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TECHNOLOGY FORESIGHT FOR HYDROGEN SOCIETY TRANSITION IN JAPAN: APPROACH OF GTAP-E-POWER MODEL

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Abstract

With its portable, storable, and zero-emission features, hydrogen energy is regarded as one of the most promising alternative energies for the next generation. Along with developing hydrogen technology applications, Japan's pilot experiments have demonstrated the feasibility of a hydrogen society. However, empirical studies are still scarce and limited to energy efficiency analysis or cost-benefit analysis, and lack inclusive discussion contributing to the evidence-based approach targeting policy implementation of the hydrogen roadmap. The research aims to provide a quantitative impact assessment of Japan's hydrogen society by applying the GTAP-E-Power model with the technology foresight parameters of 2025–2035 sourced from the SciREX Policy Intelligence Assistance System – Economic Simulator (SPIAS-e) to investigate the change in output, price, and defragmentation of supply chains of energy sectors, as well as the emission of carbon dioxide from domestic and foreign firms. In the scenario of transitioning the existing fossil power of coal, natural gas, crude oil, and other renewable energies including solar and wind power, the simulation results demonstrated that the CO_2 emission by domestic firms in the transportation and service sectors could be reduced by 3.3% and 2.3%, respectively, for power generation sectors, a total equivalent to 26.6 million tons thanks to the improvement in energy efficiency. In comparison, the export of transport equipment and energy-intensive sectors increased by 6.5% and 5.6%, respectively. Moreover, the welfare analysis of equivalent variations of Japan's hydrogen society showed an increase of $75,696 million and a 1.3% growth in GDP.

Keywords: hydrogen society, CO_2 emission, SPIAS-e, net-zero society, GTAP-E-Power

JEL Classification: C68, R11, O13, O14, Q47

Contents

1. INTRODUCTION

Japan, a highly developed country with a critical shortage of hydrocarbon resources, sees multiple values in the use of hydrogen, including energy security, industrial competitiveness, and carbon emission reductions. In 2017, Japan was the first country to adopt a hydrogen framework with its Basic Hydrogen Strategy (METI 2020). The framework promotes an end-use approach that focuses on electricity, transportation, housing, heavy industry, and refining. Meanwhile, being a leader in fuel cell technology, particularly fuel cell vehicles (FCVs), manufacturing firms from the related fields are seeking to export this technology to the rest of the world. The main issue is to experiment with different options for sourcing hydrogen to adjust its industrial and energy policy for a society that utilizes the development of hydrogen energy.

1.1 Development of Hydrogen Technology

To achieve the medium- and long-term goals in the Basic Strategy, and to realize the "hydrogen society" that the Japanese have set out, the government has consistently allocated a budget of 98.9 billion yen (approx. $693 million) in FY2022 for research and development (R&D) related to fuel cells and water electrolyzer technology (METI 2021). To effectively reduce the risk and provide an incentive to encourage private firms towards this emerging field, public-private co-investment in R&D and pilot projects is essential to create synergy (Arque-Castells and Spulber 2022). The core concern is about the mobility sector applying hydrogen technologies, such as "power to gas," which is envisioned as a resolution to renewable power intermittency for stimulating domestic hydrogen production with co-benefits.

In the market application, hydrogen energy generation has matured with several methods categorized in the table below in different colors (Table 1.1). Thanks to its feature of storable energy, the transition to a hydrogen society could be referred to as an additional accessory investment in the existing power generation sources. It is also foreseen that it will decrease hydrogen energy generation costs if the demands and R&D continue to increase (Glenk and Reichelstein 2022; Hodges et al. 2022).

Table 1.1: Hydrogen Categories by Generation Method

Gray hydrogen	Reflects fossil fuels, natural gas, and water vapor to produce H2 and CO_2 through a "steam reforming" process; large amounts of CO_2 are emitted into the atmosphere.
Blue hydrogen	Reflects fossil fuels, natural gas, and steam to produce H2 and CO_2; zero emissions, including capture of produced CO_2 and geological storage (CCS).
Green hydrogen	Produced through electrolysis of H_2O to H_2 and O_2 from source electricity generated by renewable energy; zero CO_2 emissions.
Turquoise hydrogen	Produced a hydrocarbon feedstock, such as methane (CH_4) in natural gas, as the source of hydrogen atoms; the high-temperature reactor could use green energy.
Yellow hydrogen	Electrolysis of H_2O to produce H_2 and O_2 using electricity from nuclear power generation; zero CO_2 emissions but produces nuclear waste.
Brown hydrogen	Produced by gasification, where carbons materials are heated into a gas. Similar to black hydrogen.
White hydrogen	H_2 produced as a byproduct in the production of other products (e.g., steelmaking); production volume is uncontrollable.

Source: The authors.

1.2 Japan's Roadmap for Hydrogen Society

The Basic Hydrogen Strategy was first announced in 2017 by the Ministry of Economy, Trade and Industry (METI) to set up the hydrogen roadmap with ambitions to establish an integrated hydrogen supply chain domestically and internationally by 2030, including production, transportation, storage, and consumption from upper to down stream (METI 2017). Increasing renewable energy generation capacity is vital to the government's net-zero plan. However, because renewable energy is intermittent, it cannot balance supply and demand on the power grid. In addition, the increase in renewable energy generation capacity may result in more frequent curtailments (i.e., reductions in renewable energy generation to balance energy supply and demand or due to transmission line constraints) for future renewable energy power plant operators for an optimal energy mix (Huang and Kim 2021). The ambitions were mostly reconfirmed with the long-term strategy under the Paris Agreement and the Green Growth Strategy (METI 2021) towards 2050 Carbon Neutrality to reduce carbon dioxide emissions substantially.

Moreover, the Japanese government has recognized the need for new or modernized regulations on hydrogen and ammonia, and in fact, the Sixth Basic Energy Plan (METI 2021) specifies the importance of Japan playing a leading role in international rulemaking. Despite Japanese companies taking a pioneering role in driving innovation in the field of hydrogen technology with significant government funding, Japan's regulatory and rulemaking activities have been comparatively limited. However, the success of the next phase of the hydrogen revolution depends on the establishment of a well-coordinated and consistent regulatory framework. Given Japan's status as an early adopter of hydrogen technology and a major future importer of pure hydrogen, the development of the hydrogen society still requires substantial effort in terms of implementation and popularity.

