Title

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Creating a Global Hydrogen Economy

Review of International Strategies, Targets, and Policies with a Focus on Japan, Germany, South Korea, and California

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Table of Contents

Abstract

Motivated by increasing emphasis on decarbonization, hydrogen as an energy carrier is enjoying unprecedented political and business momentum. This paper reviews the status of hydrogen strategies and progress in major global economies, with a particular focus on four leading jurisdictions (Japan, Germany, S. Korea and California). These have been among the most aggressive, though in different ways. Japan, Germany, and S. Korea have been more focused on developing a sustainable hydrogen supply chain, while California has been more focused on spurring hydrogen demand, especially in the transportation sector. Japan's strategy involves forging partnerships to import "blue" hydrogen (from methane with carbon abatement strategies) while Germany has focused on "green" (e.g., electrolytic) hydrogen production, along with plans to leverage its extensive natural gas pipelines for hydrogen distribution. Japan anticipates the power sector to be the largest consumer of hydrogen, while others expect the transportation and industry sectors to be the prime movers of future hydrogen demand. Japan, S. Korea and Germany will likely import a substantial portion of their future hydrogen supplies, while California has the potential for low-cost hydrogen production, but will need to establish demand and invest in hydrogen transportation and distribution infrastructure. In all four jurisdictions, investments are still relatively small and there exists huge opportunities for cooperation to develop a self-sustaining global hydrogen market.

Keywords: GHG emissions, sector coupling, blue hydrogen, green hydrogen, hydrogen economy

1 Introduction

A concerted and coordinated effort to keep global warming well below 2°C, has become an urgent need. Achieving this target would mean an 85% reduction in global greenhouse gas (GHG) emissions by 2050 [12]. Decarbonization would be required across sectors such as transportation, buildings, and industry. Hydrogen is a potentially important option for decarbonization plans given its versatility to be used across different sectors. Hydrogen's versatility suggests that significant increases in hydrogen use, with accompanying economies of scale and cost reductions, will aid countries in achieving their carbon targets and eventually building a carbon-neutral energy system. But building up this hydrogen system is challenging and infrastructure intensive. Strong early investments, with a clear vision of where the hydrogen system buildout is going, are needed. While many countries have latched onto this opportunity to incorporate hydrogen in their long-term energy and transportation plan, they are not all approaching this in the same manner, and no country so far has put all the pieces together.

We begin the paper by reviewing policy activities, targets, and strategies in 8 of the world's most active economies, then focus on the "big four": Japan, Germany, South Korea and California. These four are among the world's largest economies, with a combined gross domestic product (GDP) greater than $15 trillion[34]. The sheer magnitude of these economies will be an enabling factor to undertake large scale capital investments necessary for the initial commercialization and adoption of hydrogen into the energy portfolio. Notwithstanding differing emphases and patterns, these four economies share common policy drivers for hydrogen development and deployment: achieving strong climate mitigation goals, energy supply diversification, energy storage for renewables-based grid, and attaining technology leadership. Differences in their policy emphases has led to varying levels of hydrogen adoption across these economies, in different sectors, with different levels of progress. The present study analyzes the policy framework of these four jurisdictions, considering the following aspects.

1. Carbon mitigation targets and the role of hydrogen envisaged by each jurisdiction.
2. Hydrogen in transportation: fuel-cell vehicles and hydrogen refueling infrastructure.
3. Differing policy emphasis on blue and green hydrogen along with supply chain development plans
4. Hydrogen demand projections and underlying policy drivers.

The study looks to draw policy parallels and contrasts, analyze the potential impacts, and provide plausible recommendations for the four jurisdictions to better align their decarbonization strategies using hydrogen. Since the policies around hydrogen are still evolving, the inferences made here is subject to change with future strategy and policy announcements by different regions.

