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The Role of Hydrogen in Achieving Long Term Japanese Energy System Goals

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Abstract: This research qualitatively reviews literature regarding energy system modeling in Japan specific to the future hydrogen economy, leveraging quantitative model outcomes to establish the potential future deployment of hydrogen in Japan. The analysis focuses on the four key sectors of storage, supplementing the gas grid, power generation, and transportation, detailing the potential range of hydrogen technologies which are expected to penetrate Japanese energy markets up to 2050 and beyond. Alongside key model outcomes, the appropriate policy settings, governance and market mechanisms are described which underpin the potential hydrogen economy future for Japan. We find that transportation, gas grid supplementation, and storage end-uses may emerge in significant quantities due to policies which encourage ambitious implementation targets, investment in technologies and research and development, and the emergence of a future carbon pricing regime. On the other hand, for Japan which will initially be dependent on imported hydrogen, the cost of imports appears critical to the emergence of broad hydrogen usage, particularly in the power generation sector. Further, the consideration of demographics in Japan, recognizing the aging, shrinking population and peoples' energy use preferences will likely be instrumental in realizing a smooth transition toward a hydrogen economy.

Keywords: hydrogen economy; fuel cell; sustainability; Japan; energy model

1. Introduction

Following the ratification of the Paris Agreement in 2016, 195 signatory nations agreed to tackle climate change and limit global temperature rises through the intended nationally determined contributions (INDC) with established medium (2030) and long-term goals (2050) [1]. As part of the agreement, a global assessment of progress is scheduled for the year 2023 and every five years thereafter. It is apparent from early evaluations that many nations are struggling to achieve their pledged contributions, identifying a need to accelerate the implementation of climate change mitigation policies [2]. Towards this goal of accelerating climate change mitigation policy implementation, particularly in the case of renewable energy technology deployment, hydrogen may provide a complementary solution, due to its flexibility as an energy carrier and storage medium. Japan, a signatory to the Paris Agreement, has shown interest in achieving a hydrogen economy as a part of their overall climate change and energy transition strategy, as evidenced by their early, significant investment in hydrogen research and development [3].

In 2017, the Japanese government determined the "Basic Hydrogen Strategy", outlining the vision for Japan's low carbon energy society of the future and the role of hydrogen in achieving this vision. The strategy recognizes two key structural challenges for Japan's energy system. The first challenge is the high level of dependence on foreign fossil fuels for energy, and the geopolitical risk of sourcing this energy predominantly from the Middle East. The second challenge facing Japan is the need to rapidly reduce greenhouse gas (GHG) emissions: by 26% by 2030, and then by 80% by 2050. On the other hand, the strategy also outlines the potential benefits of hydrogen in meeting these challenges, including the ability to produce hydrogen from multiple energy sources including renewables, and the potential for storage and transportation. The potential for hydrogen to engender carbon free industry, transport, and power generation is also expected to create a new growth industry in Japan [4]. By meeting these challenges through innovation and diversification of the energy system, Japan hopes to create economic opportunities, while addressing the key tenets of their strategic energy plan, namely environmental improvement, economic efficiency, energy security and safety (referred to as 3E + S; [5]).

The aim of this paper is to build on modelling efforts to date, to identify policies, technologies and use cases which are most likely to succeed in underpinning the diffusion of hydrogen into society and to identify the scope of its role toward engendering sustainable energy systems. While this work focuses on the energy-import dependent nation of Japan, the findings will be useful and applicable to nations which share Japan's energy dilemmas, including increased electrification and energy demand, reliance on foreign fossil fuel imports and a demographic shift toward an aging, shrinking population while sustaining economic growth.

This study is organized as follows. Section 2 outlines a brief background of the energy system transition toward a low carbon regime and some of the potential contributions of hydrogen. Section 3 details the methodology which assesses both policy direction and energy modeling outcomes in Japan. Section 4 describes the results in three parts, first reviewing the energy modeling relevant to hydrogen, second detailing the alignment of energy modeling outcomes with policy goals, and finally, extracting the technology and policy levers which will underpin the contribution of hydrogen to achieving Japanese energy system and policy goals. Section 5 discusses key results. Implications and conclusions are presented in Section 6.

2. Background

As the energy transition progresses, a number of scholars have addressed the potential role of hydrogen in the future energy system in terms of its potential to complement renewable energy deployment by providing storage, to supplement the existing gas grid, and to provide multiple options for transport in an environmentally friendly manner [6] as detailed by sector below.

2.1. Storage

In a policy environment which has rapidly increased the amount of renewable energy through attractive subsidies, which in turn lead to rapid decreases in deployment costs, a glut of intermittent renewable energy generation has resulted, requiring innovative storage options [7]. Hydrogen's role in the future energy system is often summarized as "storage", however, considering a smart grid approach, hydrogen can provide a storage medium for intermittent renewables, a power to gas pathway, and the provision of a clean fuel, with applications in demand side management leading to economic opportunities within the electricity market [8]. In considering the transition to a renewable-rich energy system, hydrogen is not the only option for storage, as it competes with batteries, pumped hydro and compressed air, among others. For hydrogen to play a meaningful role in the future energy system, energy policy will need to support its deployment while research and development work towards reducing costs and improving its competitiveness with and alongside alternative storage options [9].