To interpret the transition to a hydrogen society, simply analyzing the advancement of technology from an engineering perspective is insufficient. There are pilot hydrogen cities equipped with hydrogen energy pipelines, such as in Kitakyushu City (Fuel Cells Bulletin 2011) and in the Harumi area of Tokyo Metropolis (Fuel Cells Works 2019); the broader scope of a sectoral approach will be more beneficial in illustrating the hopeful picture of realizing a hydrogen society. It is expected that the research will bring more insights into hydrogen policy implications from a comprehensive methodology regarding technological improvement, capital investment, the supply chain of hydrogen-related sectors, and the overall economic impact assessment for the transition to a hydrogen society.

1.3 Rephrasing the Hydrogen Strategy under the Global Trend of Decarbonization

Amid the Ukrainian crisis and the global energy crisis since 2022, Japan rephrased its hydrogen strategy to take the lead in developing pioneering regulations and support systems for a hydrogen society with decarbonization by supporting businesses in developing a low-carbon hydrogen and ammonia supply in Japan by around 2030. According to the Policy Framework (draft) for Realizing a Hydrogen Society (METI 2023), the support consists of an efficient supply infrastructure, such as tanks and pipelines, to promote international competitiveness and efficient supply chains. Moreover, Japan will also promote hydrogen production and utilization in regions through the development of local supply chains and infrastructure networks.

In the power generation sector, the use of hydrogen and ammonia is highly anticipated as a cost-effective source in ensuring energy stability while reducing CO_2 emissions from thermal power generation and promoting the expansion of demand and cost reduction through the establishment of a large-scale supply chain towards 2030. Regulations and support will also be implemented to accelerate the use of hydrogen in power generation, such as the Long-term Decarbonization Auctions and the 2030 nonfossil fuel ratio of 44% or more.

In the mobility sector, support for fuel cell vehicles (FCVs) and hydrogen station development has been provided for passenger cars, but there is a need to focus on commercial vehicles, which have greater potential for hydrogen demand and for which the advantages of FCVs are more evident. This includes expanding policy resources, including tax measures, to support the large-scale construction of hydrogen stations. For railways, the development and demonstration of a domestic hydrogen supply chain through the use of fuel cell railway vehicles and low-environmental-impact railway transportation will be promoted.

The amended Energy Conservation Law sets target goals for specific transport operators and shippers, including nonfossil energy conversion targets such as hydrogen. Future goals include the implementation of approximately 800,000 FCVs, equivalent to passenger cars, by 2030 through the accumulation of demand for long-distance transport and the establishment of hydrogen supply chains. For fuel cell railway vehicles and railway transportation, the aim is to achieve social implementation by 2030, and for hydrogen stations, the goal is to make the business self-sufficient by the late 2020s, taking into account cost reductions due to regulatory relaxation, and to establish approximately 1,000 stations by 2030. Overall, Japan is taking steps towards the creation of a hydrogen-based society with a view to achieving carbon neutrality by 2050. In addition, Japan aims to collaborate with local governments and companies to promote the use of hydrogen in various sectors and industries, including ports and factories. The country plans to invest up to 2 trillion yen ($18 billion) in the industry over the next decade.

1.4 Research Question and Structure

To understand the overall economic assessment of the transition towards a hydrogen society in Japan, the research will apply a quantitative approach to investigate the impact of implementing a hydrogen society through capital investment in the hydrogen-related infrastructure with the foresight technology of 2025–2035. The research proceeds as follows: Section 2 will provide a literature review of the hydrogen society trend and its gap in empirical studies; Section 3 will introduce the methodology of the calibration for the technological improvement parameters and the structure of the analytical model; Section 4 demonstrates the scenario and the setting of policy shocks; Section 5 displays the simulation results and their interpretation; and Section 6 presents concluding remarks including policy implications, research limitations, and future prospects.

2. LITERATURE REVIEW

2.1 R&D Measures for Hydrogen Society Roadmap

Climate change and the interdependency of the global market have highlighted the need for new energy solutions. In 2020, the Japanese government established a target to attain carbon neutrality by 2050 through the attainment of net-zero greenhouse gas emissions. This determination led to the proposed establishment of a “hydrogen society,” with the promotion of fuel cell electric vehicles, hydrogen-based power generation, and synthetic gases in the industry sector. Despite the fact that hydrogen remains an emerging and scarce source of energy, the importance of renewable energy options to meet global energy demands while reducing CO_2 emissions should not be underestimated.

A hydrogen society could refer to Japan’s “smart community” concept, which leverages digital and communication technologies to efficiently manage power generation and consumption. The success of this policy is vital for securing Japan’s future economic growth, energy security, and environmental well-being. However, the reliance on imported energy carriers poses a significant challenge for Japan’s energy system and energy security. To accommodate the “hydrogen society” indicated in Japan’s basic hydrogen strategy with its carbon neutrality target in 2050, Japan’s energy policy has greatly strengthened the green transition by reducing dependence on fossil fuel power plants while promoting renewable energy infrastructure for industry and households.

Over a period of several decades, Japanese energy policy has favored an ambition to advance the development of fuel cells that are cheaper, more efficient, and longer lasting, as well as the advancement of hydrogen production, storage, transportation, and fuel supply systems to facilitate the widespread use of fuel cells. The Japanese government and industry are strongly supportive of this policy, and a political consensus is forming that Japan should shift away from nuclear power and actively pursue an efficient, integrated, and environmentally friendly hydrogen society. To strengthen this strategy, Japan should explicitly focus on expanding research and development efforts in key energy sectors (Behling, Williams, and Managi 2015). The capture of R&D factors would provide measurable indicators, which could substantially help the analysis in making a feasible roadmap for a hydrogen society.

In a recent study, Burandt (2021) utilized a stochastic large-scale open-source energy system model, coupled with full hourly power system dispatch, to analyze the potential impact of hydrogen imports on the power system, electricity prices, import dependency, and other industrial sectors. The findings indicate that the integration of hydrogen imports would have a significant impact on power system development, leading to a substantial shift toward renewable energy sources, such as solar PV, onshore and offshore wind, and hydroelectric power. Notably, solar PV is expected to be the primary source of electricity, accounting for 40%–45% of total generation, while onshore wind power is expected to largely complement it, and hydropower is expected to provide baseload power in all cases. Furthermore, hydrogen imports have the potential to lower the average price of electricity generation in highly urbanized areas, replacing electrification of buildings and the industrial sector with hydrogen-based technologies. It is important to acknowledge the limitations of the modeling approach utilized in the study, and future analyses should consider these limitations in order to provide a more comprehensive outlook.