2 Materials and Analysis

2.1 Global Overview of Hydrogen Policies, Strategies, and System Developments

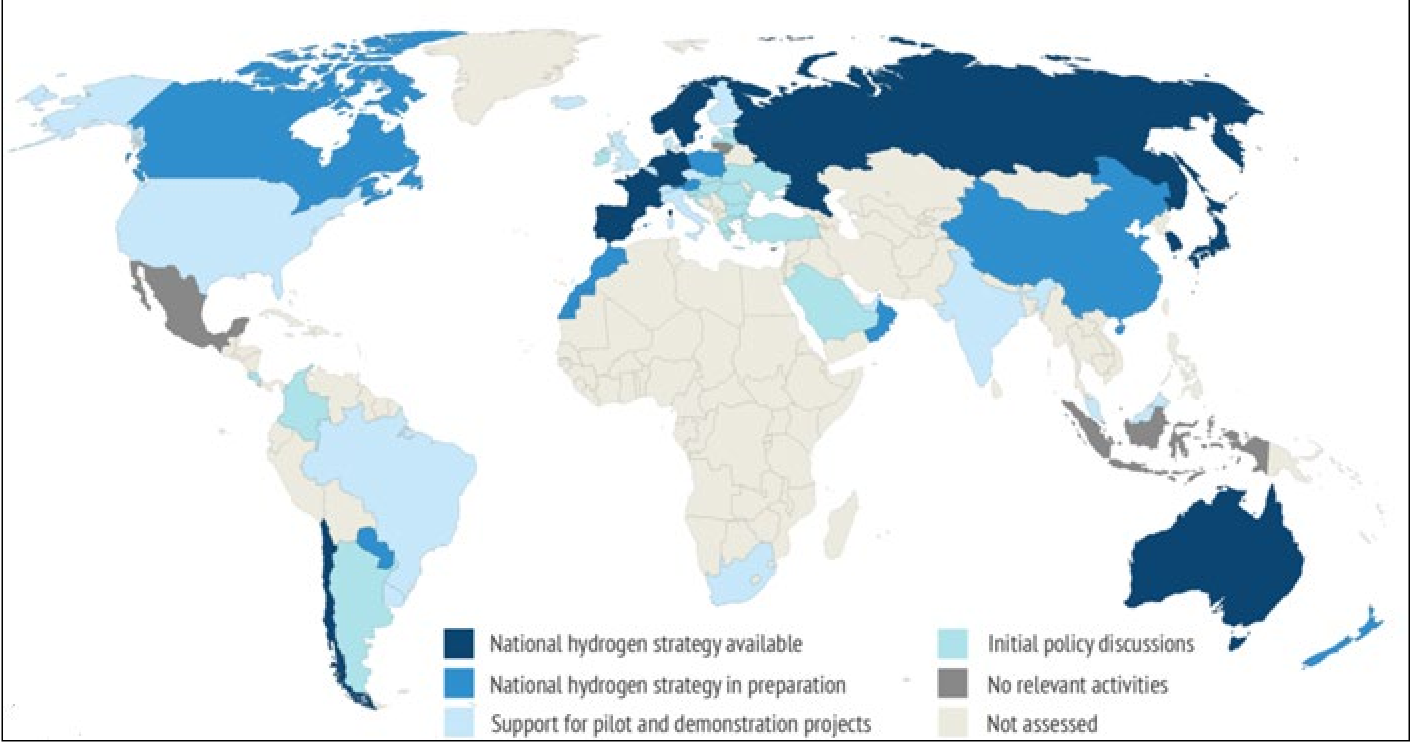

Figure 1. Status of hydrogen support/policy globally as of 2021 [5]

Worldwide, many countries are aggressively pursuing hydrogen policies and system developments as seen from Figure 1. These take different forms, such as a focus on developing the transportation system with fuel-cell vehicles and stations, or a broader systems perspective, developing initial supply and demand side initiatives, or creating an overarching hydrogen supply strategy.

2.1.1 Japan

Japan is one of the first countries to roll out a comprehensive hydrogen strategy in 2017, and it has since set out specific plans to become a “hydrogen society” [6]. The strategy notably seeks to achieve cost parity with competing fuels, such as liquefied natural gas for power generation. In March 2019, the Government released its third strategic roadmap for hydrogen and fuel cells. Japan considers its domestic uptake of hydrogen as a viable way to increase its energy self-sufficiency; decarbonize its economy; increase industrial competitiveness; and position Japan as a fuel cell technology exporter. The key consideration for large-scale uptake of hydrogen in Japan will be cost. Japan is enroute to establishing a global supply chain for importing low-cost hydrogen mostly produced using fossil fuels and utilizing carbon, capture and storage (CCS) technology which is currently more economically competitive than renewable hydrogen. Japan is interested in importing green hydrogen if the price is competitive, and at least one Japanese company has signed an investment deal for green hydrogen projects in New Zealand [7].