2.2. Supplementing the Gas Grid

Similar to the envisaged role for hydrogen as a storage medium, its use by blending it with natural gas in city gas networks and for district heating has shown promise in achieving carbon reduction goals in European energy markets, alongside biomass and other decarbonization measures [10]. In terms of the maximum blend achievable, recent studies have identified an upper limit of approximately 30% hydrogen in city gas, such that calorific values of city gas are maintained and no infrastructure or appliance changes are required [11]. Incorporating hydrogen produced from renewable energy into the gas grid has been shown to enable the multiple policy goals of the decarbonization of the city gas supply, temporal storage, accommodation of renewable generation fluctuations and the coupling of the electricity, heat and transport sectors, leading to both multiple challenges and economic opportunities [12]. It is important to note that this use of hydrogen could also be extended to industrial uses, as the city gas network is representative of all existing natural gas pipelines.

2.3. Power Generation

Hydrogen can be used for power generation through a number of approaches including fuel cells (closely linked with storage applications), open and closed Rankine cycles, and blending with natural gas and other fossil fuels in various ratios between 1 and 10 percent hydrogen concentration [13]. In Japan hydrogen fuel use in the power generation sector is considering both the direct firing of hydrogen in newly developed turbines and its mixture with other fuels, prominent among them natural gas [14]. Problematically, direct firing of hydrogen produces nitrogen oxides which necessitate denitrification facilities downstream of the turbine [13,14].

2.4. Transport

Hydrogen, or Fuel Cell Vehicles (FCV), have the potential to provide long term sustainable transport options [15], having the potential to displace conventional gasoline vehicles as their design and efficiency improves over time [16]. Overall cost of ownership is also an important factor as hydrogen competes directly with electrification of the transport sector [17]. Depending on the nature of the national transport sector, hydrogen may be a less efficient option. However, in terms of broad applications, hydrogen may have the advantage of being a more suitable option for heavy duty, long range, air [18] and mass transit applications [19]. It is worth noting that on the other hand, electric vehicles are only competitive if the source of their electricity does not emit carbon dioxide (CO_2) or other GHGs.

Most authors agree that hydrogen could play a role in the energy transition in terms of storage, supplementing the gas grid and for transportation, among other sectors. However, the combined analysis of policy goals and energy system modelling to align these often-disparate approaches remains rare. Using Japan, a nation which is likely to benefit from hydrogen infrastructure due to its heavy reliance on imported fossil fuels, as a case study, we seek to assess the likelihood of the emergence of a hydrogen economy and its ability to meet the requirements of the Japanese energy system as envisaged by national level policy.

3. Materials and Methods

The methodology combines qualitative literature review with the leveraging of quantitative modeling. The aim is to contrast the policy ideals of the Basic Hydrogen Strategy with national-level modeling outcomes to identify policy and technology levers which can drive a sustainable hydrogen economy in Japan.

The benchmarks against which modeling outcomes and estimates will be compared are summarized in Table 1, adapted from the key points of Japan's Basic Hydrogen Strategy [20].

Table 1. Benchmark factors, mid and long-term targets for the Basic Hydrogen Strategy. CCS: carbon capture and sequestration, RE: renewable energy, FCV: fuel cell vehicle.

Benchmark Factors	Mid Term (~2030) Target	Long Term (~2050) Target
Source of supply	Developing international H_2 supply chains and domestic RE based power-to-gas supply	CO_2 free hydrogen (including fossil fuels with CCS to H_2 and RE to H_2)
Annual volume (t/year)	300,000	5,000,000–10,000,000
Cost (US$/kg)	3	2
Power generation cost (JPY/kWh)	17 (commercialization)	12 (replacing gas-fired generation)
Mobility ➢ Hydrogen stations ➢ FCVs ➢ FC Buses ➢ Forklifts	900 800,000 1200 10,000	Replacing gas stations Replacing gasoline vehicles Introducing large FCVs-
Fuel cell utilization (Ene-Farm [1])	5,300,000	Replacing traditional residential energy systems

[1] Ene-Farm is a hot water supply and warm water heating system that also enables households to generate power through a chemical reaction combining hydrogen extracted from LP gas or city gas with oxygen in the air.

Using the above table as an overarching guide we undertook a review of Japanese energy system modelling outcomes from recent academic scholarship was undertaken to establish a consensus on prominent hydrogen end uses, generation sources and the potential range of its deployment within society. This literature review assessed documents published from the year 2010 onwards using keyword and associated document analysis using the Scopus document search function iteratively. While not exhaustive, this approach allows for a selection of recent peer-reviewed analysis articles to form the evidence base for the study. The 18 documents identified as suitable for further analysis are detailed in Table 2 including the year of publication, title, model used, and main themes explored: storage, gas grid supplementation, power generation, and transportation.

The focus and combination of themes varies among the recent works considered, with 13 of 18 studies investigating energy storage, power generation or transportation, and seven considering augmentation of the gas grid either in general or specific terms.

Table 2. Scholarship of energy system modeling reviewed in this study. Themes: S: Storage, G: Gas grid supplementation, P: Power generation, T: Transportation.

