The Analysis of The Impossible Triangle in Hydrogen Production Technologies

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Abstract. In the current global context, the transformation of the world's energy structure is of utmost importance. Hydrogen energy, being a zero-carbon source, serves as a crucial catalyst for achieving green and low-carbon transition. Despite China being the largest producer of hydrogen energy worldwide, it still heavily relies on coal-based energy systems and consumption patterns. It is essential to acknowledge that an inherent attribute of any single form of energy is its impossibility to fulfill all three aspects simultaneously: economy, cleanliness, and security. By delving into the theoretical connotation of this "energy impossible triangle" and considering factors such as energy security, economic viability, and environmental sustainability associated with various hydrogen production methods; we can analyze a feasible pathway for transforming China's hydrogen energy structure. This transformation necessitates gradually integrating advantages from existing coal-based systems while tailoring production structures according to local conditions. The development of hydrogen energy should be guided by both resource allocation capabilities and actual demand for sustainable growth. Additionally, establishing a comprehensive energy system will greatly facilitate the transition toward more efficient hydrogen production structures.

Keywords: Impossible triangle, hydrogen production technologies, comprehensive energy system.

1. Introduction

Since the onset of industrialization, there has been a remarkable acceleration in the development of people's living standards. However, due to the extensive use of fossil fuels such as oil and natural gas, global environmental problems have become prominent. The global carbon dioxide emissions reached a record high, of which the proportion of carbon emissions in the Asia-Pacific region continued to increase. Greenhouse effects are intensifying, natural disasters occur frequently, and the global climate continues to warm, causing sea levels to continue to rise. Additionally, The conflict between Russia and Ukraine impacted the international energy market and triggered a world energy crisis. Therefore, it is urgent to reconstruct the global energy structure.

As a "zero-carbon" energy source, which is clean, environmentally friendly, renewable, and high, it is an important carrier for the use of energy terminals to achieve green low-carbon transformation [1]. The increasing use of low-carbon hydrogen is the future trend of global energy [2], and its contribution to the "carbon peaking and carbon neutrality goals" is significantly prominent.

As shown in figure 1, globally, hydrogen energy is still mainly produced by reforming fossil fuels to produce hydrogen, while renewable energy hydrogen production technologies account for a relatively small proportion, and grey hydrogen combined with carbon capture technologies are not yet widely used; therefore, grey hydrogen is currently the main source of hydrogen energy today, but it is still not able to meet the needs of carbon emission reduction and the energy structure transition. The development of hydrogen production technology requires addressing the trade-offs and compromises inherent in the Impossible Triangle. Continuous exploration and optimization through practical applications are necessary to strike a balance between high efficiency, low cost, and environmental friendliness.
China is a major hydrogen producer in the world, the hydrogen energy industry is experiencing a positive trend of development. But the main means of hydrogen production in China are fossil fuel hydrogen production and industrial by-product hydrogen production, which have large carbon emissions and still cannot meet China's demand for carbon emission reduction. China has made a solemn commitment to the world to achieve peak carbon emissions and carbon neutrality. The green transformation of the energy sector is crucial and inevitable to accomplish this goal [3]. At present, China's hydrogen energy industry is in the early stage of development, and China's hydrogen source structure is far from the world's hydrogen source structure, and hydrogen preparation technology still needs to be optimized. In light of the current energy development situation in China, achieving a coordinated and harmonious "secure-economical-green" energy system has emerged as a crucial strategic choice [3].

This paper studies the three main hydrogen production methods and development direction, the benefit analysis of the three main hydrogen production methods and analyzes the hydrogen production technology in combination with the "energy impossible triangle". The purpose of this study is to provide a basis for the decision-making of hydrogen energy applications and to provide ideas for China's energy transformation route.