2.1.2 United States

Recent legislation such as the Bipartisan Infrastructure Bill [8] has earmarked close to $8 billion for scaling up hydrogen technologies and establishing at least four hydrogen hubs (large, geographically concentrated demands) on a national level. Additionally, national-level cost targets, such as the "Hydrogen Shot," seek to reduce the cost of clean hydrogen by 80% to $1 per kilogram in a decade[9]. California has been leading the US efforts to deploy hydrogen with transportation-focused policies that have resulted in among the most fuel-cell vehicles in the world through 2020. In California, policies such as the Zero-Emission Vehicle mandate, Low Carbon Fuel Standard (LCFS), Advanced Clean Trucks regulation, and Clean Vehicle Rebate Program have encouraged the uptake of hydrogen, especially in the transportation sector.[10–13]. California has over 90% of both the fuel-cell vehicles and hydrogen refueling stations in the country. However, the currently high retail costs of hydrogen (over $15/kg in many cases) have been a major impediment to the growth of fuel-cell vehicle sales. This is covered in more detail in the California-focused sections below.

2.1.3 European Union

The European Union has made hydrogen a key plank in its aim to eliminate its greenhouse gas emissions by 2050, with a major emphasis on installing zero-carbon-emissions hydrogen (via electroloysis) within and around the EU in the coming decade. To accelerate the development of clean hydrogen, on July 8, 2020 the European Commission adopted a new hydrogen strategy [14]. One specific goal is 80 GW of new electrolysers by 2030, with half inside the EU and half near it, providing hydrogen to EU states. Almost all Member States have included plans for clean hydrogen in their National Energy and Climate Plans, 26 have signed up to the "Hydrogen Initiative", and 14 Member States have included hydrogen in the context of their alternative fuels infrastructure national policy frameworks. Some have already adopted national strategies or are in the process of adopting one[15]. In addition, industry is playing a leading role in EU hydrogen planning and investments. A consortium of gas companies and researchers in the EU have developed a concept (and detailed design/costing) of a "hydrogen backbone" initiative, to encourage and support the development of an EU-wide hydrogen system by ensuring that a low cost transmission system is developed to connect supply and demand nodes[16]. Many other initiatives are occurring within member states, such as Germany. France and the Netherlands.

2.1.4 Germany

In June 2020, Germany rolled out a national hydrogen strategy that eyes a 200-fold increase in electrolyzer capacity—of up to 5 GW by 2030. An additional 5 GW of capacity may be added by 2035 and no later than 2040[17]. According to the IEA Future of Hydrogen Report, as of 2030 German hydrogen demand is expected to increase significantly, about 340 TWh between 2015 and 2030, with industry (+164 TWh) and mobility (+70 TWh) being the main growth contributors. Germany has been focusing on establishing a strong supply chain, backed by import agreements as well as by bumping up the production capacity of green hydrogen domestically. The technology development for hydrogen systems have been historically funded and supported by the National Organization for Hydrogen and Fuel-cell Technology (NOW).

2.1.5 France

To promote the deployment of industrial projects and supporting innovation aimed at decarbonization, France adopted the "Hydrogen Deployment Plan for the Energy Transition" in 2018. France committed to having 20,000 - 50,000 light-duty and 800 - 2,000 heavy-duty fuel-cell vehicles, as well as 400 - 1,000 hydrogen refueling stations by 2028[18]. Further, the plan stresses on achieving a 40% share of hydrogen from renewable sources by 2028. As part of government's €100 billion COVID 19 recovery plan, €7 billion was devoted to the development of green hydrogen for the period from 2021 to 2030. The "National Strategy for the Development of Decarbonized and Renewable Hydrogen", announced jointly by the Minister of Ecological Transition and the Minister of Economy in September 2020, set the 3 priorities of this investment: (1) decarbonizing industry by developing a French electrolysis sector, (2) developing the use of decarbonized hydrogen for heavy-duty mobility, and (3) supporting research, innovation, and skills development. France is targeting 6.5 GW electrolysis capacity by 2030.

