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System Integration and Cold Energy Utilization: Advancing LNG Technology for a Low-Carbon Future

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Abstract: As a clean and efficient energy carrier, Liquefied Natural Gas (LNG) plays an increasingly critical role in the global energy transition. This paper conducts a comprehensive review of the LNG technology system, focusing on the optimization of LNG regasification processes, cold energy recovery and utilization, integration innovation with renewable energy systems, and analysis of the economic and environmental benefits of technological applications. By summarizing key research achievements in the LNG field in recent years, particularly the coupling technologies with solar energy systems, Organic Rankine Cycle (ORC), and hydrogen production, this paper systematically elaborates on the core value of LNG technology in improving energy efficiency, reducing carbon emissions, and promoting the development of multi-energy complementary systems. Meanwhile, combined with relevant case studies, it analyzes the impact of different parameters on LNG system performance, and prospects the future development trends and challenges of LNG technology, providing references for related research and engineering applications.

Keywords: Regasification Process; Cold Energy Recovery; System Integration; Hydrogen Production; Environmental and Economic Analysis.

1. Introduction

Against the backdrop of global climate change response and the transition towards a low-carbon energy structure, the energy sector is undergoing profound transformations. Natural gas, with its lower pollutant emissions compared to coal and oil, has become a crucial transitional option bridging traditional fossil fuels and new energy sources, and its share in global energy consumption continues to grow. Liquefied Natural Gas (LNG), which significantly reduces volume through cryogenic liquefaction, effectively addresses the challenges of high long-distance transportation costs and large-scale storage difficulties associated with natural gas. It has emerged as a critical bridge connecting resource-rich regions with consumption hubs. Driven by energy security adjustments and low-carbon demands, global LNG trade is steadily expanding, and its proportion in primary energy consumption and strategic importance are expected to further increase.

The LNG technology system encompasses core processes such as liquefaction, storage, transportation, regasification, and cold energy utilization. Among these, regasification is a key terminal process that directly determines the stability of natural gas supply. Additionally, the cold energy released during this process holds significant potential for recovery, which could substantially enhance the energy efficiency of the entire industry chain. However, traditional regasification methods (e.g., seawater heating) exhibit notable limitations: low energy utilization efficiency, significant irreversible losses, and ineffective cold energy recovery—contradicting the globally advocated principles of energy conservation and emission reduction.

In recent years, with the rapid advancement of renewable energy technologies and the rise and commercialization of new energy carriers such as hydrogen, the LNG technology sector has witnessed innovative breakthroughs. Integrated innovations combining LNG systems with clean energy sources like solar and wind power, as well as research into coupling LNG processes with hydrogen production and liquefaction, have become industry hotspots. These explorations provide new technological pathways for enhancing the comprehensive energy efficiency of LNG systems and reducing carbon emissions across the entire industry chain, thereby promoting the upgrading of the LNG industry towards low-carbon and high-efficiency directions.

Based on significant research achievements in the LNG field in recent years, this paper systematically reviews the current status and directions of technological development from five dimensions: first, optimization of regasification processes, exploring ways to improve efficiency and supply stability; second, cold energy recovery and utilization, outlining application scenarios and their value; third, system integration innovations, summarizing coupling models and advantages; fourth, environmental and economic analysis, assessing the comprehensive benefits of new technologies; and fifth, future trends and prospects, predicting long-term development pathways and breakthrough points. The overall research aims to provide comprehensive references for related technology development, engineering practices, and policy formulation, supporting the high-quality development of the LNG industry amid the global wave of low-carbon transition.

2. Technological Progress in LNG Regasification Processes

LNG regasification is the process of heating low-temperature liquid natural gas to normal-temperature gaseous state to meet the conditions for pipeline transportation or end-user use. The core challenge of this process lies in how to efficiently heat LNG to achieve stable gasification while minimizing energy consumption and reducing environmental impacts. Currently, mainstream LNG regasification processes can be divided into three categories: open-cycle, closed-cycle, and hybrid-cycle. These processes vary significantly in energy efficiency, cost, and applicable scenarios.

