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The impact of hydrogen trade on the low-carbon transition of energy systems

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ABSTRACT

In this study, a hydrogen trade module was developed based on the GCAMv6.0 model to investigate the role of hydrogen trade in the low-carbon transition of energy systems, we conducted a study using Japan as an example. The results indicate that hydrogen imports in Japan will replace the local production of gray and blue hydrogen, leading to an increase in hydrogen demand and penetration rate in end-use sectors. Among the import pathways, ammonia shipping is the primary mode. Therefore, Japan should prioritize the development and popularization of hydrogen production, trade, and end-use technologies, and contribute to the expansion of hydrogen imports in the local region.

Keywords: hydrogen import, energy system, low carbon transition, Japan

1. INTRODUCTION

Hydrogen energy is not a new concept, as existing industrial sectors heavily rely on fossil fuels for hydrogen production. In order to achieve emission reductions, there is a need for cleaner and low-carbon hydrogen production, with green hydrogen from renewable energy sources being the optimal choice for decarbonization [1]. However, due to variations in renewable energy endowments and regional cost differentials, some countries rely on hydrogen imports to ensure affordable and clean hydrogen supply [2,3]. According to the report by IRNEA, under the 1.5°C scenario in 2050, nearly one-fourth of the hydrogen will be supplied through international trade [4]. Major countries worldwide have placed significant emphasis on hydrogen's role in climate change mitigation and energy transition policies [5–7], with Japan outlining its objectives for both local hydrogen production and hydrogen imports in its policy planning [8]. Therefore, this study aims to analyze the role of hydrogen energy trade in the low-carbon transformation of the energy system, using Japan as a case study.

2. METHODOLOGY

The model used in this study is the GCAMv6.0 model, which is a global integrated assessment model that divides the world into 32 regions, allowing for the exploration of energy system transitions under climate change across different regions globally [9]. Based on this model, a hydrogen trade module was developed to investigate the impacts of hydrogen energy and hydrogen trade on global emissions reduction and energy system transformation. Two scenarios were designed in terms of hydrogen trade, namely the "Trade" scenario considering hydrogen trade and the "NoTrade" scenario without considering hydrogen trade, allowing for a comparison of the effects brought about by hydrogen trade. The study covers the time period from 2015 to 2050, with a time step of 5 years. In addition to the original model, the following modifications were made to explore the factors influencing hydrogen energy and hydrogen trade:

2.1 Carbon emission constraints

Regarding carbon emission constraints, we established carbon-neutral emission trajectories tailored to China, the European Union, Japan, India, Russia, South Korea, and the United States based on their respective net-zero targets, while other regions adopted globally uniform carbon emission constraints, with specific settings referenced from Yang et al.'s study [10].

2.2 Electricity sector

For the electricity sector, we updated the data based on the latest information from the ATB database up to 2022 [11]. Furthermore, taking into account regional variations in onshore wind and solar photovoltaic (PV)

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installation costs, we referred to the Renewable Power Generation Costs report by IRNEA to incorporate these differences [12].

2.3 Hydrogen production

Building upon the original model, we further differentiated hydrogen based on different production technologies, categorizing it into gray hydrogen (hydrogen produced from fossil fuels), blue hydrogen (hydrogen produced from fossil fuels with carbon capture and storage), green hydrogen (hydrogen produced from renewable energy sources and electrolysis), and pink hydrogen (hydrogen produced from nuclear energy). In terms of hydrogen production costs, we updated the cost estimates based on Wang et al.'s research [13]. To capture the regional cost differentials in wind and solar PV hydrogen production, the original model incorporated cost variations mainly driven by differences in the wind and solar resource potentials across regions. In this study, we further considered the impact of regional variations in wind and solar PV installation costs on hydrogen production costs, referring to the Renewable Power Generation Costs report by IRNEA and the Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Green Hydrogen Cost and Potential report [2,12].

2.4 Hydrogen trade

To depict international hydrogen trade resulting from regional disparities in hydrogen production costs, a hydrogen trade module was developed based on the original model. The module employed a bilateral trade modeling approach, allowing for trade decisions between any two regions based on the differences in hydrogen production costs. In terms of trade modes, three shipping methods were considered: ammonia, liquid hydrogen, and LOHC. The costs of trade included conversion costs, transportation costs, and reconversion costs, with specific cost settings referenced from the Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers report [14].