2. the Current Primary Hydrogen Production Technologies

2.1. Fossil Fuel Reforming for Hydrogen Production

Fossil fuel reforming hydrogen production mainly refers to coal, natural gas, and petroleum hydrogen production. The rise of the petroleum industry led to the gradual slowdown of coal hydrogen production technology [4], and due to the characteristics of China's resource endowment rich in coal, poor in oil and little gas [5], the current hydrogen production structure in China is still dominated by coal, while the world's fossil fuel hydrogen production raw materials are mainly natural gas.
Coal hydrogen production technology is one of the important ways to clean coal utilization, mainly including coal gasification, coal coking and coal supercritical water gasification three processes [5]. The traditional fossil fuel hydrogen production process is simple, abundant output, and the technology is relatively mature.

However, according to Figure 2, the process not only emits ash and sulfur-containing substances but also has a cumbersome production process and complex equipment [4]. The configuration of carbon capture, utilization, and storage technology (CCS technology) for fossil energy reforming hydrogen production can be used as an important transition for China's hydrogen energy transformation [6].

At present, the mainstream carbon capture technology is divided into three types: traditional CCUS technology, biomass utilization process (BECCS), and direct air capture (DACCS). In the short and medium term, carbon capture technology is mainly traditional CCUS technology. In the long term, DACCS will become the main force due to its nearly infinite carbon reduction capacity and a huge carbon stock market.

2.2. Industrial By-product Hydrogen Production

The industrial by-product hydrogen production raw materials are represented by coke oven gas, chlorine, and alkali tail gas, and other hydrogen-rich tail gas [7], and hydrogen is extracted according to the differences in the physical properties of the products. There are three main hydrogen extraction technologies: membrane separation hydrogen extraction technology, cryogenic separation hydrogen extraction technology, and pressure swing adsorption hydrogen extraction technology.

China's industrial by-product gas emissions are huge, and the potential for hydrogen production is huge. Coke oven gas hydrogen production is an important way to obtain industrial hydrogen at a large scale, low cost, and high efficiency. Based on the practical significance of the double carbon goal and the growth of hydrogen demand, the in-depth development and utilization of coke oven gas is particularly important [7].

However, in the process of industrial by-product hydrogen production, purification and impurity removal steps are required, which cannot be used as a large-scale centralized hydrogen energy supply source. Therefore, the upgrading of hydrogen extraction technology is the main problem facing the development of industrial by-product hydrogen technology.

2.3. Electrolysis of Water for Hydrogen Production

According to the different electrolytes, electrolytic water technology can be divided into four types: alkaline electrolytic water hydrogen production technology (ALK), anion exchange membrane electrolytic water hydrogen production technology (AEM), proton exchange membrane electrolytic water hydrogen production technology (PEM), high temperature solid oxide electrolytic water hydrogen production technology (SOE) [8].

At present, alkaline electrolytic water hydrogen production technology has been widely used in the market, proton exchange membrane technology has a large space for improvement, solid oxide electrolytic water technology has been in a small-scale demonstration stage, and anion exchange membrane is still in the development and test stage. The proportion of renewable energy in the future energy system will continue to increase, and the role of electrolytic energy storage and energy conversion technology will become more and more important [5].

There are three development directions for this technology: First, further, explore at the material level and the electric reactor process level to improve electrolysis efficiency and reduce energy consumption [9]; Second, replace traditional power with renewable energy such as photovoltaic and wind power to reduce costs; Third, improve the flexibility of power system through integrated energy storage.
3. Embodiment of the Impossible Triangle

In 2011, the World Energy Council (WEC) proposed the "impossible triangle" problem in the energy field, that is, the environmental protection, safety, and economy of the energy system cannot be taken into account at the same time [10].

The theory is embodied in the process of hydrogen energy production: the realization of economy will lead to low production import costs, while it may need to restrain clean environmental protection investment, and make energy highly dependent on external resources and poorly controllable; the realization of environmental protection may lead to the upgrading of production equipment and the change of supply mode, thus affecting stability and reducing economy; the realization of security requires enriching the system capacity, improving the hydrogen production system, inhibiting environmental protection investment and increasing capital investment.

