive system to accommodate low temperature environments and enhance winter endurance performance.

Some high-end NEVs are equipped with advanced battery thermal management systems that transfer the waste heat generated by the battery to other components through heat pumps and heat exchangers to achieve heat recycling. For example, the BMW i-series vehicles adopt intelligent battery thermal management systems that can automatically regulate the flow of heat according to the battery's temperature status. The i3's heat pump system indirectly takes away the battery heat through a heat exchanger while meeting the passenger cabin cooling demand [2].

In addition, there is the brake energy recovery system. It has been widely used in NEVs, but the current research direction is to further improve its energy recovery efficiency and effectively utilize the heat generated during braking. Some studies have been carried out. For example, based on the problems of the braking system of pure electric heavy-duty trucks on long downhill sections, a novel braking energy management strategy based on receding - horizon control was proposed to optimize the distribution of braking energy during downhill driving. The results show that this strategy not only prevents brake thermal fade and ensures braking safety but also recovers a large amount of braking energy and protects the health of the battery [3].

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This shows that waste heat recovery technology has significant energy-saving and emission-reduction effects in the energy field. It can significantly improve energy efficiency, reduce production costs and environmental impact. It also shows that future research can try to learn from existing studies and apply the results to optimize waste heat recovery technology in NEVs. Consider applying HENG to NEVs to reduce carbon emissions, and the reduced volumetric heat value can be compensated by optimizing the engine. In NEVs, MATLAB can be used to create algorithm models to explore ways to improve the performance of WHRS.

5. Economic forecasting

5.1 Benefits of Application in NEVs

5.1.1 Lower energy consumption and higher mileage

The energy of NEVs mainly comes from batteries, and the driving endurance of batteries has always been one of the key factors restricting their development. The waste heat recovery system converts the waste heat generated during the operation of the motor, battery pack, and electronic equipment into usable thermal or electrical energy and reintroduces it into the vehicle's operation. This effectively reduces the vehicle's direct consumption of battery energy and improves the vehicle's performance in low temperature conditions. Teng Haixu et al. found that the energy efficiency of the dual heat source mode is better than that of the air source mode. The lower the ambient temperature, the more obvious the improvement in energy efficiency. Under the condition of -20℃ and complete fresh air, the heating capacity and COP were increased by 4.9% and 14.2% respectively compared with the air source mode [4]. This shows that the dual heat source mode (air source + waste heat source) can significantly improve heating performance in extremely low temperature environments. Meanwhile this mode can reduce dependence on traditional heating methods (such as PTC heating).Then the energy consumption will reduce and driving mileage increase.

In addition, waste heat recovery technology can also extend battery life by optimizing battery pack thermal management. When batteries operate within a suitable temperature range, their performance and lifespan can be better guaranteed. The waste heat recovery system can use the recovered waste heat to provide a stable thermal environment for the battery pack, reducing battery performance degradation caused by temperature changes and further enhancing the overall performance and economy of NEVs. This means that users can reduce the frequency of battery replacement during vehicle use, thereby saving the high cost of battery replacement.

5.1.2 Environmental benefits and carbon emission reduction

With the increasing global attention to climate change and the strict control of carbon emissions, reducing carbon emissions in the transportation sector has become an important direction for development. NEVs already have a relatively low level of carbon emissions, and the application of waste heat recovery technology further reduces their energy consumption, thereby decreasing carbon emissions.

Moreover, the application of waste heat recovery technology can also reduce dependence on traditional energy sources, further promoting the sustainable development of new energy vehicles. By converting waste heat into usable energy, new energy vehicles can more efficiently utilize their limited battery power, reducing the demand for charging from the power grid. This, in turn, indirectly reduces carbon emissions during the power generation process. This comprehensive emission reduction effect, from energy production to vehicle use, gives waste heat recovery technology significant environmental importance in the field of new energy vehicles. Yang H et al. have studied the role of sustainable financial technology in the energy transition and found that oil rents have a negative impact on environmental sustainability. However, technological innovation, environmental innovation, and green innovation can significantly mitigate this negative impact [12]. Waste heat recovery reduces dependence on traditional energy sources, which can precisely alleviate this negative impact. It is evident that the energy transition is imperative.