2.5 Hydrogen end-use technology

Hydrogen plays a crucial role in deep decarbonization in both the transportation and industrial sectors. To better capture the application of hydrogen energy in end-use sectors, the following updates were made based on the original model: In the industrial sector, this study introduced hydrogen cracking technology in the refining sector, which can utilize centrally produced or locally produced green hydrogen [15]. Additionally, in the chemical sector, the study considered hydrogen as an input material, replacing gray hydrogen required in the original chemical sector [16]. In the transportation sector, updates were made to the cost of electricity and hydrogen technologies for various transportation modes based on the Energy Efficiency and New Energy Vehicle Technology Roadmap 2.0 and the Path to Hydrogen Competitiveness: A Cost Perspective report, aiming to promote the application of hydrogen technologies in the transportation sector. Finally, to ensure the rapid adoption of hydrogen technologies, adjustments were made to the share of hydrogen technologies to reflect the increasing penetration rate of hydrogen energy in end-use sectors.

3. RESULTS

3.1 Impact of hydrogen imports on hydrogen production

Hydrogen imports in Japan will start to replace domestically produced, costlier pink hydrogen and blue hydrogen by 2040. As shown in Figure 1, considering hydrogen imports, domestic hydrogen production in Japan will be rapidly replaced by imported hydrogen after 2040. By 2050, hydrogen production will decrease from 1.7EJ in the NoTrade scenario to 0.4EJ in the Trade scenario. Specifically, blue hydrogen and pink hydrogen will experience the largest decline, with production decreasing by 94% and 97% respectively compared to the NoTrade scenario. After considering trade, imported hydrogen will become the primary source of hydrogen energy, accounting for approximately 80% of total hydrogen.

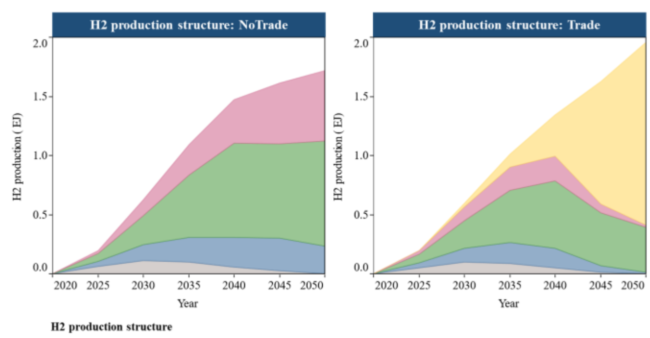

Fig. 1 Impact of hydrogen imports on hydrogen production

3.2 Impact of hydrogen imports on hydrogen production

As shown in Figure 2, hydrogen imports will increase the penetration rate of hydrogen energy in the transportation and industrial sectors and reduce the share of fossil fuels. Since the transportation sector relies more on on-site hydrogen production, hydrogen imports will have a greater impact on the industrial sector. By

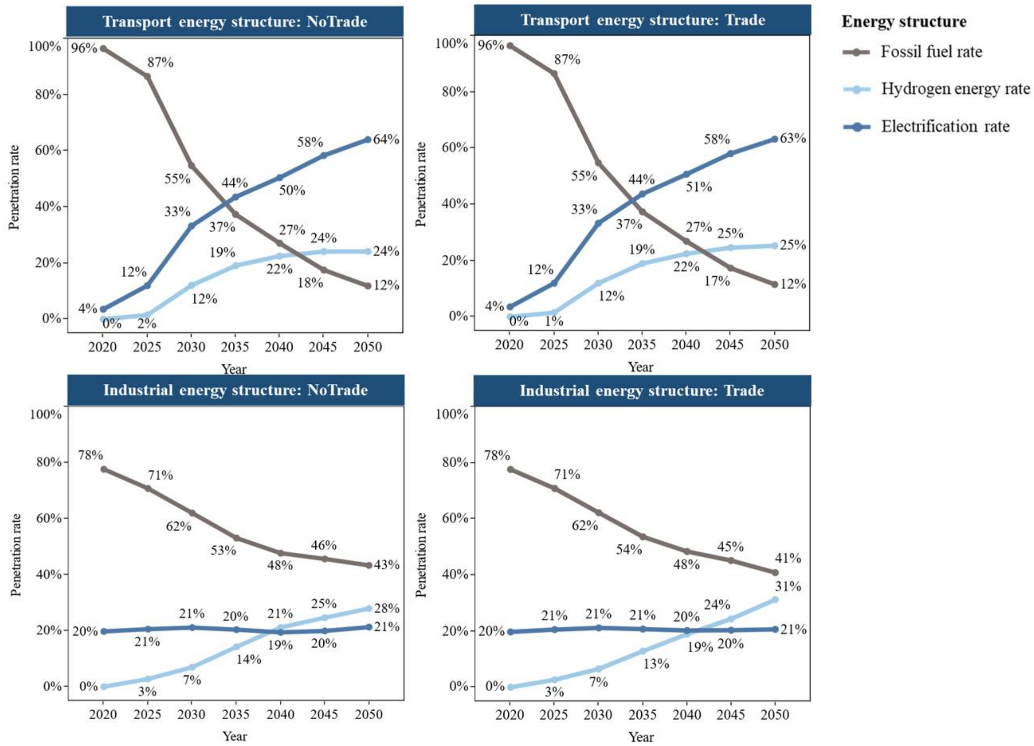

Fig. 2 Impact of hydrogen imports on end-use energy

2050, compared to the NoTrade scenario, the Trade scenario will increase the share of hydrogen energy by 1% in the transportation sector and 3% in the industrial sector, while reducing the share of industrial fossil fuels by 2%.