2.1. Traditional Regasification Processes and Their Limitations

Traditional open-cycle regasification processes use seawater as the heating medium, realizing LNG gasification through Submerged Combustion Vaporizers (SCV) or Open Rack Vaporizers (ORV). Among them, SCV directly heats LNG by using high-temperature flue gas generated from natural gas combustion. Although it has high gasification efficiency, it consumes a large amount of natural gas and results in high carbon emissions. ORV, on the other hand, uses the sensible heat of seawater to heat LNG. While it does not require additional fuel consumption, its winter operation stability is poor in some regions due to the limitation of seawater temperature. Moreover, the large temperature difference between seawater and LNG leads to significant irreversible losses, resulting in low system exergy efficiency.

Closed-cycle regasification processes achieve heat transfer through the circulation of intermediate media, with typical equipment including Intermediate Fluid Vaporizers (IFV) and Shell-and-Tube Vaporizers (STV). This process is not limited by seawater temperature and has high operational stability. However, the heat exchange process of the intermediate medium increases system complexity, and heat exchange efficiency is greatly affected by the thermal conductivity of the medium. In addition, traditional regasification processes generally suffer from insufficient cold energy recovery. A large amount of cold energy released during LNG gasification is directly carried away by seawater or air, causing energy waste and potentially exerting low-temperature impacts on the marine ecological environment.

2.2. Optimization Directions of Regasification Processes

In recent years, researchers have continuously improved the energy efficiency of regasification processes by optimizing heat exchange structures, selecting appropriate working fluids, and introducing new heat sources. In terms of heat exchange structure optimization, the application of Multi-Channel Heat Exchangers (MCHX) has significantly reduced exergy losses caused by temperature differences. Some studies have combined pinch technology to optimize the layout of flow channels, further improving system heat exchange efficiency and reducing exergy losses. In terms of working fluid selection, the application of new environmentally friendly working fluids not only improves heat exchange efficiency but also solves the environmental problems associated with traditional working fluids.

Furthermore, the use of industrial waste heat or renewable energy as heat sources for regasification has become an important direction to reduce process energy consumption. Some studies have proposed using industrial waste heat for LNG regasification, which not only realizes the resource utilization of waste heat but also reduces the energy consumption of the regasification process and decreases reliance on fossil energy. Another case study applied heat generated by solar collectors to LNG regasification, effectively reducing carbon emissions during the regasification process by leveraging local abundant solar energy resources.

3. LNG Cold Energy Recovery and Utilization Technology

A large amount of cold energy is released during the LNG regasification process. Effective recovery and utilization of this cold energy can not only improve the comprehensive energy utilization efficiency but also create significant economic and environmental benefits. According to the temperature ranges of cold energy utilization, LNG cold energy recovery technologies can be divided into three categories: low-temperature utilization, medium-temperature utilization, and normal-temperature utilization. These technologies differ significantly in application scenarios and energy efficiency.

3.1. Cold Energy for Power Generation

Converting LNG cold energy into electrical energy is one of the important directions of cold energy recovery. Its core principle is to use LNG cold energy as a low-temperature heat source and form a temperature difference with high-temperature heat sources such as the environment or industrial waste heat to drive power cycles for power generation. Currently, power generation technologies based on LNG cold energy mainly include Rankine Cycle (RC), Organic Rankine Cycle (ORC), and Brayton Cycle (BC).

The Organic Rankine Cycle (ORC) is the most widely used in LNG cold energy power generation due to its advantages of flexible working fluid selection and adaptability to low-temperature difference conditions. In some integrated systems proposed by studies, a series ORC is used to recover LNG cold energy, and the cold energy of LNG is used to condense the organic working fluid, which improves the power generation efficiency of ORC compared with traditional cooling methods. Other studies have introduced an ejector refrigeration cycle into the LNG cold energy power generation system, further improving the system power generation efficiency by optimizing the working fluid ratio.