2.2 Applicable Sectors for Hydrogen Society

A hydrogen society could help in transitioning from a fossil fuel energy system to a sustainable green economy, taking into account technical, environmental, economic, and social factors. Trattner, Klell, and Radner (2022) highlight the potential of a hydrogen society in facilitating the transition from a fossil-based economy to a sustainable green economy, taking into consideration technological, environmental, economic, and social factors. This transition necessitates a complete shift from fossil fuels to renewable energy sources, such as solar, wind, hydro, environmental heat, and biomass, employing electrochemical machines, including electrolyzers, batteries, and fuel cells, to enhance efficiency and reduce CO_2 emissions in all areas of mobility, industry, household, and green energy services. The initial markets for green hydrogen could be intermediate commodities for industrial applications, followed by power generation and mobility (Acar et al. 2019). A range of well-designed multi-generation systems that harness the solar spectrum and generate value-added system products, such as electricity, heat, Cl_2, NaOH, clean water, and ammonia, are available. Encouraging sustainable methods of hydrogen production is crucial for promoting international initiatives.

In the realm of sustainability, implementing green power and hydrogen in the mobility sector is crucial, as it can replace traditional fossil fuels and lower carbon emissions in industrial applications. However, the adoption of hydrogen as an energy carrier requires alterations to combustion chambers and burners, and the replacement of fossil fuels in each process must be taken into account. As the utilization of hydrogen for fuel cell electric vehicles grows, a major automotive company in the Republic of Korea has deemed the current hydrogen supply infrastructure and strategies for developing the hydrogen industry feasible (Kim et al. 2023). Various methods for hydrogen production and transportation are being explored, including natural gas reforming, renewable energy, and green hydrogen. In an effort to reduce the price of hydrogen gas, the Korean government is providing subsidies to the private sector to encourage the installation of more hydrogen refueling stations.

To promote a stable supply of, and demand for, hydrogen, countries should capitalize on their strengths to produce hydrogen and develop appropriate fueling strategies through public-private partnerships and international cooperation. In Japan, policymakers face significant challenges in ensuring sustainable energy security in the aftermath of the Fukushima nuclear crisis. Therefore, they need to decarbonize the energy system while ensuring safety and continuity in case of natural disasters. According to Khan, Yamamoto, and Sato (2020), the hydrogen fuel cell vehicles (HFCVs) could barely meet in Japan’s green transition even with incentives provided by the government to promote HFCVs as an environmentally friendly technology. Thus, potential demand for HFCVs and government incentives remain critical factors in the adoption of hydrogen as an energy carrier in Japan. The mobility, industry, service, and household sectors are highly correlated with a potential spillover effect generated among different users. Therefore, a comprehensive model platform could serve as a better analytical tool for interpreting an integrated power grid and hydrogen society.

2.3 Integrated Power System in the Case of Norway

In order to foster the development of low-carbon hydrogen, the Norwegian government has implemented various R&D-related support measures. The “Hydrogen Strategy” was published by the government in June 2020, referring to the entire energy sector and providing a roadmap for hydrogen. According to the IEA (2022), Norway plans to gradually phase out its oil export industry by 2050, and hydrogen will play a central role in the transition towards a low-emission society. This shift towards hydrogen highlights the importance of decarbonization in Norway. Although the oil sector still accounts for approximately 30% of Norway's CO_2 emissions, hydrogen is expected to replace fossil fuels in the transportation and industrial sectors.

In light of Norway's ambitious greenhouse gas reduction target of achieving a 90%–95% reduction (excluding sinks) from 1990 levels by 2050, green energy hydrogen fuels are seen as the key to low emission technology (IEA 2022). Despite this, the adoption of hydrogen technology remains limited due to the lack of policy and regulatory support, as well as limited public awareness. In order to promote the widespread use of hydrogen technology, various factors, such as environmental awareness and benefits, the availability of hydrogen infrastructure, the compatibility of household and industrial heat appliances, fuel price levels, media coverage, and support for the hydrogen market, need to be taken into account (Høyland, Kjestveit, and Skotnes 2023).

To investigate the economic impacts of policies aimed at reducing fossil fuel production and promoting the hydrogen demand in integrated power systems, Computable General Equilibrium (CGE) models can serve as a valuable tool. Espegren et al. (2021) employed a dynamic multi-regional CGE model to simulate Norway's energy transition, demonstrating the potential for significant decarbonization by 2050 with the aid of hydrogen. Nonetheless, the study also highlights challenges and trade-offs associated with the transition, including potential impacts on GDP growth. The analysis indicates that GDP growth rates will initially be lower than in the main alternative scenario but will recover after 2030. In order to analyze integrated power systems with various energy sources, the use of CGE models can be beneficial, as they allow for a thorough examination of the economic implications of different policy measures aimed at achieving a sustainable energy system.

Damman et al. (2021) employ a hybrid approach that combines qualitative sociotechnical analysis with quantitative modeling to explore the sociotechnical dynamics that led to the current situation in Norway regarding hydrogen in the energy transition. This method of analysis can be particularly useful in complex situations, with multiple pathways and solutions being considered. They employ two models, namely the bottom-up optimization model of the national energy system (TIMES-Norway) and the top-down general equilibrium model (REMES), to conduct a quantitative analysis of the viability of different routes toward a zero-emission society in Norway by 2050. The study points out that effective transformation necessitates the consideration of numerous pathways and the plausible condition for each pathway to be realized. Norway's abundant resources of hydropower, onshore and offshore wind, and heavy dependence on oil and gas offer various opportunities for hydrogen energy solutions, thereby shedding light on the potential and challenges of deploying and producing hydrogen on a large scale.

2.4 The Potential of Hydrogen Society for Decarbonization

Hydrogen energy is a critical element in achieving a low-carbon society, but its expansion faces various obstacles, including technical, financial, and institutional challenges. While there have been recommendations from the government and business perspective, studies on hydrogen station users are limited, and respondents often lack sufficient information on the technology. The characteristics of a future hydrogen economy are currently subject to debate. Oliveira, Beswick, and Yan (2021) propose a vision in which hydrogen is primarily used for decarbonization with a three-stage hydrogen deployment plan that includes various sectors, including industry, transportation, building and heating, and electricity, showing that hydrogen could decarbonize around 18% of energy-related sectors. Meanwhile, Hienuki et al. (2021) conducted a survey of users who refuel at hydrogen stations to evaluate the social acceptability of these stations. They compared the acceptance of users of self-refueling hydrogen stations with that of existing gas stations. By assessing users' confidence in the technology, they were able to improve the acceptability of hydrogen stations and build on the existing acceptability model.