Year	Title	Model	Themes	Ref
2010	Estimates of GHG emission reduction potential by country, sector, and cost	DNE21+	P	[21]
2013	A global energy outlook to 2035 with strategic considerations for Asia and Middle East energy supply and demand interdependencies	Macroeconomic, supply & demand, tech. assessment	T	[22]
2014	Development and environmental impact of hydrogen supply chain in Japan: Assessment by the CGE-LCA method in Japan with a discussion of the importance of biohydrogen	GTAP-LCA	S, T	[23]
2015	Diffusion of low emission vehicles and their impact on CO_2 emission reduction in Japan	AIM/Enduse	S, T	[24]

Table 2. *Cont.*

Year	Title	Model	Themes	Ref
2017	Significance of CO_2-free hydrogen globally and for Japan using a long-term global energy system analysis	GRAPE	S, P, T	[25]
2017	Economic evaluation toward zero CO_2 emission power generation system after 2050 in Japan	Dynamic optimized multi-regional power generation model	P	[26]
2018	Hydrogen in low-carbon energy systems in Japan by 2050: The uncertainties of technology development and implementation.	MARKAL	P, T	[27]
2018	Japan's hydrogen strategy and its economic and geopolitical implications	Policy review	S, G, P, T	[28]
2018	A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO_2-free hydrogen	OPGM	S, P, T	[29]
2019	Potential and sensitivity analysis of long-term hydrogen production in resolving surplus RES generation—a case study in Japan	Simulation	S, G, P	[30]
2019	Can Japan enhance its 2030 greenhouse gas emission reduction targets? Assessment of economic and energy-related assumptions in Japan's NDC	Analytical Framework	P	[31]
2019	Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges	Multi-Model Comparison	S, G, P, T	[32]
2019	Hydrogen market penetration feasibility assessment: Mobility and natural gas markets in the US, Europe, China and Japan	Economic penetration feasibility study	S, G, T	[33]
2019	Hydrogen technologies and developments in Japan	GRAPE	S, G, P, T	[34]
2019	A region-specific analysis of technology implementation of hydrogen energy in Japan	Simulation	S, G, T	[35]
2019	Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets	AIM/Enduse, DNE21+	S, P, T	[36]
2020	Investigating the economics of the power sector under high penetration of variable renewable energies	OPGM	S, P	[37]
2020	Hydrogen Penetration and Fuel Cell Vehicle Deployment in the Carbon Constrained Future Energy System	Modified DNE	S, G, P, T	[38]

Note: MARKAL: MARKet and ALlocation, DNE: Dynamic New Earth, AIM/Enduse: A partial equilibrium, recursive dynamic model, GRAPE: Global Relationship Assessment to Protect the Environment, GTAP-LCA: Global Trade Analysis Project-Life Cycle Analysis, OPGM: Optimal Power Generation Mix.

4. Results

The results are described in two parts. First, the results of the national level energy model literature review were summarized by sector, with key findings and quantitative hydrogen penetration levels relevant to the target years of 2030 and 2050 detailed. This is followed by an assessment of modeling outcomes and their consistency with Japan's Hydrogen Strategy benchmark factors as defined in the methodology. Costs are all expressed in Japanese Yen (JPY), using an exchange rate of 110 JPY per US Dollar and 125 JPY per Euro.

4.1. Storage

Utilizing storage in their model Ishimoto et al. [25] indicated that hydrogen storage utilizing electrolysis from renewables could play a role in underpinning the future electricity supply through the deployment of approximately 65% efficient electrolyzers in pursuing 25% emission reductions by 2030, and 50% reductions by 2050 compared to 2005 levels. Li et al. [30] posited that 57.5% of curtailed renewable energy in Kyushu could be reutilized via storage, and the effective ratio of gross renewable production could be increased from 59% to 74%. Monthly hydrogen production projections vary from 1000 to 2500 GJ using Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEV) as storage media in the transportation sector, and Solid Oxide Fuel Cells (SOFCs) in the residential sector. Results from [24] indicate that renewables could supply up to 59% of national electricity by 2050 in an 80% emission reduction scenario (compared to the base year of 1990).

Iida and Sakata [34] reviewed METI's "Strategic Roadmap for Hydrogen and Fuel Cells" and subsequent policy reports, leading to the conclusion that hydrogen could supply up to 13% of Japan's total power needs. Further, with hydrogen produced from gas reforming with carbon capture and sequestration (CCS) and electrolysis at a cost of 20 JPY/Nm^3, they detailed a Japanese vision for energy production from Proton Exchange Membrane Fuel Cells (PEMFCs) and SOFCs [34]. It is important to note here that the role of CCS in meeting the large carbon reductions required in many modeling predictions referred to in this paper is contingent on its emergence as a commercial scale technology, currently impaired by public opposition and technological challenges. In baseline simulations without aggressive long-term decarbonization, Lee [23] forecasted a 227% increase in fuel cell deployment by 2060 compared to 2008 levels. This indicates that hydrogen could play an even greater role in scenarios in which long term emission reductions are prioritized. Further, Matsuo et. al., [29] simulated zero-emissions power supply scenarios using 100% renewables with varying output levels for a 1000 TWh demand, identifying that hydrogen storage deployed in tandem with batteries and pumped-hydro resulted in the lowest unit cost for electricity, at 18.3 ± 0.6 JPY/kWh, followed by hydrogen alone (20.9 ± 0.7 JPY/kWh), followed by distributed renewables with batteries and pumped-hydro (21.8 ± 1.2 JPY/kWh). Adding 25 GW of nuclear capacity was found to further reduce these costs to 15.6 ± 0.4 JPY/kWh [37].

Shimizu et al., [35] showed that using renewable energy based electrolysis can help to reduce life-cycle emissions through the deployment of FCVs and cogeneration fuel-cell plants, especially in densely populated regions. Tlili et al. [33] identified that renewable energy based electrolysis using alkaline and PEM electrolyzers can become cost-competitive with Steam Methane Reformation (SMR) by 2040, if continued investment in research and development causing cost reductions, high load factors, low electricity prices (8250 JPY/MWh for alkaline, and 5500 JPY/MWh for PEM) and support mechanisms such as carbon taxes, tax exemption, or grid fee exemption are enacted to promote electrolysis. However, using electricity directly from the grid can increase the lifecycle GHG emissions (i.e., carbon footprint) of electrolysis beyond that of SMR, hence electrolysis can assist in GHG reduction only if electrolysis from renewables is promoted through policy.