2.1.6 Netherlands

In June 2019, the Dutch government presented the new climate agreement aimed at reducing CO_2 emissions in the country by setting a national reduction goal of 49% by 2030 and by 95% by 2050 compared to 1990[19]. Low-carbon hydrogen is set to play a major role in achieving these emission reduction targets. The Netherlands currently has significant hydrogen production from natural gas for the chemical and refining industry. Its vast potential for offshore wind generation, would enable a rapid scale up of low-carbon hydrogen production via electrolysis. The national climate agreement sets to scale up electrolysis to 500 MW of installed capacity by 2025 and 3-4 GW by 2030. In 2020, hydrogen fuel-cell vehicle fleet in the Netherlands comprised of about 400 vehicles, and 7 hydrogen vehicle fueling stations. The national climate agreement targets 15,000 fuel-cell cars, 3,000 heavy-duty vehicles and 50 filling stations in 2025, and 300,000 fuel-cell cars in 2030[20].

2.1.7 South Korea

In January 2019, Korea announced its Hydrogen Economy Roadmap [21]. The roadmap outlines the roll out of 6.2 million fuel-cell electric vehicles and 1,200 refilling stations by 2040. Additionally, the plan aims to roll out 2,000 hydrogen buses by 2022 and 41,000 by 2040. Korea aims to become the world's largest producer of hydrogen-powered vehicles and fuel cells by 2030 and eventually to develop hydrogen ships, trains, and machinery. Of the total 6.2 million vehicles to be produced by 2040, 3.3 million would be exported. To achieve these targets, the government provides a subsidy of about 50% of the purchase price of a hydrogen passenger vehicle and subsidizes up to 50% of the installation cost of refueling stations. In 2018, demand for hydrogen was 130,000 tons and is estimated to increase to 470,000 tons by 2022, 1.94 million tons in 2030, and 5.26 million tons in 2040. Korea has a limited domestic capacity for eco-friendly hydrogen production, and it plans to establish overseas bases for hydrogen production. By 2040, South Korea aims to meet 70% of domestic demand through hydrogen from electrolysis and overseas production and 30% by reformed hydrogen.

2.1.8 China

In October 2016, China released the Energy Saving and New Energy Vehicle Technology Roadmap as part of the Chinese government's "Made in China 2025" 10-year plan. The FCEV Technology Roadmap (Chapter 4 in the document) outlines China's long-term goals regarding the deployment of fuel-cell vehicles and infrastructure. China's target for FCEV deployment is 50,000 FCEVs (80% passenger cars) and 300 refueling stations by 2025, and 1,000 refueling stations (50% of hydrogen production from renewable sources), and overall, 1 million FCEVs by 2030. Also, 5,000 FCEVs (40% passenger cars) and 100 refueling stations were targeted by 2020. Overall demand for hydrogen demand is expected to reach 35 million tons (Mt) in 2030 (at least 5% of China's energy consumption), 60 Mt in 2050, and 100 Mt (20% of the country's total energy consumption) by 2060 according to the China Hydrogen Alliance, a government-backed industry association[22].

A summary of jurisdictions' targets and strategies is provided in Table 1 below. The global picture is that of a nascent hydrogen market but with plenty of ambition. Among the most ambitious are California, Germany, South Korea, and Japan, though these four jurisdictions have different areas of focus and emphasis. We explore and compare these in more detail below.

Table 1: National/regional status and targets related to hydrogen, as of March 2022.

	EU	US (primarily CA)	Germany	France	Netherlands	Japan	Korea	China
Current FCEVs stocks	—	CA: 12703 Cars, 76 Buses	1347 Cars, 54 Buses	382 Cars, 26 Buses	442 Cars, 25 Buses	6631 Cars, 110 Buses	16098 Cars, 108 Buses	7355 Cars, Trucks and Buses
FCEV LDV stock target	3.7 M by 2030	CA: ~ 50 k by 2025, 1 M by 2030	—	5 K by 2025 20 K-50 K by 2030	15 K by 2025, 300 K by 2030	200 K by 2025, 800 K by 2030	100 K by 2025, 6.2 M by 2040 (2.9 M domestic, 3.3 M Export)	50 K by 2025, 1 M by 2030
FC Buses and Trucks targets	45 K by 2030	—	—	200 by 2023, 800-2000 by 2028	3000 by 2030	1,200 Buses by 2030	40,000 Buses + 30,000 Trucks by 2040	—
Current number of Hydrogen Refueling stations (HRS)	200	CA: 50	101	47	8	142	112	118
HRS target	1,500 by 2025, 3,700 by 2030	CA: 170 by 2026	400 by 2025, 1000 by 2030	100 by 2025, 400 -1000 by 2030	50 by 2025	320 by 2025, 900 by 2030	1200 by 2040	300 by 2025, 1000 by 2030
Hydrogen production capacity/demand and projections	6 GW electrolysis cap. & 1 Mt Green H2 by 2025, 40 GW electrolysis cap.[1] &10 Mt Green H2 by 2030	—	5 GW electrolysis cap. by 2030	6.5 GW electrolysis cap. by 2030	3-4 GW electrolysis cap. by 2030	—	5.26 Mt 2040 estimated demand	—
Investment	—	—	€9 billion by 2030[2]	€7 billion by 2030	—	—	—	—