Although the installation and maintenance of WHRS will add some costs for enterprises in the production of automobiles, it can bring considerable economic benefits to users. As enterprises, to achieve long-term development, it is necessary to consider user needs. Only by meeting customer demands can market competitiveness be enhanced. In the current fierce competition among automobile manufacturers, why has Xiaomi's car, which started late, quickly become popular? It is precisely because it considers user needs and thinks for users, such as having an attractive design, affordable prices, and reliable quality. Enterprises should not be detached from the users. Including users in the consideration is the right way. Overall, the application of waste heat recovery technology in new energy vehicles has good economic benefits and a relatively short cost recovery period, providing strong support for the development of new energy vehicles.

5.2 Future Technology Direction

5.2.1 High efficiency heat pump technology

With the development of NEVs, it is essential to continuously optimize heat pump air conditioning technology to enhance heating and cooling efficiency and reduce energy consumption. Gao Chunyan and her team have developed three plans to enhance the heating performance of heat pump air conditioners in low-temperature environments. These plans involve improving the circulation design of heat pump systems, optimizing the selection of refrigerants, and enhancing the performance of compressors. By reducing reliance on PTC heaters and minimizing frosting, these measures aim to extend the system's lifespan and improve reliability [5]. The development of efficient heat pump technology will provide stronger support for the application of NEVs in cold regions, expand the market, and broaden the customer base.

5.2.2 Intelligent thermal management system

As AI technology advances, the thermal management systems of future NEVs will become more intelligent. These systems will automatically adjust their thermal management strategies based on the vehicle's real time operating conditions and environmental factors. By integrating advanced sensors and controllers, these systems can achieve precise temperature control of key components such as motors, batteries, and passenger cabins, thereby enhancing the efficiency and effectiveness of waste heat recovery. Yu Guoqiang and colleagues have studied the adaptability of hydrogen fuel cell vehicles in high-temperature environments, particularly focusing on the performance of fuel cells. This indicates that research on hydrogen fuel cell vehicles under high-temperature conditions is still lacking, highlighting the importance of intelligent thermal management systems [13]. In the future, it is possible to develop intelligent thermal management systems based on artificial intelligence and the Internet of Things, which can monitor and adjust the vehicle's thermal state in real time, ensuring the efficient operation of WHRS.

5.2.3 Integration of waste heat recovery and vehicle power system

Liu F Z et al. studied a Regional Integrated Energy System (RIES) that includes electric vehicles (EVs) and a hydrogen-blended natural gas system. They proposed a two-layer energy coordination optimization model that uses a V2X (vehicle to everything) generalized energy conversion framework and flexible hydrogen blending strategies to optimize the charging and discharging scheduling of EVs and the efficient use of hydrogen and natural gas. The results show that this model can significantly enhance the charging management capabilities of EVs, reduce the economic costs of the system, and decrease carbon emissions, thereby improving environmental benefits [14]. The hydrogen-blended natural gas strategy used in the model can significantly reduce carbon emissions and improve the environmental benefits of the system; by optimizing the charging and discharging strategies and energy conversion, it also reduces the economic costs of the system. In the future, this strategy can be further optimized, and a waste heat recovery system can be integrated into the blending strategy, seamlessly connecting with the vehicle's power system and battery management system to achieve more efficient energy management.

5.3 Economic Advice

By establishing unified design standards, certification standards, and energy utilization efficiency standards, it can ensure that waste heat recovery systems achieve a certain level of efficiency when recovering and utilizing waste heat. Strict safety and environmental standards are also needed to ensure that the system does not pose safety hazards to users during operation and meets environmental requirements. It can not only ensure the quality and performance of waste heat recovery systems and protect users' safety and related rights and interests, but also increase the acceptance and market share of NEVs through this way.

Strengthening the cross-field cooperation is a good solution too. Car manufacturers can cooperate with energy companies, material-making companies, electronic information companies, and so on. Car manufacturers provide vehicle design and operation data and point out the defects in materials. Energy companies optimize the design. Material making companies develop high-performance materials based on the defects. Electronic information companies develop intelligent thermal management systems and optimize scheduling algorithms and apply them to the waste heat management of automobiles to improve the utilization rate of waste heat.

6. Conclusion

This paper systematically analyzes the application value of waste heat recovery technology in the field of NEVs. First, the paper provides an overview of the current application status of waste heat recovery technology, from its basic principles to the analysis of waste heat sources. Then, from the perspective of technical feasibility, it examines the compatibility of WHRS with the power systems of NEVs. It discusses the adaptability of key technologies such as thermoelectric conversion and the ORC. It also explores how waste heat recovery technology can

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enhance driver sense of comfortable and boost market competitiveness. Finally, from an economic standpoint, the paper demonstrates the positive impact of waste heat recovery technology on reducing energy consumption costs and extending battery lifespan. From the user's point of view, its commercial potential is analyzed and verified by examples.