4.2. Gas Grid Supplementation

It was estimated that at a price of 88 JPY/Nm^3, hydrogen could contribute up to 34% of the annual gas heating load in Kyushu [30]. Further, in [35] it was identified that fuel cells for household level cogeneration, using hydrogen blended with city gas used for reforming, could play a key role in mitigating lifecycle GHG emissions in densely populated areas, where one such fuel cell can benefit multiple households. Analysis of the potential for blending hydrogen into gas networks in Japan, China, the USA, and Europe, identified that Japan had the highest hydrogen penetration cost, making it unlikely to replace natural gas. This result highlights the need for policy-based incentives and interventions such as feed-in tariffs to promote hydrogen's penetration in the Japanese network [33]. Under the maximum hydrogen penetration case in [38], the authors identified a moderate role for hydrogen in city gas of approximately 272.14 GJ in 2050, ~6% of all imported hydrogen utilized in Japan.

4.3. Power Generation

Akimoto et al. [21] expected hydrogen power to play a role in GHG emission reduction through power generation as early as 2020. This prediction has proven true, albeit utilizing imported hydrogen at a relatively small scale, blended with natural gas in an 80 MW power station in Kawasaki, Kanagawa Prefecture [39]. Considering hydrogen as a primary fuel imported from overseas priced at 30–40 JPY/Nm^3, MARKAL simulations [27] predicted that hydrogen could make up some 22–50% of the electricity generation in Japan depending on factors such as the deployment of new nuclear power plants and the efficiency of CCS plants. In [32], using the Dynamic New Earth (DNE21+) model, domestic hydrogen produced from electrolysis was shown to help achieve 80% emission cuts, and results in 25% of power generation coming from hydrogen by 2050. Using imported hydrogen priced at 20–35 JPY/Nm^3 for the same emission targets in other models, the share of electricity generation incorporating hydrogen and other clean technologies is expected to be as large as 50%.

Iida and Sakata [34] predicted that direct combustion of hydrogen will play a significant role in supplying energy after 2040 with the increased penetration of renewables causing problems due to power-system interconnection (i.e., the 50 Hz and 60 Hz networks in the East and West of Japan). Direct firing of hydrogen, along with hydrogen gas turbine and hydrogen gas engine combined heat and power (CHP) systems, were found to play a prominent role in the realization of a hydrogen economy [25]. Nagashima [28] highlighted utility-scale power generation from hydrogen as an important indicator of Japan's hydrogen fuel network reaching price maturity and the success of the Basic Hydrogen Strategy. The study expresses the need for large scale investment to reduce hydrogen power costs, and voices concerns about the plan hinging on the simultaneous maturation of CCS technology. In addition to the city gas role identified in [38], electricity generation through direct firing or blending with LNG is identified as a major use case (~2345 GJ in 2050), accounting for ~53% of all imported hydrogen utilization.

While acknowledging that hydrogen generated from Russian natural gas with CCS is likely to be the cheapest approach, domestic production through electrolysis from wind and solar may become cost-competitive due to the avoidance of liquefaction, transportation and regasification costs associated with hydrogen imports. Oshiro et al., [36] found that in low carbon budget scenarios (75% emission reductions by 2050 compared to 2010 levels) closely aligned with Japan's INDC goals, imported hydrogen will play a significant role as a part of the primary energy supply. Inoue and Yamada [26] demonstrated that hydrogen used in hydrogen turbines will play a significant role in decarbonizing the electricity supply sector. Using 2013 as the base year, scenarios in which 2050 emission levels must be reduced by 85%, 90% and 91% require 20 TWh, 93 TWh and 120 TWh of hydrogen-based generation respectively. Matsuo et al., explored pathways to achieving zero emissions electricity generation by 2050 by simulating multiple scenarios which utilize imported hydrogen and hydrogen from renewables used in fuel cells and hydrogen-fired generators. In one such case, utility-scale hydrogen helps renewables penetrate 55% of the generation mix. The cost effectiveness of incorporating hydrogen into the energy mix is highlighted by results from multiple scenarios that indicate that electricity costs with 600 TWh of hydrogen included were found to be in the range of 8.2 to 13.8 JPY/kWh, whereas without hydrogen the unit costs rose to 20–24.9 JPY/kWh [29]. While additional nuclear was shown to reduce the unit cost of electricity, hydrogen emerges as a key technology for economic and flexible zero-carbon power in this study.

Matsuo et al. [37] explored the impact of direct combustion of hydrogen using clean hydrogen imported at 10–30 JPY/Nm^3 in a zero CO_2 emissions power supply sector. They found that for a demand of 1000 TWh, using a combination of 25 GW of nuclear and 200 TWh of hydrogen-based thermal power resulted in electricity costs of 11.8 ± 0.7 JPY/kWh, and 25 GW of nuclear with 100 TWh of hydrogen-based thermal power resulted in costs of 12.8 ± 0.1 JPY/kWh. Comparing this result with the aforementioned cases from the same study in which hydrogen is used for storage alone, electricity costs are significantly higher, at 15.6–21.8 JPY/kWh.