In China, the prominent performance of the energy "impossible triangle" dilemma is that in the process of realizing the transformation of energy structure and pursuing the goal of energy ecology, there is an imbalance between the energy security of stable energy supply and the energy economy of energy cost control [11]. At present, there are three major constraints in China's energy structure transformation: "long-term constraints" to ensure economic growth and reasonable price development; "supplementary constraints" to ensure low-carbon cleanliness; and "rigid constraints" to ensure energy security. At the current stage, China's hydrogen production system takes coal as the core. If the clean and renewable energy system is introduced on a large scale in hydrogen production technology, it will lead to an increase in overall uncertainty and a decline in considerable controllability. The system needs to allocate additional reserve capacity to achieve energy balance [10].

The solution to the impossible energy triangle needs to find a balance point under multiple constraints, and the selection of the balance point of the elements needs to be combined with industrial demand and resource conditions.

3.1. Energy Security

Energy security and reliability correspond to the safety and stability objectives of high-quality development of energy [12]. In terms of the external dependence on raw materials for different hydrogen production technologies, countries with high external dependence on oil and gas are easily affected by price fluctuations and resource shortages in the international oil and gas market [13].

China's economy has entered the high-quality development lane, and the energy demand has maintained a high level of operation, and the energy production has fallen short of demand [14]. Although China's coal can basically maintain the balance of supply and demand, its natural gas and oil are highly dependent on foreign countries. The world energy crisis caused by the conflict between Russia and Ukraine has greatly impacted energy security.

However, the large-scale replacement of the traditional coal-based production mode with new energy will affect the energy market on a large scale, thus affecting national energy security. Therefore, in the process of production structure transformation, it is necessary to give full play to the role of coal as the main energy source to guarantee the bottom line [15]. At the same time, it is necessary to strengthen the innovation cooperation in the field of clean energy demand, so that hydrogen production can slowly transform into a clean energy system [16].

3.2. Energy Economy

The feasibility of an energy economy corresponds to the low-price goal of high-quality energy development [12]. In terms of hydrogen production cost, the cost of electrolytic hydrogen production is relatively high. The biggest factor affecting the cost of fossil fuel hydrogen production and industrial by-product hydrogen production is the price of raw materials. The biggest factor affecting the cost of electrolytic hydrogen production is the cost of the electrolytic tank, electricity price, and annual operation hours [17].
In terms of energy efficiency, the energy efficiency of electrolytic hydrogen production is lower than that of other mainstream technologies, and the energy consumption is larger. Therefore, the hydrogen production structure should be the key to promoting a comprehensive energy system and vigorously developing clean and renewable energy.

3.3. Energy Environmental Protection

The feasibility of an energy economy corresponds to the green and clean goal of high-quality energy development [12]. In terms of carbon emissions, the carbon emissions of fossil fuel hydrogen production technology are relatively large, and the carbon emissions of industrial by-product hydrogen production technology are relatively low.

However, as thermal power is the main energy supply source in China, the traditional electrolytic hydrogen production technology still has a large carbon emission. Therefore, to meet the transformation of production structure, renewable energy technologies need to be coupled and comprehensive energy system integration needs to be improved.

4. Conclusion

Under the current international energy situation, the energy structure must be transformed. As a clean, efficient, safe, and sustainable "zero carbon" energy, hydrogen energy is an important carrier for energy terminals to achieve green and low-carbon transformation. The energy impossible triangle dilemma is an inherent characteristic of a single energy system. Therefore, the analysis of the impossible triangle from the perspective of hydrogen production provides ideas for the transformation of China's hydrogen energy production structure.

First of all, China's energy structure and consumption system are mainly coal, which leads to the main dependence of hydrogen energy production on coal; secondly, the large-scale and large-scale transformation of hydrogen energy production structure is unstable, and should be gradually coupled with the original advantages of the coal energy system; moreover, the transformation route of production structure is based on local conditions, and should be combined with its own resource allocation and energy demand to develop hydrogen energy. Finally, the construction of a comprehensive energy system should be accelerated in the process of production structure transformation.

References