Utilizing the power exchange market, in addition to on-site photovoltaics, can improve the unit cost of hydrogen. The power-to-gas (PtG) technology for hydrogen production could serve a mean of stabilizing power systems and reducing CO_2 emissions. Yoshida et al. (2022) examine the potential of PtG technology as a means of stabilizing power systems and reducing CO_2 emissions through hydrogen production. They propose a mixed-integer linear programming model to optimize the annual hydrogen production schedule, with the unit cost of hydrogen production as the evaluation index. The results indicated that PtG technology could serve as a promising solution for reducing emissions in the industrial sector, particularly as more variable renewable energy sources are introduced in the future, and can contribute to the introduction of hydrogen demand for industrial applications.

In relation to the potential of solar thermal-to-gas (StG) conversion systems in facilitating the transition towards zero-carbon energy in Japan, this technology is considered highly promising due to its ability to convert renewable energy into synthetic gases such as hydrogen and methane, which can effectively store intermittent renewable energy (Wai, Ota, and Nishioka 2022). The production of synthetic chemical gases through StG conversion has significant potential as an alternative to fossil fuels, and the Japanese government is promoting cost-effective renewable energy generation and efficient PtG conversion, specifically for hydrogen production, decarbonization, and storage. Furthermore, Japan is presently engaged in the development of carbon recycling technologies aimed at decreasing CO_2 emissions and capturing carbon from the industrial sector.

To achieve a transition towards sustainable sociotechnical systems and establish energy conversion, it is imperative to consider the social dimensions of hydrogen conversion. These dimensions encompass contextual disparities and challenges, including technical feasibility, compliance with national regulations, public acceptance, and economic viability. Incorporating a societal perspective is crucial to ensure stable efficient functioning of sociotechnical systems. However, hydrogen, despite being capable of complementing renewable electricity and contributing to various energy-related sectors, is not the prevailing energy source at present. To meet the future demand for hydrogen, the hydrogen economy must be expanded, and the adoption of green hydrogen in sectors such as chemical synthesis should be prioritized along with conventional energy sources to ensure the hydrogen supply chain for production to achieve economies of scale. Furthermore, hydrogen can aid decarbonization efforts by virtue of its high mass energy density, light weight, ease of electrochemical conversion, and capacity to store energy over extended periods. It would be desirable to develop a quantitative measure to capture the transition of energy sources toward a hydrogen society supported by the technology advancement for assessing the impact on industry and GHG emissions.

3. METHODOLOGY

To make a comprehensive impact assessment for transitioning to a hydrogen society, it is essential to utilize the instrument with the commonly accepted scope of database and a consistent approach. However, under the existing literature on hydrogen mainly focuses on energy efficiency. Moreover, the economic analysis is still limited to cost-benefit analysis, and we find evidence-based technological parameters for implementing hydrogen power with the foresight technology indicators and apply a CGE model to come up with the impact of the hydrogen society.

3.1 The Capture of Technological Improvement

To quantitatively evaluate the social and economic policies regarding science technology for presenting multiple possible policy options, it is indispensable to capture the technological characteristics of tangible and knowledge capital as intangible fixed assets compilation in the input-output tables (Kuroda et al. 2018). The multisectoral economic general interdependence model explicitly captures the impact on the economy and society through the general interdependence of the economy in terms of both flows and stocks by industry sector based on the activity of three dimensions: main product, intra-ICT, and intra-R&D.

The model uses a reference case of a technological scenario (science and technology and social technology) that is exogenously given to the economy and society without any specific policy measures to compare its impact on the economy and society using various indicators to establish the direction of economic and social change. In addition, the ScREX Policy Intelligence Assistance System – Economic Simulator (SPIAS-e) was created to serve as an analytical tool for understanding the characteristics of science and technology and their economic and social impacts in the scenario of Japan's economy in the projection of 2021–2050 (Huang and Kuroda 2021), the parameters of which could be utilized for economic analysis.

3.2 GTAP-E-Power Model

For analyzing the energy or power system impact on the economy on a global scale, the Global Trade Analysis Project (GTAP) model developed by Prude University is commonly used (Hertal 1997). The GTAP model is based on a CGE framework with the input-output tables contributed by the research community. In many extensions of the GTAP model, the GTAP-E-Power is an electricity-detailed economy-wide model that has decomposed different power generations from fossil fuels of coal, crude oil, and natural gas, or renewable energy such as hydro, solar, and wind power (Peters 2016a,b). The GTAP-E-Power model implements the GTAP model in presenting economic indicators of output, price, external trades, and carbon dioxide emission from 75 sectors, which makes it a useful policy tool for identifying a domestic or global economic issue (Huang, Iwaki, Liou, 2023). Although hydrogen energy is still not included in the model, we could utilize the parameters sourced from other available databases such as SPIAS-e and other key literature to illustrate the impact of the hydrogen society roadmap.

4. SCENARIO

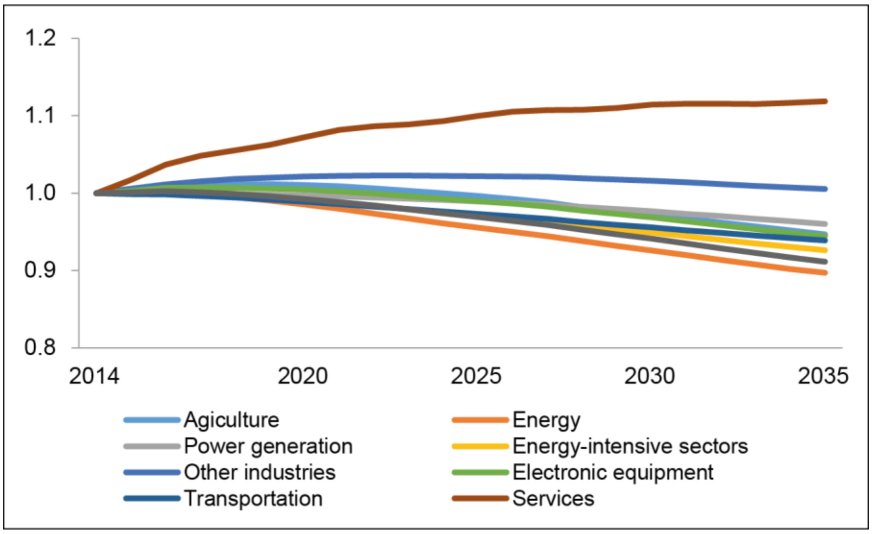
We create a scenario of a roadmap toward a hydrogen society in the GTAP-E-Power model. As indicated, in the absence of the hydrogen energy sector in the model scope, we hereby assume higher productivity thanks to the technological improvement with hydrogen energy generated by different power sources. Therefore, instead of differentiating the hydrogen sources, we demonstrate the implementation of a hydrogen society by using the parameters sourced from SPIAS-e for technological improvement and the assumptions of hydrogen cost (IEA 2021) as the policy shocks.