4.4. Transportation

For transportation, Oshiro et al. [36] indicated hydrogen as one of the "low-carbon carriers" that will aid in mitigating sector emissions through multiple emission mitigation scenarios of varying degrees. In a MARKAL scenario in which 2050 emission reduction goals are achieved, approximately 40% of the transportation sector is driven by imported hydrogen [27]. Of all scenarios modelled in [32], the greatest mitigation in emissions from the transportation sector is achieved in the DNE21+ scenario, with domestic production of hydrogen by electrolysis. Matsuo et al. [22] suggest that in a scenario driven by carbon taxes and strong incentives for advanced, carbon-neutral technologies, electric and FCVs could represent 23% of new vehicle sales worldwide, and 19% in Asia by 2035. This will lead to a reduction in the demand for oil, and a consequent mitigation in carbon emissions.

Using a multi-region comprehensive model with multiple sectors, Oshiro and Matsui [24] demonstrate that an 82% reduction in emissions from 1990 levels is possible in the transportation sector, and that FCEVs would comprise 25% of the freight transport sector under such a scenario. They also note that the carbon tax required to achieve comparable emission cuts without hydrogen would be 41.5% higher than the tax implications from hydrogen vehicle deployment. In [25], it is estimated that the 2050 share of light duty FCVs will be approximately 20%, while that of FC trucks will be approximately 57% of the national fleet. In the case of electric vehicles, a direct competitor to hydrogen fuelled vehicles, sales are already quite strong globally, accounting for some 7.2 million vehicles operating globally at the beginning of 2020, with sales accounting for approximately 2.6% of all new global passenger vehicle sales [40].

Nagashima [28] highlighted Japan's need to promote FCVs abroad to be able to scale up the hydrogen transport sector within Japan, as despite its relative maturity, the Japanese market alone cannot sustain the hydrogen vehicle industry financially. Using a multi-sector simulation approach, a growth of 847% in the FCV sector between 2008–2060, driven by a 120–130% growth in steam reforming, electrolysis and biohydrogen [23]. Sensitivity analyses indicate that FCVs are the most sensitive to cost reductions, and hence prime candidates for research and development investment. In achieving a zero-emission energy generation mix, determining that the sale of hydrogen into sectors such as transportation boosted the penetration of renewables from 47% to 55%, aiding in decarbonization of the energy supply, while utilizing an excess of 364.25 GJ of hydrogen to potentially fuel 41 million FCVs annually [29]. The authors also noted the possibility for sufficient excess hydrogen to fuel 109 million FCVs annually, however this was not considered economically feasible, as demand of this scale was considered unlikely. A region-specific analysis showed that just a 1% replacement of conventional vehicles by FCVs fuelled by hydrogen from steam reforming would reduce life-cycle GHG emissions by 4300 t-CO_2-eq/year in Fukuoka, 1500 t-CO_2-eq/year in Okinawa, and 1400 t-CO_2-eq/year in Tokyo [35].

While FCVs have a strong potential to lower emissions, regional factors such as the source of hydrogen, its transportation, population density, and average distance travelled per vehicle play a key role in the effectiveness of FCVs. In exploring the economic feasibility of FCV deployment, it was noted that hydrogen could be sold at as high as 1760 JPY/kg in Japan while maintaining cost-competitiveness with fossil fuels [33]. Due to high gasoline tax rates, Japan could be the first nation to achieve cost-competitive hydrogen deployment by 2025 using tube trailers for inter-region transportation, instead of pipelines, which are assumed to be more expensive. Transport is heavily underpinned by hydrogen in the model established in [38] with the total quantity set aside for transport estimated at 239.49 GJ, predominantly for passenger vehicles. This contribution is sufficient for the deployment of approximately 37.3 million passenger FCVs by 2050, about half of the 2017 passenger fleet. The introduction of hydrogen vehicles could avoid a portion of gasoline taxes for end users (i.e., those relevant to air pollution and noise etc.), however, a taxation regime cognizant of road use and other administrative costs will need to be maintained.

4.5. Other Sectors

Hydrogen use was identified outside of the four focus sectors of this study. First, hydrogen use is considered nominally as a GHG emission mitigation measure in petroleum refining to help meet 2030 emission goals [31]. Additionally, Akimoto et al., consider the use of hydrogen in the production of iron and steel to mitigate GHG emissions in Japan by 2020 [21]. Hydrogen has a distinct advantage in carbon free high temperature heat processes, renewable sources of power are generally unable to provide industrial level process heat.

Focusing on the four key sectors identified, we summarize our findings alongside Japanese mid and long term targets in Table 3, energy and weight equivalence conversions are made using average heat values of fuels from [41].

Table 3. Model Outcomes and Hydrogen Strategy Target Comparison.