The Brayton Cycle (BC) is suitable for large-scale cold energy power generation scenarios, especially in coupling with gas turbines. In the LNG cold energy-gas turbine combined cycle system proposed by relevant studies, LNG cold energy is used to cool the intake air of the gas turbine, improving air density and gas turbine power output. Meanwhile, LNG cold energy is used to recover the waste heat of gas turbine exhaust, significantly improving the overall efficiency of the system.

3.2. Cold Energy for Hydrogen Liquefaction

As an important component of the future clean energy system, the hydrogen liquefaction process consumes extremely high energy. The temperature range of LNG cold energy is highly matched with the pre-cooling stage requirements of hydrogen liquefaction. Using LNG cold energy for the pre-cooling process of hydrogen liquefaction can significantly reduce liquefaction energy consumption.

In systems proposed by some studies, the cold energy released during the LNG regasification process is used for the pre-cooling of hydrogen, which then enters the deep cooling cycle. Compared with traditional processes, this significantly reduces the total energy consumption of hydrogen liquefaction. Such systems not only improve the hydrogen production rate and annual production capacity but also enhance the exergy efficiency of the liquefaction process. Other studies have further improved the exergy efficiency of the system by optimizing the parameters of the LNG cold energy-hydrogen liquefaction system while effectively controlling the levelized cost of hydrogen.

3.3. Cold Energy for Refrigeration and Air Separation

The application of LNG cold energy in the fields of refrigeration and air separation also has significant advantages. In terms of refrigeration, LNG cold energy can be directly used in cold storage, air conditioning systems, or industrial refrigeration. For example, some studies have applied LNG cold energy to food cold storage, maintaining the low temperature of the cold storage through direct cold energy exchange, which significantly reduces energy consumption and operating costs compared with traditional electric refrigeration. In the field of air separation, LNG cold energy can replace the low-temperature refrigeration link of traditional air separation equipment, significantly reducing air separation energy consumption and improving the energy utilization efficiency of air separation equipment.

4. Integrated Innovation of LNG Systems with Renewable Energy

With the rapid development of renewable energy technologies, the integration of LNG systems with clean energy sources such as solar and wind energy has become an important path to achieve "zero-carbon" energy systems. This integration not only enables the use of renewable energy to provide energy for processes such as LNG regasification and cold energy recovery but also compensates for the intermittency of renewable energy through the energy storage characteristics of LNG, realizing multi-energy complementarity.

4.1. Integration of LNG with Solar Energy Systems

As the most abundant renewable energy source globally, solar energy has broad prospects for integration with LNG systems. A typical innovative solar-LNG integrated system takes Parabolic Trough Solar Collectors (PTSCs) as the core, heating heat transfer oil through solar energy to drive ORC for power generation. Meanwhile, the cold energy released from LNG regasification is used to drive another ORC for power generation and provide a cold source for hydrogen liquefaction.

The innovations of such systems lie in two aspects: on the one hand, solar energy replaces traditional fossil energy, reducing carbon emissions during the LNG regasification process; on the other hand, the recovery of LNG cold energy improves the comprehensive energy efficiency of the solar energy system. Relevant dynamic analysis shows that this integrated system can maintain stable hydrogen production in different seasons, demonstrating good seasonal adaptability.

4.2. Integration of LNG with Wind Energy Systems

As another important renewable energy source, the intermittency of wind energy can be alleviated through the energy storage characteristics of LNG. Specifically, when wind power output is excessive, the surplus electrical energy can be used to drive electrolyzers for hydrogen production, and the hydrogen can be liquefied and stored using LNG cold energy. When wind power output is insufficient, liquefied natural gas can be regasified for power generation, or hydrogen fuel cells can be used for energy supplementation, realizing the balance between supply and demand of the energy system.