4.1 Technological Improvement

We refer to the projection of economic indicators as technology foresight because of its featuring in the accumulated flow of tangible and intangible capital stock. In SPIAS-e, the indicators in the 50-year projection are generated along with the higher efficiency generated by information communication technology (ICT) and demographic change (Huang and Kuroda 2021).

The price index of tangible capital aggregated from 93 sectors represents the cost of capital input (Figure 4.1); a higher index indicates a higher cost. Between 2014 and 2035, the energy sectors show the lowest value, implying that the sector has more significant technological improvement; on the other hand, the services sector shows a high value, indicating that the demographic change in Japan has made the cost of services expensive. The indicators could be referred to as spillover effects contributed by the R&D (Huang, Liou, and Iwaki 2021). We thus calibrated the index from 2025–2035 as our parameters for technological improvement (Table 4.2).

Figure 4.1: The Price Index of Tangible Capital



Source: Sectors aggregated from SPIAS-e.

Table 4.2: Technological Improvement Parameters

Sectors	2025–2035
Agriculture	4.96%
Energy sectors	6.10%
Power sectors	2.95%
Energy-intensive sectors	4.64%
Manufacturing	1.64%
Electronic equipment	4.59%
Transport equipment	5.97%
Transportation	3.51%
Services	-1.72%

Source: Sectors aggregated from SPIAS-e.

4.2 Hydrogen Society Policy Shock

The energy and power generation sectors in the GTAP-E-Power model are more specific than sectors classified in SPIAS-e. Therefore, for simplicity and consistency, we unified the parameters for these two sectors and the capital investment ratio for hydrogen generation (Table 4.3).

4.2.1 Productivity Growth

In 2025–2035, the R&D activity accumulated in the business-as-usual (BAU) path shows a lower price index for most of the sectors, especially in the energy (6.1%), transport equipment (5.97%), and agriculture (4.96%) sectors, indicating that firms could achieve the same performance with less input. Nevertheless, due to the shrinking population, productivity growth decreased in the services (–1.72%) and manufacturing (–1.64%) sectors.

4.2.2 Capital Investment

To achieve a hydrogen society, capital investment in hydrogen generation is fundamental. The investment ratio for fossil fuel power generation is assumed to be 10% following the equipment installation with associated sectors. In comparison, the ratio is set at 50% for the renewable energy source of solar and wind power because of the declaration of the net-zero carbon neutrality goal. The total investment volume is $924.7 million.

4.2.3 Energy Efficiency

According to the cost estimate of hydrogen energy generation by the IEA (2019), as of 2019, the relative cost of H2 per KG by steam methane reforming (oil and gas), coal gasification, and electrolysis (renewable energy) is 1:2:4; we hereby assume that the hydrogen generation efficiency for sectors of services and manufacturing could increase by 20%, 10%, and 5% for each power generation method, respectively. Moreover, given the evidence that a higher usage rate would also increase the efficiency, we thus assume that the peak load power generation for energy-intensive sectors for the simulation analysis.

Table 4.3: The Technology and Policy Shocks

(Unit: %)

Sectors	Productivity Growth	Capital Investment*	Energy Efficiency
Coal	6.10	n.a.	n.a.
Crude oil	6.10	n.a.	n.a.
Natural gas	6.10	n.a.	n.a.
Petroleum	6.10	n.a.	n.a.
Power transmission	2.95	n.a.	n.a.
Coal-fired power**	2.95	10.0	10.0
Oil power**	2.95	10.0	20.0
Gas power**	2.95	10.0	20.0
Nuclear power**	2.95	10.0	10.0
Solar power**	2.95	50.0	5.0
Wind power**	2.95	50.0	5.0
Hydro power**	2.95	10.0	5.0
Other powers	2.95	n.a.	n.a.
Agriculture	4.96	n.a.	n.a.
Electronic equipment	4.59	10.0	n.a.
Transport equipment	5.97	10.0	n.a.
Energy-intensive sectors	4.64	n.a.	n.a.
Manufacturing	–1.64	10.0	n.a.
Transportation	3.51	10.0	n.a.
Sea transportation***	3.51	n.a.	n.a.
Services	–1.72	n.a.	n.a.

Note: *Total investment volume is $924.7 million.

**For energy-intensive sectors, the power supply efficiency is assumed to double.

***Productivity growth is assumed to be at the same level as the transportation sector.

Source: By authors based on SPIAS-e and the assumptions of the IEA (2019) and METI (2021).

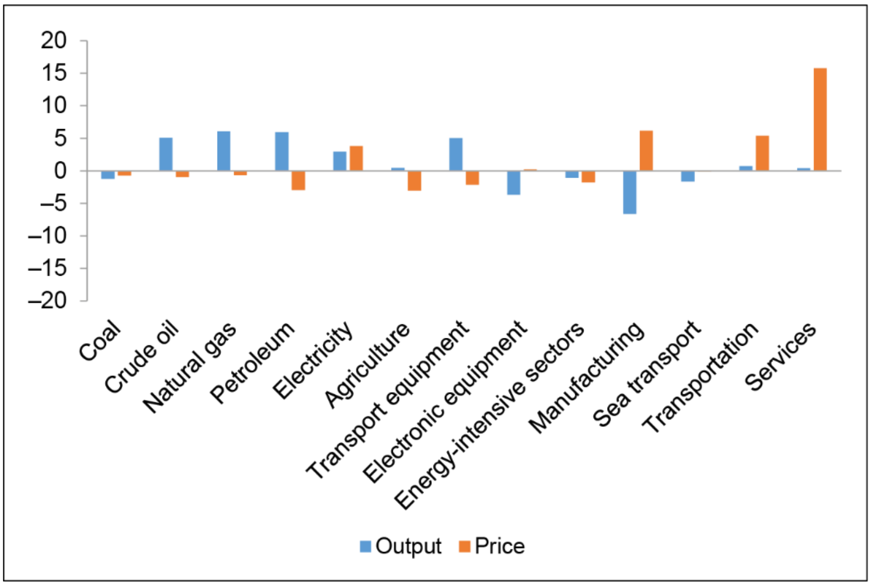
5. SIMULATION RESULTS

Based on the scenario's technological change parameters and policy shocks, we obtained the results of a roadmap toward a hydrogen society. Since the parameters were calibrated for ten years, it implied that the simulation results could be regarded as a ten-year accumulated economic indicator (Figure 5.1). We hereby discuss the simulation results from four perspectives: (1) output and price change, (2) external trades and supply chain, (3) carbon dioxide emission, and (4) GDP and welfare analysis.