Key Sector	2030 Target	2050 Target	Model Outcomes
Storage	• RE based power-to-gas supply • A portion of 300,000 t/year	• CO_2 Free H_2 • A portion of 5,000,000–10,000,000 t/year	• 1000–2500 GJ/month (~1,572,000–3,930,000 t/year) using RE based electrolysis in Kyushu [30] • Increasing RE to 59% of national electricity supply, 13% of total power needs from H_2 [34]
Gas grid	• 5,300,000 Ene-Farm Systems • A portion of 300,000 t/year	• Replacing traditional residential energy systems • A portion of 5,000,000–10,000,000 t/year	• ~34% of gas heating load in Kyushu [30] • Multi-household use fuel cells play a key role in mitigating household emissions [35] • Up to 272.14 GJ (~2,208,000 t/year) of H_2 per annum in 2050 blended with city gas [38]
Power generation	• 17 JPY/kWh (commercialization) • $330 JPY/kg • A portion of 300,000 t/year	• 12 JPY/kWh (replacing gas-fired generation) • 220 JPY/kg • A portion of 5–10,000,000 t/year	• Imported H_2 at 330–440 JPY/kg leads to 22–50% of electricity generation from H_2 [27] • Domestic H_2 production leads to 25% of electricity from H_2, while up to 50% of electricity is possible with import prices of 220–385 JPY/kg [32] • 600 TWh of H_2 based electricity (~55% of generation mix) by 2050 using a mixture of imported and domestically produced H_2 leads to energy costs between 8.2–13.8 JPY/kWh [29] • 200 TWh of direct H_2 combustion combined with 25 GW nuclear capacity leads to energy costs between 11.1–12.5 JPY/kWh in 2050 [37] • H_2 based generation identified as a major use case in 2050, utilizing 53% of imported H_2 [38]

Table 3. *Cont.*

Key Sector	2030 Target	2050 Target	Model Outcomes
Transport	• 900 Hydrogen Stations • 800,000 FCVs • 1200 FC Buses • 10,000 Forklifts	• Replace incumbent gasoline infrastructure	• 40% of transport sector driven by H_2 in 2050 [27] • 19% of new vehicle sales in Asia by 2035 [22] • 25% of freight sector transitions to FCEVs by 2050 [24] • 2050 share of light duty FCVs ~ 20% and FC trucks ~ 57% [25] • Almost 8.5x growth in the FCV sector from 2008–2050 [23] • An excess of 364.25 GJ of H_2 could potentially fuel 41 million FCVs annually by 2050 [29] • 238.65 GJ of H_2 per annum for some 37 million FCVs by 2050 [38]

Although model outcomes do not always correlate directly to the Japanese Hydrogen Strategy targets, significant overlap can be identified in the summary shown at Table 3, discussed further below.

5. Discussion

Building on the results of the literature review, we first assess which policies underpin modeled findings. Second, building on the alignment of modelling outcomes with national benchmarks and current policy approaches, we discuss future policy implications for each of the key sectors with respect to the realization of a hydrogen economy in Japan.

Our literature review identified three main stimulatory policy types. The first promising class of policies can be broadly described as ambitious reduction targets. These include 80% emission cuts, cognizant of CCS capture limitations [27], INDC commitments [22], and low carbon budget scenarios [36]. This finding is consistent with identified policy levers for a successful energy transition in Japan, highlighted in [42].

The second policy instrument which tends to encourage the hydrogen economy is a price on carbon, or carbon taxes. Carbon taxes and subsidies are identified alongside strong INDC commitments in [22], while carbon taxes in the range of 17,500 JPY/t-CO_2 and 58,300 JPY/t-CO_2 are considered essential to achieve carbon reductions at the IEA 450 ppm scenario level [33], 75% reductions by 2050 [29], and 80% reductions [25], respectively. These prices are markedly higher than current international norms, in which prices range between less than 110 JPY/t-CO_2 and 13,200 JPY/t-CO_2 [43].

The third policy instrument identified as stimulatory to the penetration of hydrogen into the energy system is increased investment, both into the deployment of complementary technologies and infrastructure, and also toward research and development. Specifically, investment in low emission demand side technologies, and the expansion of nuclear and renewable was extolled in [22]. For the realization of some modeled scenarios, government and private investment is required for research and development to reduce the cost of hydrogen enabling technologies by up to 20% per annum [26]. Wind and solar are prominent among continued investment targets for research and development toward a hydrogen economy [29]. Electrolysis is another critical technology for the utilization of renewable energy for hydrogen production for a number of sectors, identified a sector requiring significant continued investment to become cost competitive with other technologies and approaches [35]. Investment in research and development, as well as the other stimulatory policies has been identified to lead to an expansion in renewable energy deployment, considered complementary to the low carbon production of hydrogen [22,29].

Though the models reviewed here reported a myriad of outcomes, they generally support optimism regarding the feasibility of the Hydrogen Strategy. Further, promotion of hydrogen usage in multiple sectors engenders consistently positive environmental outcomes.

The 2030 source of supply benchmark seeks to develop international hydrogen supply chains alongside a domestic renewables-based power-to-gas supply. Several research outcomes identify the need for reasonably priced international hydrogen imports, followed by the identification of the potential for domestic renewables to hydrogen, storage, and utilization options. The 2050 goal for hydrogen supply source is even more ambitious, seeking CO_2 free hydrogen generated predominantly domestically from renewables and fossil fuels with CCS. Although fossil fuel pathways will be somewhat contingent on CCS achieving commercial scale deployment and public acceptance [44], the shift to hydrogen based power generation, heating, and storage holds promise for greater deployment of renewables throughout Japan.

It is important to recognize that the production source of hydrogen remains a key issue in terms of achieving global carbon reduction goals. Offshore production of hydrogen from fossil fuel sources without CCS as currently occurs is synonymous with the offshoring of CO_2 production, an undesirable outcome. The recognition of this issue should be a further motivation for aiming for more ambitious 2050 targets as a priority.

In terms of annual volume targets, even the ambitious 10 million ton per annum use envisaged in the 2050 target, a combination of aggressive FCV deployment, storage, gas grid blending and direct firing for power generation suggests that these targets may be exceeded, depending on the combination of use cases enacted. The Kyushu region appears to be particularly well suited to heating from hydrogen, as well as its use as a storage and power generation medium, leading to increased deployment of renewable energy, currently being curtailed in this region [45].