Current FCEV stocks data for CA and Japan from CAFCP (*https://cafcp.org/by_the_numbers*), for other countries from *https://www.iphe.net*; Current H2 fueling stations data from www.H2station.org's 2021 Press Release; EU targets from EU FCH JU Hydrogen Roadmap (2019), and EU hydrogen strategy for climate-neutral Europe (2020), Other country-level targets from Germany National Policy Framework to Support the Deployment of Alternative Fuels Infrastructure (2016) and Germany National Hydrogen Strategy (2020), Plan de déploiement de l'hydrogène pour la transition énergétique (2018) and National strategy for the development of decarbonised and renewable hydrogen in France (2020), Netherlands National Climate Agreement (2019), Japan New Strategic Roadmap for Hydrogen and Fuel Cells (2019), South Korea Roadmap for Hydrogen Economy (2019), and China Hydrogen Fuel Cell Vehicle Technology Roadmap (2016).

2.2 Drivers, present status, and road maps for the hydrogen economy in Japan, Germany, California, and South Korea

2.2.1 Why are these jurisdictions interested in hydrogen?

Figure 2 provides a comparison of the GHG emissions on a per capita basis for the four jurisdictions. From 2000-2017, Japan reduced its GHG emissions by 6%, Germany by 14% and California by 23%. On the other side, South Korea's economy was expanding rapidly after 2000, which resulted in an increase in GHG emissions till 2010. All four jurisdictions have set very aggressive GHG reduction target for 2030. Scenario studies across the globe show that a higher constraint on GHG emissions is a precondition for greater penetration of hydrogen into the energy stream.