5.1 Change of Output and Price

Generally speaking, the energy sectors show an increase in output, excluding a slight fall in coal. Given that the volume of Japan's output for energy sectors is minimal, the increase could be disregarded. However, the price decrease could imply the transition of energy sources. The output and price of electricity both showed growth, indicating the rising importance of electricity from all power generation sources.

Figure 5.1: Output and Price Change



Agriculture output showed a slight 0.5% growth and a 3.1% decrease in price thanks to the higher productivity of smart and autonomous systems. On the other hand, transport equipment showed a vibrant growth of 5.0% with a decreased price, reflecting Japan's competitiveness in the new vehicle production that fits the energy transitions. Meanwhile, it is notable that the output decreased by 3.7% in electronic equipment and 1.0% in the energy-intensive sector despite its increase in productivity. The manufacturing sector's output fell by 6.6%, with the price increasing by 6.1%, indicating the decaying influence.

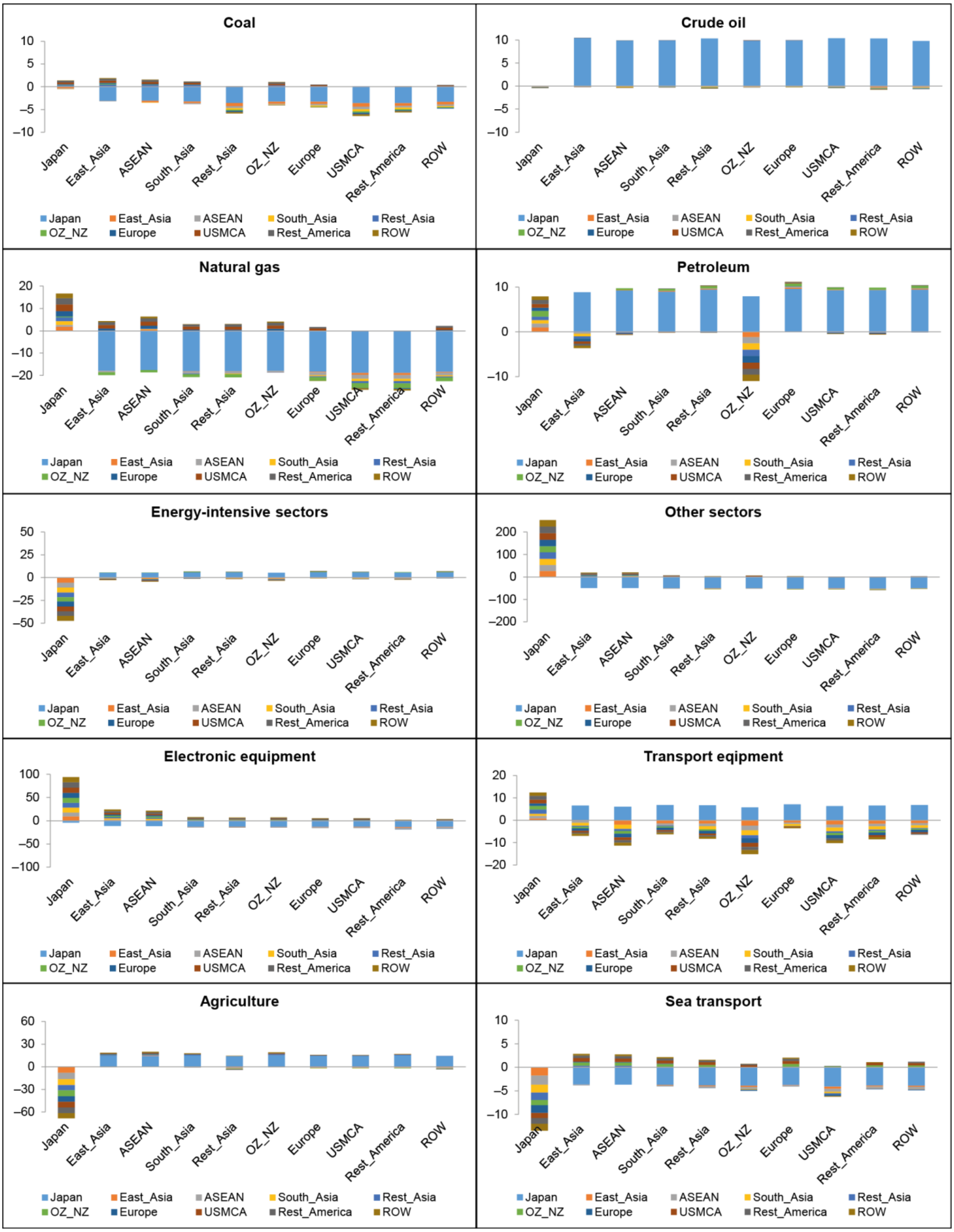
The demographic change has threatened Japan's service sector, which has the highest economic share. However, the energy transition has helped activate the sector, with slight increases of 0.7% in transportation and 0.4% in services. Even though the price increases reached 5.4% and 15.8%, the positive growth in the services sectors plays a role in maintaining the long-term stability of economic performance.

5.2 External Trades and Supply Chain

The scenario of policy shocks on power efficiency and investment in hydrogen society-related sectors may also impact the global supply chain regarding the percentage change of trade volume with trading partners (Figure 5.2). Therefore, interpreting the potential consequences may assist firms and facilitate policymaking in preparing for the adjustment of production and fluctuation.

Figure 5.2: Changes of Import from Trading Partner Country

(Unit: %)



Coal

Crude oil

Natural gas

Petroleum

Energy-intensive sectors

Other sectors

Electronic equipment

Transport eqipment

Agriculture

Sea transport

5.2.1 Energy Sectors

Since Japan only produces very little energy, we shall disregard the change in Japan's export to other countries. In addition to the stable situation in the coal and crude oil sectors, Japan increases its import of natural gas from Europe and from Asian regions, while exporting refined petroleum to other regions. Meanwhile, Australia and New Zealand reduced the import of petroleum from other regions but substantially increased imports by 7.9% from Japan, which could imply other possible energy partnerships.