3.3 Main import pathways for hydrogen

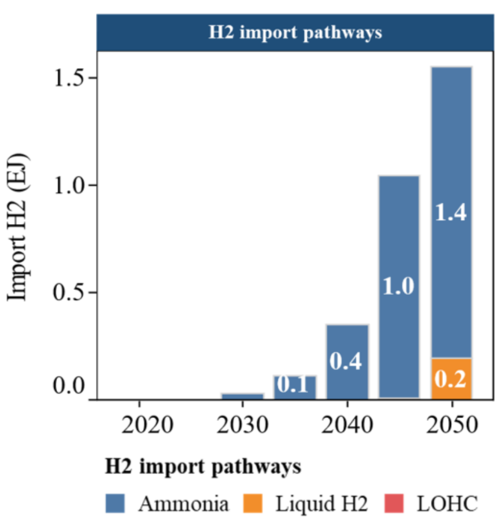

Fig. 3 Main import pathways for hydrogen

Figure 3 illustrates the primary methods of hydrogen impor in Japan. As shown in the graph, ammonia shipping is the predominant import method, with a significant increase in ammonia shipping volume starting from 2045. By 2050, ammonia shipping accounts for 87% of the total import volume. Liquid hydrogen, on the other hand, only gains a competitive advantage by 2050. Compared to ammonia, liquid hydrogen has lower conversion costs but higher transportation costs, making it more suitable for short-distance transportation. LOHC (Liquid Organic Hydrogen Carriers) struggles to gain an advantage in hydrogen importation due to its higher conversion and re-conversion costs.

4. DISCUSSION:

Compared to other regions, Japan has a relatively poor renewable energy resource endowment. However, as the demand for emissions reduction intensifies, green hydrogen is expected to remain a primary method for hydrogen production in Japan. In the context of hydrogen energy imports, hydrogen imports will replace centrally produced gray hydrogen and blue hydrogen, will be limited. Therefore, even if there is a reliance on imported hydrogen to meet local hydrogen demand in the future, it is crucial to vigorously develop green hydrogen production technologies to satisfy future hydrogen needs.

Furthermore, hydrogen imports will bring about cheaper and cleaner hydrogen supply to the local market, increasing the penetration rate of hydrogen in end-use sectors. The increased penetration of hydrogen energy will facilitate emissions reductions in sectors that are traditionally difficult to decarbonize. Therefore, to better achieve established emission reduction goals, it is important to prioritize the development of hydrogen and hydrogen trade, and promote the widespread adoption of hydrogen technologies in end-use applications.

Lastly, the scale of hydrogen trade is determined by the cost reduction of trade technologies. Investing in research and development for various forms of hydrogen trade conversion and transportation technologies will contribute to rapid cost reduction in hydrogen trade, thereby enabling the scaling up of hydrogen trade at an earlier stage.

5. CONCLUSION:

In the face of stringent emission reduction targets, the low-carbon transformation of the energy system is necessary, and hydrogen energy will provide a new solution for the transition. Due to regional disparities in renewable energy resources, hydrogen imports are needed to meet local hydrogen demand. This study developed a hydrogen trade module based on the GCAMv6.0 model to reveal the role of hydrogen imports in Japan's low-carbon energy system transition. The results show that hydrogen imports in Japan will replace domestically produced high-cost grey and blue hydrogen from 2040 onwards, and the provision of cleaner and more affordable hydrogen will stimulate an increase in hydrogen demand. Furthermore, hydrogen imports will impact the increased penetration of hydrogen in the transportation and industrial sectors, reducing the share of fossil fuels and lowering carbon prices. Lastly, in terms of regional distribution and import methods, hydrogen imports are concentrated, with ammonia shipping being the primary import method, and East Africa and Australia being the main import regions, while liquid hydrogen shipping mainly comes from neighboring regions. Based on the above conclusions, Japan should vigorously develop green hydrogen production technologies to meet future hydrogen demand. Emphasis should be placed on the development of hydrogen energy and hydrogen trade, promoting the adoption of hydrogen technologies in end-use sectors. Additionally, support for the development of renewable energy generation and hydrogen production technologies in underdeveloped regions can provide more diverse and cost-effective import options.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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