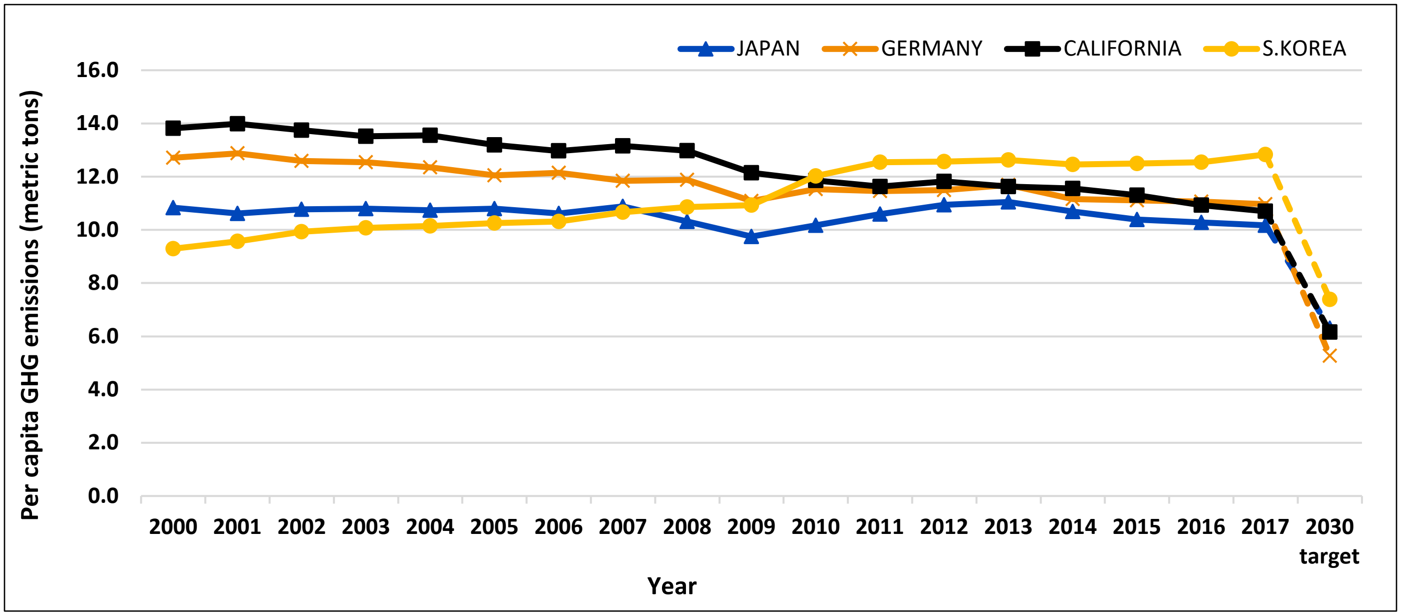

Figure 2.Region wise per-capita GHG emissions from 2000 to 2017 and targets for 2030[23–26].

Japan has the world's third largest GDP, but also the second highest dependence on foreign fuels among countries of the Organization for Economic Cooperation and Development (OECD). Beyond energy efficiency efforts, the nation's most viable option to improve energy self-sufficiency had been nuclear power, but most of its reactors remain idle today due to the political aftermath of the Fukushima nuclear disaster in 2011. By 2050, Japan aims for an 80% reduction in GHG emissions (the base year is not clearly defined). The most significant decarbonization is expected in the commercial and residential sectors, followed by transportation. Also, the high import cost of energy is another pressing problem for Japan. Given this backdrop, Japan adopted "The Basic Hydrogen Strategy" in 2017: a plan to transform Japan into a world-leading "hydrogen society", a first of a kind comprehensive hydrogen policy. Japan pins its hope on hydrogen to achieve its climate as well as economic goals. The strategy underpins the necessity for developing a supply chain of zero carbon hydrogen, from its production to transportation and application in various sectors. An approximate $1.5 billion has been spent on hydrogen programs by the Ministry of Economy Trade and Industry (METI) over the last six years. In 2018, the ministry spent close to $272 million for hydrogen research and subsidies which amounts to 3.5% of Japan's energy budget. METI's funding is mostly directed to R&D programs and it is channeled through the governmental research institution, New Energy, and Industrial Technology Development Organization (NEDO)[6,27].

Germany has committed itself, together with the other European Member States, to achieving greenhouse gas neutrality by 2050. Germany has been pursuing a long-term shift towards a renewable energy ecosystem known as the Energiewende. Recently there has been increasing interest around the long-term role of hydrogen in the overall decarbonization plan. The National Organization for Hydrogen and Fuel-cell Technology (NOW) a handle of the German government acts as a link between politics, academia, and industry for promoting hydrogen technologies and sustainable mobility. One of NOW's key tasks is coordinating the National Innovation Program on Hydrogen and Fuel-cell Technology (NIP). The first phase of NIP ran from 2007 to 2016, with 700 million euros in funding for basic research and demonstration on hydrogen technologies. NIP II began in 2017 and is foreseen to run until 2026 with funding of 1.4 billion euros, predominantly contributed by the private sector. The transportation sector is the focus in NIP II, with majority funding directed towards market introduction and integration [28]. But in June 2020, the German federal government adopted the first German National Hydrogen Strategy with an overall budget of 9 billion euros, which expands hydrogen's role beyond transportation.

South Korea is pursuing a hydrogen-based economy to address its economic, energy and environmental challenges [29]. South Korea is one of the world's largest emitters of greenhouse gases on a per capita basis. With the world's lowest total fertility rate, South Korea's population is aging more quickly (even Japan), and this adversely affects its economic growth potential. Like Japan, South Korea is overall dependent on imports for its energy needs. With this background, the Hydrogen Economy Roadmap adopted in 2019 lays out plan to address each of these concerns and specifically targets greater hydrogen adoption in the transportation, industry, and power generation.