5.2.2 Other Manufacturing Sectors

With a more stable power supply for energy-intensive sectors such as the steel, chemical, and machinery sectors, Japan has become more self-sufficient, with a strong export increase of 5.6% to all regions. Moreover, Japan's core competitiveness in transport equipment also showed in the notable increase in export by 5.7% to 7.2%, especially in Europe and in Asian regions. It is interesting to see the significant increase in export of 15% in Japan's agriculture sector, which mainly contributed to its high value added and smart system. As no policy shock is provided for, Japan could substitute the import with domestic supply for the sea transport sector.

On the other hand, the demand for Japan's manufacturing and electronic equipment sectors showed a significant decrease, implying Japan's diminishing comparative advantages in the global production networks. Nevertheless, the high interdependence between Japan and the world for energy-intensive and transport equipment sectors may highlight the importance of developing the essential process toward a hydrogen society by providing next-generation transport equipment and upgrading the products from energy-intensive sectors.

5.3 Carbon Dioxide Emission

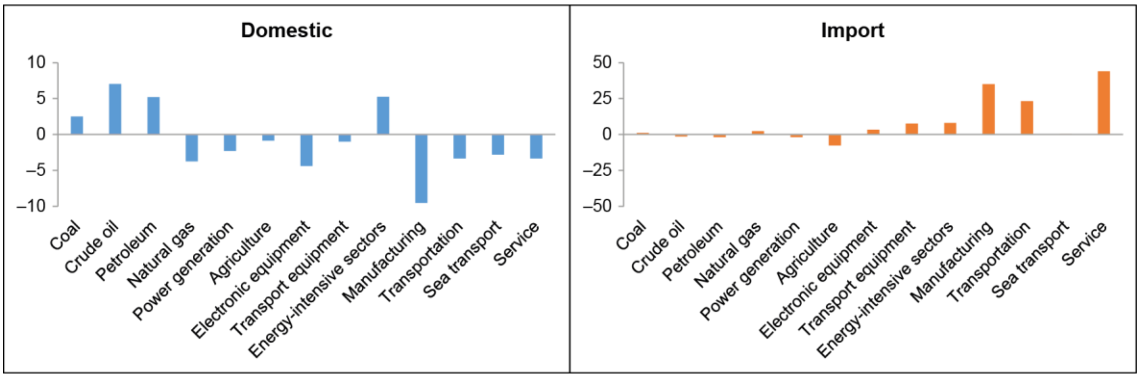
Reducing carbon dioxide emissions through the use of renewable energy is the primary measure to achieve the net-zero carbon neutrality goal (Figure 5.3). The technological improvement parameters we set for policy shocks could project possible pathways of CO_2 emission with informative policy implications toward the reduction target. However, as the shocks only apply domestically in Japan, we hereby focus more on the domestic carbon dioxide emission.

A higher emission of fossil fuel may imply a fluctuation in the energy transition, while natural gas showed an emission decrease of 3.7%. By implementing the assumed high-efficiency hydrogen energy generation equipment, the power generation sectors, including coal, crude oil, and natural gas, have contributed to a 2.3% decrease in emissions, or 6.8 million tons. Other significant emission reductions could refer to electronic equipment (–4.4%) and manufacturing (9.5%) sectors, implying the reconstruction of the global supply chain. On the other hand, the energy-intensive sectors showed an increase of 5.2% in emissions due to Japan's sectoral comparative advantage as a trade-off for other manufacturing sectors.

Japan's core competitiveness in transport equipment production has paid off in reducing emissions by 1.0%, which is small but unneglectable because the production of so-called "zero-emission" electronic vehicles is notorious for massive CO_2 emissions during its production process. Interestingly, even without energy efficiency policy shocks, the sea transport sector could reach a 2.8% emission reduction, mainly because of the change in external trades and the productivity growth in global logistics.

Meanwhile, the 3.3% emission reduction or a total of 19.8 million tons in the transportation and services sectors is impressive, representing vital indicators for transitioning to a hydrogen society. Lastly, we might begin to worry about the massive emission increase if we look at the indicators from the import firms. This is mainly because no technological improvement parameters were set or policy shocks applied to regions other than Japan.

Figure 5.3: Change of Carbon Dioxide Emission
(Unit: %)



5.4 Change in Employment

Along with the demographic change and the technological improvement toward the hydrogen society, sectoral employment also shows the transition (Table 5.1). By implementing the new facilities for hydrogen generation, employment shows a significant growth in solar power (12.9%) and the power transmission system (12.9%), natural gas (12.5%), and thermal power (10.3%), while a decrease is evident in coal (–11.6%) and petroleum (–7.5%). Energy-intensive and other sectors decline by 6.4%–6.9%, whereas a substantial increase is evident in transportation equipment (10.5%).

In regard to the number of employees, the higher efficiency and automatic system have decreased transportation by 413,712 people. Nevertheless, the service shows an increase of 614,248 people, indicating a more specific workload allocation to maintenance or the medical care sectors. As a shrinking and aging population is inevitable in Japan, the employment change should not be taken as a shock, but rather a process of transition toward the hydrogen society. The technological improvement could still sustain efficient logistics, transportation, and service with a satisfactory quality of life and mitigate climate change with clean and renewable energy sources.

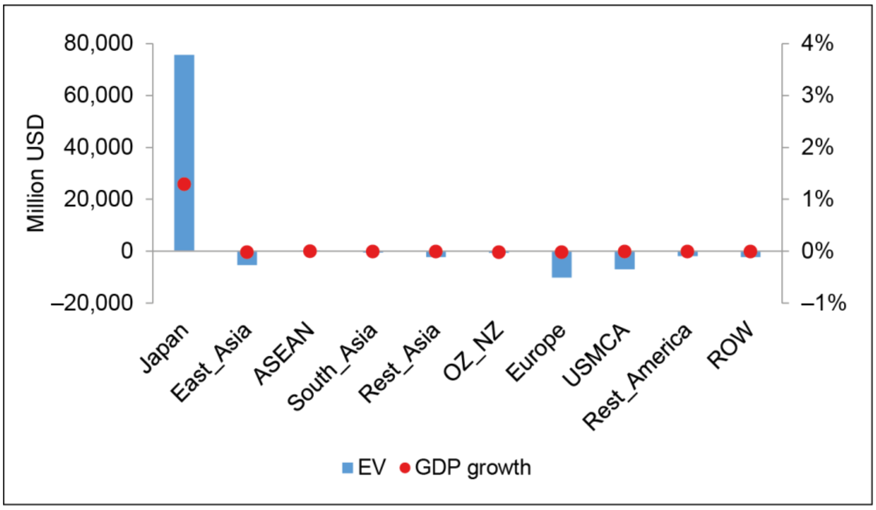
Table 5.1: Change of Employment

Sector	**People**	
Agricultural, forestry, fishery, and animal husbandry	–8,324	–0.2%
Coal	–4,247	–11.6%
Oil mining	196	7.0%
Natural gas	6,969	12.5%
Petroleum	–1,136	–7.5%
Thermal power	11,335	10.3%
Solar power	2,652	12.9%
Other power	3,418	7.7%
Power transmission	12,879	12.9%
Transport equipment	105,103	10.5%
Energy-intensive sector	–290,334	–6.4%
Other sectors	–226,982	–6.9%
Electronic equipment	–14,402	–1.0%
Transportation	–413,712	–11.8%
Sea transportation	–57,473	–23.2%
Service	614,248	1.2%