By providing dual arguments on technical feasibility and economic benefits, this paper elucidates the comprehensive benefits of waste heat recovery in the field of NEVs. Waste heat recovery technology is not only applicable to the currently popular battery electric and hybrid vehicles but can also be extended to future new energy transportation modes such as hydrogen fuel cell vehicles. It even holds reference value for fields like industrial waste heat utilization and energy storage system optimization. However, its cost effectiveness relies on large scale application. Therefore, future research could further focus on developing more efficient miniaturized waste heat recovery devices to meet the space constraints of NEVs. It could also concentrate on exploring intelligent vehicle thermal management technologies to achieve dynamic synergy between waste heat recovery and the entire vehicle energy system. By continuously optimizing the technology and expanding its application scenarios, waste heat recovery is expected to become an essential support for the sustainable development of NEVs.

References

[1] Song J,Li X ,Ren X, et al.Performance analysis and parametric optimization of supercritical carbon dioxide (S- CO_2) cycle with bottoming Organic Rankine Cycle (ORC)[J]. Energy,2018,143406-416.

[2] Zou Huiming, Tang Zuohang, Yang Tianyang et al. Research progress on thermal management technology of electric vehicles [J]. Journal of Refrigeration,2022,43(03):15-27+56.

[3] Li X ,Zhao X ,Xu S , et al.A novel braking energy management strategy for battery electric trucks with hydraulic retarder on long downhill[J].Energy,2025,322135684-135684.

[4] Teng Haixu, Chen Shaolong, Wang Jun, et al. Experimental study on the influence of waste heat recovery of CO2 heat pump system on heating performance in vehicles J/OL1 Journal of Automotive Engineering,1-12[2025-05-08].

[5] Gao Chunyan, Hong Lianjie, Liang Kunfeng et al. Analysis of heating performance of waste heat recovery thermal management system for pure electric vehicles [J]. Journal of Henan University of Science and Technology (Natural Science Edition),2024,45(06):9-18+117-118.

[6] He Jiawen, Zhang Xin, Li Xinlin, et al. Research on the characteristics of waste heat recovery of electric drive system for pure electric passenger vehicles [J]. Journal of Automotive Engineering, 2024, 14(05):848-857.

[7] Liu Yongkang, Li Jing, Lu Nan, et al. Research on fuel cell waste heat recovery control strategy based on fuzzy control [J/OL]. Journal of Electrical Engineering,1-9[2025-15]

[8] Li R ,Wu Z ,Luo J , et al.Development and validation of a 200 kW PEM fuel cell system with a novel PCM-integrated waste heat recovery strategy[J].Journal of Energy Storage,2025,122116697-116697.

[9] Lianbo M ,Suilin W ,Junhui L , et al.Effect of hydrogen-enriched natural gas on flue gas waste heat recovery potential and condensing heat exchanger performance[J].Energy,2024,286

[10] Tariq H A ,Anwar M ,Kazmi A A S , et al.Techno-economic and composite performance assessment of fuel cell-based hybrid energy systems for green hydrogen production and heat recovery[J].International Journal of Hydrogen Energy,2025,104444-462.

[11] Noorbakhsh H ,Chaboki A Y ,Rezvani A .Optimal 4E analyses of an innovative polygeneration system for freshwater, hydrogen, and power production by waste heat recovery of ship engine and thermal energy storage[J].International Journal of Hydrogen Energy,2025,127405-420.

[12] Yang H ,Lu Z ,Urinov B , et al.Sustainable financial technologies in hydrogen energy: Transforming investment, risk management, and global markets[J].International Journal of Hydrogen Energy,2025,128291-305.

[13] Yu Guoqiang, Zhao Jingang. Research on high temperature adaptability of hydrogen energy vehicles based on fuel cell characteristics [J]. Heavy Duty Vehicles,2024,(06):1-2.

[14] Liu F Z ,Liu Y Y ,Jia J H , et al.Bi-level energy co-optimization of regional integrated energy system with electric vehicle to generalized-energy conversion framework and flexible hydrogen-blended gas strategy[J].Applied Energy,2025,390125868-125868.