Regarding the cost of hydrogen (per kg), many models use scenario-based approaches, assessing at what cost hydrogen imports need to be achieved in order to support different levels of hydrogen-based electricity generation in the mid-term. Although these results highlight the role of hydrogen prices around the benchmark value of 330 JPY/kg in 2030 in increasing hydrogen-based electricity generation (especially compared to renewable-based hydrogen approaches), they do not clarify the pathway to achieving these prices. As imported hydrogen is highlighted as a potential major source for direct firing for electricity generation, more investigation of import prices and the factors which affect them, especially for a resource-poor nation such as Japan remain a priority.

For the cost of electricity derived from hydrogen, benchmark figures are aggressive, decreasing from 17 to 12 JPY/kWh between 2030 and 2050. In investigating future energy mixes which incorporate hydrogen, a 55% hydrogen energy mix was shown to engender 2050 electricity prices of between ~8 and 14 JPY/kWh, while a commensurate contribution from nuclear energy brings these costs down to between ~11 and 13 JPY/kWh by 2050. The suggested nuclear contribution of 25 GW nameplate capacity is achievable without new construction of nuclear power in Japan, which currently has approximately 31.7 GW of operable nameplate capacity [46]. A prudent low-carbon energy mix is theoretically able to meet the environmental and economic goals of the hydrogen strategy by 2050.

The mobility benchmarks in the Japanese hydrogen strategy are particularly granular, giving numerical targets for deploying hydrogen stations, FCVs, buses and forklifts, however the majority of research is focused on passenger vehicles, with some consideration given to buses and freight applications. By 2050, estimates range between 20 and 55% of the passenger fleet converting to FCVs (up to 41 million passenger FCVs), and for the freight fleet, between 25 and 57%. While these numbers fall short of absolute replacement of the incumbent transportation regime by 2050, growth rates suggest that the majority of personal and freight-based transport will be underpinned by hydrogen within the long-term target timeframe. To support this growth in hydrogen-based transportation, the hydrogen strategy calls for 900 hydrogen stations by 2030, and replacement of the gasoline infrastructure by 2050. As of July 2020, there are 132 operational hydrogen refueling stations in Japan [47], and according to the Japanese hydrogen station network cooperative JHyM (Japan H_2 Mobility), this number will increase to 160 by the end of 2020, 320 by 2050 and the target number of 900 by 2050, sufficient to service 800,000 FCVs [48]. The well-developed electric rail system, prevalent in Japan may also play a role in domestic goods transportation into the future. Additionally, a shift in the passenger transportation market, cognizant of the aging population, toward autonomous vehicles, fewer personally owned vehicles and public transportation may impact on these modeled outcomes.

In terms of domestic fuel cell usage, although model outcomes suggest that individual (i.e., Ene-Farm) and multiple household fuel cells will be critical to decarbonizing the domestic sector, no specific estimates of 2030 or 2050 deployments are given. Current manufacturer sales figures suggest that approximately 350,000 Ene-Farm units have been sold to date [49], meaning significant deployment growth is required to meet mid and long-term goals and to improve the round-trip efficiency of electrolysis, storage, and utilization of hydrogen [50].

Alongside the above policy strategies and perspectives, it should be also noted that future demographic trends will impact on energy demand, which is given little attention in the reviewed literature. Previous research highlights that changes in household structures reflective of an aging, shrinking population in Japan has played a role in reducing both direct and lifecycle energy-related CO_2 emissions [51–53]. In line with future demographic projections for Japan, it is expected that lifecycle GHG emissions will continue to reduce [54,55]. In addition, the concentration of the population into urban regions may affect demand levels for transportation, particularly for passenger cars [56] and household fuel cells. Nevertheless, in order to promote the penetration of hydrogen into society, it is essential to pay attention to the critical resources necessary for its production and use as these materials are considered vital yet are constrained due to supply risks [50,56–59]. Finally, in Japan, addressing the diverse perceptions toward hydrogen energy use compared with conventional energy types among stakeholders may be effective in smoothening the implementation of the hydrogen energy system [60].

Summarizing the literature review and benchmark alignment outcomes, Figure 1 details the national targets and timeline for the introduction of hydrogen into the Japanese energy system, along with the strategies and policies considered vital, and identifies the critical factors requiring further investigation.