In the wind power-LNG-hydrogen integrated system proposed by relevant studies, wind power is prioritized for grid power supply, and surplus electrical energy is used for hydrogen production. The hydrogen is pre-cooled by LNG cold energy before entering the liquefaction system. Meanwhile, the cold energy generated during the LNG regasification process drives ORC for power generation to supplement grid electricity. System dynamic simulation shows that this integrated system can significantly improve the power supply reliability of the grid while achieving significant carbon emission reduction.

4.3. Integration of LNG with Multi-Energy Complementary Systems

In addition to integration with a single renewable energy source, LNG systems can also be integrated with multiple energy forms such as solar, wind, and geothermal energy, as well as technologies such as energy storage and hydrogen, to build multi-energy complementary systems, further improving energy utilization efficiency and system stability. A typical geothermal energy-LNG-hydrogen multi-energy complementary system uses geothermal energy as the basic heat source to drive ORC for power generation. Meanwhile, LNG cold energy is used to provide a cold source for the condenser of the geothermal energy system, improving ORC efficiency. In addition, the system is integrated with electrolyzers and hydrogen liquefaction units to realize hydrogen production and storage.

Performance analysis of such systems shows that they perform excellently in terms of power generation capacity, hydrogen production rate, and cost control. Compared with single-energy systems, their energy utilization efficiency is significantly improved, and carbon emissions are greatly reduced. This multi-energy complementary model not only makes full use of the characteristics of different energy sources but also realizes the efficient and stable operation of the system through the cold energy and energy storage functions of LNG, providing a "self-sufficient" energy solution for energy-scarce areas such as remote regions or islands.

5. Environmental and Economic Analysis of LNG Systems

The promotion and application of LNG systems require not only consideration of technical feasibility but also comprehensive environmental and economic analysis to evaluate their sustainability and market competitiveness. Based on research achievements in recent years, this section reviews the environmental and economic performance of LNG systems from three aspects: carbon emission reduction benefits, economic cost analysis, and sensitivity factors.

5.1. Environmental Benefits: Carbon Emission Reduction

As a relatively clean energy source, the full-life-cycle carbon emissions of LNG are significantly lower than those of traditional fossil energy sources such as coal and oil. The carbon emission reduction benefits of LNG systems, especially those integrated with renewable energy, are even more significant, mainly reflected in the following three aspects: first, LNG replaces fuels such as coal and oil, directly reducing carbon emissions during the combustion process;

second, the improved energy efficiency of processes such as LNG regasification and cold energy recovery reduces energy consumption, leading to indirect emission reduction; third, integration with renewable energy further reduces reliance on fossil energy.

Relevant studies show that solar-LNG-hydrogen integrated systems have significant carbon emission reduction effects in specific regions. If similar cold energy recovery and renewable energy integration technologies are widely adopted in global LNG systems, considerable annual carbon emission reductions will be achieved, exerting a positive impact on global climate change mitigation. In addition, power plants adopting hydrogen-LNG combined cycles have significantly lower carbon emission intensity than traditional natural gas power plants, with remarkable emission reduction effects.

5.2. Economic Cost Analysis

The economic costs of LNG systems mainly include initial investment costs, operation and maintenance costs, and fuel costs (if applicable). The cost structure of different LNG systems varies. The initial investment of traditional LNG regasification systems is mainly concentrated on equipment such as vaporizers and pipelines, while systems integrated with renewable energy require additional consideration of the costs of equipment such as solar collectors and electrolyzers.

In terms of initial investment, the unit investment cost of traditional vaporizers is relatively low, while the unit investment cost of LNG systems integrated with solar energy increases due to the addition of various equipment. However, in terms of operating costs, integrated systems have significant advantages: traditional LNG regasification systems have high operating costs, while solar-integrated systems have significantly lower operating costs due to the zero-cost nature of solar energy.

In terms of the levelized cost of hydrogen, the cost of some integrated systems has significant advantages compared with traditional fossil energy-based hydrogen production and single solar energy-based hydrogen production. In addition, the unit fresh water cost of solar-LNG-seawater desalination integrated systems is significantly lower than that of traditional seawater desalination, demonstrating good economic competitiveness.