5.5 Welfare Analysis and GDP

In the GTAP model scope, we use equivalent variations to compare the utility change in the *ex ante* and *ex post* conditions to evaluate the welfare (Figure 5.4). The regional utility is the function of goods, including energy consumed by households in the region. We calibrated the technological growth parameters, capital investment for hydrogen-related sectors, and energy efficiency assumptions, which contributed to a substantial improvement in welfare by $75,696 million. Although the relevant parameters are not applied to other regions, ASEAN showed a $299 million increase in welfare, implying that its economy was also affected positively by our assumed hydrogen society transition in the regional supply chain.

Figure 5.4: Welfare and GDP Growth



Consistent results in GDP also reveal that the transition to a hydrogen society could bring a 1.3% economic growth. Upgrading the hydrogen energy system with strategic investment could lead to a higher quality of life with less CO_2 emission. The hydrogen society roadmap could positively impact the economy even for a country like Japan with its tremendous pressure on demographic change with a shrinking population.

6. CONCLUSIONS

The composition of a hydrogen society is complex, and it requires an interdisciplinary approach and inclusive analysis to coordinate critical factors to accelerate the development drawn in the roadmap effectively. But, more importantly, a broader approach to socioeconomic analysis could substantially motivate more stakeholders to cooperate for comprehensive implementation for expanding the demand to realize a hydrogen society with clean and sustainable development.

The main contribution of the research is its evidence-based inclusion of the 2025–2035 foresight technology indicator for an assumed hydrogen society transition scenario with GTAP-E-Power economic modeling for plausible policy intuitions. The simulation results provided wide-ranging information that could assist industries in adjusting the fluctuation and opportunity along with the hydrogen society. This method allowed more specialists to join the policymaking process with their expertise to strengthen and accomplish the policy recommendations gradually.

6.1 Policy Implications

Based on the simulation results of Japan’s hydrogen society transition, we found that capital investment in power generation sectors for hydrogen energy generation equipment could improve energy efficiency, thereby contributing to stimulating Japan’s economy by increasing GDP by 1.3% with an improvement of welfare by $75,696 million, as well as an estimated reduction in CO_2 emissions of 19.8 million tons in the transportation and services sectors.

More specifically, the hydrogen society transition could reduce Japan’s dependence on fossil fuels with a more resilient global supply chain for energy-intensive, transport equipment, and even agriculture sectors. Furthermore, the investment in hydrogen-related sectors also reinforced Japan’s competitiveness and created the possibility of an energy partnership with Australia and New Zealand and production networks with ASEAN.

Our study indicates that the attainment of economies of scale is imperative to markedly decrease the expenses associated with hydrogen energy. The robustness of the hydrogen supply chain hinges upon the existence of a robust demand for hydrogen energy across all sectors, including transportation, manufacturing, and residential domains. Moreover, to ensure the smooth functioning and upkeep of the hydrogen supply chain, the establishment of production networks in crucial domains such as hydrogen fuel cell vehicles (HFCVs) and other vital constituents of the hydrogen infrastructure is crucial and would yield benefits for regional collaborators in Asia and the Pacific.

The transformation in employment patterns underscores the significance of building capacity and providing training in hydrogen-related industries. While advancements in efficiency could lead to the displacement of some traditional jobs in the fossil fuel sector, the demand for sustainable energy is expected to generate employment opportunities for technicians and service-oriented sectors, thereby enabling greater international mobility of human resources. This transfer of knowledge and skills is likely to have a spillover effect, not only within the region but also among regions, owing to the growing adoption of renewable energy sources such as offshore wind power and associated manufacturing industries. Continuous policy dialogues concerning technology transfer and stakeholder partnerships are vital for effective policy formulation and collaboration within the global supply chain. Finally, we recommend the establishment of a hydrogen society pilot zone to facilitate the adoption of hydrogen energy.

6.2 Research Limitation

To fill the gap in hydrogen studies between the engineering approach and economic analysis, the research applied a GTAP-E-Power model to simulate Japan's hydrogen society transition with technological improvement parameters calibrated from SPIAS-e. However, even though informative economic indicators were identified through the assumed scenario in the simulation of policy shocks, limitations are inevitable for the current research scope. For instance, the assumption of technological improvement might be oversimplified under the homogeneous energy efficiency parameter setting for all sources of energy goods and power generations. Therefore, more precise indicators of energy parameters should be make to improve the accuracy of the simulation results.

Moreover, the GTAP-E-Power model scope is a static model and thus the recursive impact could not be measured, making it difficult to reflect the fiscal feasibility of massive infrastructure investment. In addition, it is unrealistic that the parameters of technological improvement only occur in Japan, which has dramatically restricted the revelation of the global hydrogen supply chain. It is desirable to overcome these limitations so that the GTAP-E-Power analysis can be a more practical instrument for interpreting the hydrogen society.

6.3 Future Prospects

Along with recovering from the COVID-19 pandemic, more hydrogen-related systems will be installed to meet the roadmap and the goal for a net-zero carbon society. To cope with the research limitations indicated above, it would be indispensable to apply more accurate parameters for technological improvement indicators for Japan and other regions, specifically to the particular power generation sources, to better illustrate the impact of transitioning to a hydrogen society.

Notwithstanding, it will be essential to revise the GTAP-E-Power model scope from static to dynamic to appropriately capture the recursive impact of investment choices to enable policymakers to designate feasible fiscal plans to support the project under the evidence-based references.

Finally, and fundamentally, similarly to the effort expended in distinguishing renewable energy sectors of solar and wind power generation from fossil fuel, it will be necessary for economists and the statisticians to think about extrapolating hydrogen energy into an independent sector. This task will greatly help in analyzing the interdependence among sectors and making straightforward policy recommendations to accelerate the realization of a hydrogen society.

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