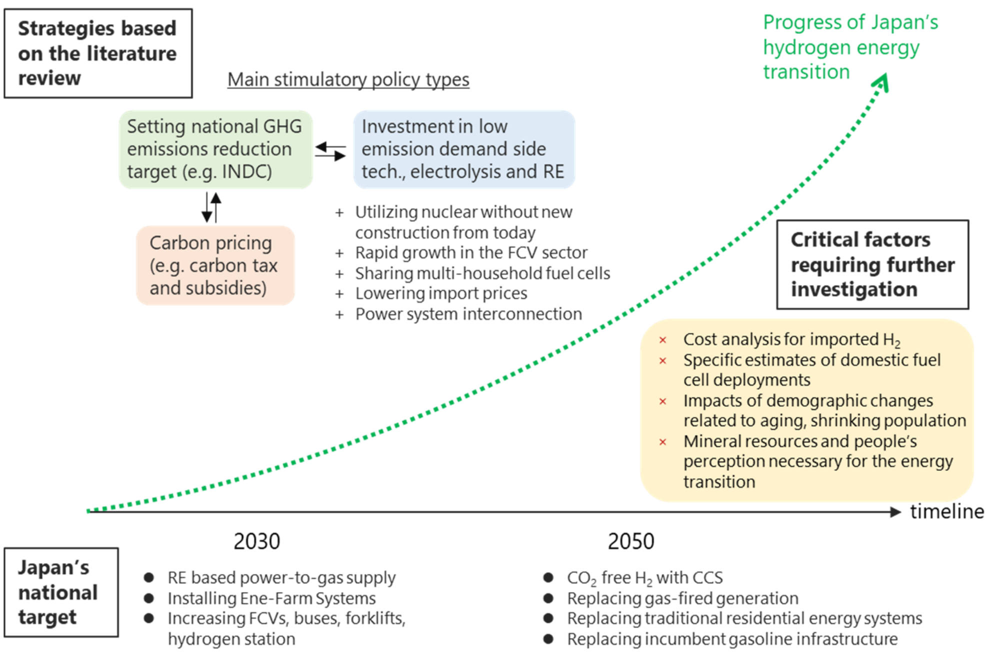

Figure 1. Schematic figure of strategies and future perspectives obtained from this study for Japan's hydrogen energy transition.

6. Conclusions

This study reviewed recent literature specific to energy system modeling and the Basic Hydrogen Strategy in Japan, cognizant of the goal of achieving a hydrogen economy, to contribute to 2050 climate change mitigation goals while satisfying national environmental improvement, economic efficiency, energy security and safety (3E + S) ambitions.

While no conclusive modelling outcomes were identified in the literature which completely satisfy all of the Japanese Hydrogen Strategy benchmarks, either in the mid or long-term, the potential for significant achievement of key sectoral aspects within the strategy were identified. The progressing of the key sectors of storage, supplementing the gas grid, power generation, and transportation appear reliant on three key stimulatory policy approaches, namely the setting of ambitious targets, carbon pricing regimes and investment in both low-emission technologies and the research and development that underpin them. In terms of the requisite future energy mix, a need for the further transition away from fossil fuels toward renewable energy was identified along with the need to incorporate existing carbon neutral nuclear generation assets to meet Japanese INDC commitments and to underpin a hydrogen economy.

Modelling outcomes for Japan tended to favor a strong shift away from fossil fuels toward renewable energy, with a small contribution from nuclear in the short to mid-term. As a result, our analysis and synthesis of these outcomes is optimistic toward the realization of such an energy system. It is important however to consider the overall feasibility of a renewables dominated energy system in Japan and other nations (in terms of critical materials required [61] and energy return on energy invested for certain renewable energy types [62]), and the compatibility of such an energy system with sustainable economic growth (cognizant of social, energy and environmental impacts [63] and the need to balance achieving environmental goals and economic growth [64]). This uncertainty is reflected in the present study in terms of economic feasibility aspects and energy system stability issues, however further consideration of these impacts on the timing and quantity of hydrogen introduced into the energy system as a result is required, along with empirical evidence of the feasibility of such a transition, yet to be demonstrated [65].

While the storage, gas grid supplementation, and transportation sectors appear to be conducive to hydrogen supplanting or complementing existing infrastructures, some questions remain for power generation. One outstanding issue clarified by the literature review is that import hydrogen prices appear to be key to a successful hydrogen economy in Japan. This is particularly true for the mid-term and for the success of either co-firing or direct firing of hydrogen for electricity. Modeling work identifies how certain import hydrogen price points are conducive to hydrogen-based electricity generation, however it does not uncover the likelihood of these prices being achieved or the factors which underpin them. More work identifying the enabling factors for a conducive imported hydrogen price would be a valuable addition to this research. In addition, specific estimates for domestic fuel cell deployments and the nature of these fuel cells (in home or community based) is currently lacking.

The results of this study can also be aligned with Japan's overall energy policy: environmental improvement, economic efficiency, energy security and safety (3E + S). The alignment with lowering the impact of energy production and distribution with environmental concerns is a primary motivator for the transition to a hydrogen-based energy system and is captured in the approaches described above. The energy transition is also well aligned with Japan's interests in maintaining and expanding its economy, particularly in the area of leadership in advanced technology. For the area of energy security, the long-term goal of nearly total domestic capability for hydrogen production would enhance the reliability of Japan's energy supply over its current heavy reliance on outside sources of most primary energy sources. The approaches to expanding the hydrogen energy economy described above appear to have the capability to vastly improve Japan's energy security, particularly in the long term and should be a prime motivator to move toward the 2050 goals as quickly as possible. Without major indigenous energy resources, internal production of hydrogen using renewable and advanced energy sources would alleviate much of the dependence on unpredictable external energy sources. In addition, hydrogen as an energy storage medium, could reduce issues of market volatility for other, competing energy sources. Finally, the production, distribution, storage and use of hydrogen in a safe manner has been widely demonstrated. Further research and development of hydrogen safety issues should be undertaken to support a much broader network of hydrogen facilities and uses.

Additionally, the social aspects of the hydrogen economy need to be analyzed in future work, as clarified by this study which highlighted not only the need to consider shifting demographics and social issues such as the aging, shrinking population in Japan, but also the need to consider people's preferences and perceptions toward using hydrogen as part of their daily lives. Finally, as this study was undertaken during the COVID-19 global pandemic, we anticipate that some of the estimates referred to in the analyzed models may be delayed or negatively impacted due to the economic and social impacts of the pandemic.

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