6. Future Development Trends and Challenges

Although significant progress has been made in LNG technology, it still faces numerous challenges in the context of advancing the "dual-carbon" goals and energy system transformation, while several important development directions have also emerged. From the perspective of technological development trends, future LNG cold energy recovery will progress towards higher efficiency parameters and diversified applications**. For instance, the development of supercritical CO_2-based Brayton cycles for LNG cold energy power generation will further enhance power generation efficiency. Simultaneously, integrating LNG cold energy with carbon capture technology—utilizing LNG cold energy to achieve CO_2 liquefaction and storage—will further improve the environmental performance of the system. In terms of the integration of LNG and hydrogen energy, beyond using LNG cold energy for hydrogen liquefaction, future efforts will explore synergy between the two in transportation, storage, and other aspects. Examples include developing LNG-hydrogen hybrid fuel engines, which reduce carbon emissions while leveraging LNG's high energy density to compensate for hydrogen storage limitations. Additionally, the cryogenic environment of LNG storage tanks will be utilized to achieve efficient hydrogen storage, increasing hydrogen storage density. Digitalization and intelligence are also critical development directions. Technologies such as big data and artificial intelligence will be employed to achieve dynamic optimization and intelligent regulation of LNG systems. For instance, optimizing the operational parameters of solar-LNG integrated systems based on real-time meteorological data and user demand, or using digital twin technology to simulate the full lifecycle performance of LNG systems, enabling predictive maintenance and operational optimization.

Regarding challenges, the primary issue is the high technological cost. Although LNG systems have low operational costs, the initial investment—particularly for systems integrated with renewable energy—remains high. The elevated cost of certain key equipment directly limits the large-scale adoption of the technology. Secondly, system integration complexity is a significant hurdle. The integration of LNG with renewable energy, hydrogen energy, and other technologies involves multidisciplinary and multi-system coordination, which undoubtedly increases the complexity of system design and operation. For example, matching the intermittency of solar energy with the continuity of LNG regasification requires advanced control strategies and energy storage technologies for support. Lastly, there is a lack of standards and regulations. Currently, the design, operation, and safety standards for integrated LNG and renewable energy systems are not yet fully developed. This leads to poor comparability of research results and poses certain risks in engineering applications. Aspects such as safety protocols for using LNG cold energy in hydrogen liquefaction and carbon emission accounting standards for systems still need further clarification.

7. Summary

As a key link connecting natural gas resources and clean utilization, LNG technology plays an irreplaceable role in the global energy transition. Through a systematic review of LNG regasification processes, cold energy recovery and utilization, integrated innovation with renewable energy, and environmental and economic analysis, this paper draws the following conclusions:

1). LNG regasification processes have developed from traditional seawater heating to high-efficiency and environmentally friendly directions. The application of multi-channel heat exchangers, new working fluids, and renewable energy heat sources has significantly improved regasification efficiency and reduced energy consumption and carbon emissions.

2). LNG cold energy recovery and utilization technologies have been continuously enriched, and their applications in power generation, hydrogen liquefaction, refrigeration, and air separation have demonstrated significant economic and environmental benefits. Among these, the coupling of ORC cycle and hydrogen liquefaction is a current research hotspot.

3). The integration of LNG systems with renewable energy sources such as solar and wind energy has realized multi-energy complementarity, which not only improves the comprehensive energy utilization efficiency but also compensates for the intermittency of renewable energy, providing an important path for building "zero-carbon" energy systems.

4). Environmental and economic analysis shows that LNG systems integrated with renewable energy have significant carbon emission reduction effects and strong market competitiveness in terms of cost control.

In the future, with the development of efficient cold energy recovery technology, in-depth integration of LNG and hydrogen, and digital and intelligent technologies, LNG systems will play a more important role in the energy transition. However, it is also necessary to address challenges such as high technical costs, complex system integration, and lack of standards. Through policy support, technological innovation, and international cooperation, the large-scale application of LNG technology will be promoted to contribute to the achievement of global "dual carbon" goals.

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