Unlike in Japan, South Korea or Germany, there is no overarching "hydrogen strategy" in California, but there are policy drivers that encourage the use of hydrogen in different sectors, notably in the transportation sector. This sector accounts for close to 40% of GHG emissions in the state [30]. Establishing a primary market for hydrogen in the transportation sector is critical for California to achieve its goal of reaching carbon-neutrality by 2045, as mandated in 2018 by executive order EO B-55-18. The state spent more than $300 million over the past ten years, funding rebates for purchase of fuel-cell cars, transit buses, and the construction of refueling stations. California has also passed legislations that encourage hydrogen in decarbonizing sectors other than transportation. Legislations like Senate Bill (SB) 100 which aims to achieve a zero-carbon electricity grid by 2045 encourage the uptake of hydrogen for electric power generation. Legislations like SB 1369 (promotes green electrolytic hydrogen production) encourage the expansion of hydrogen supply chains that could feed into both transport and non transport sectors[31].

Overall, we find that concerns related to the environment, energy security, and economic growth is driving a clean energy transition employing hydrogen as one of the vectors in these jurisdictions.

2.2.2 Future hydrogen demand projections

Today, hydrogen is consumed predominantly by the refining industry. Chemical industry uses hydrogen for ammonia and fertilizers production. Hydrogen is also employed in metal production & fabrication, methanol production, food processing, and electronics sectors. Annual global demand for hydrogen has grown more than three folds since 1975, to reach 70 million metric tons (MMT) by 2018[32]. Currently, Germany and California have similar hydrogen demands of roughly 1.3-2 MMT/year and is used predominantly for refining. Japan and South Korea's annual demand are lower at about 200 metric tons per year and is mostly used in the power sector [29,33]. Future hydrogen demand projections in the four jurisdictions from existing literatures are illustrated in Figure 3. The scenarios project a high and low case demand for hydrogen across 2030 and 2050. Missing data (like for South Korea in 2050) was linearly interpolated. There was no information available for a possible low demand scenario in South Korea.

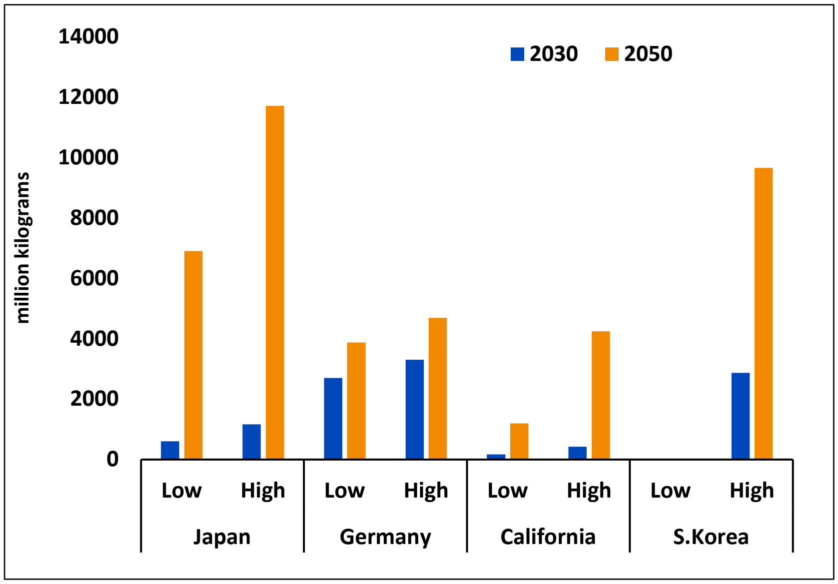

Figure 3. Hydrogen demand projections for low carbon scenarios in 2030 and 2050 [28,33,34]

In the German and Californian scenarios, hydrogen will be consumed mainly by the transportation sector, (followed by industry), while Japan's hydrogen demand will be driven by the power sector. Japan has been promoting hydrogen use in both grid connected and off grid power generation. Japan, which has historically been an epicenter of natural disasters have made a concerted effort through national programs such as ENE FARM, to incentivize fuel-cell-based power systems

While it is unclear if the hydrogen demand in South Korea will be dominated by transportations sector, the Korean roadmap places significant emphasis on the transportation sector. Globally too the transportation sector is projected to be the largest consumer of hydrogen by 2050 [35]. Hence, we will focus on this sector a bit more in detail for these jurisdictions.

2.2.3 FCEV and HRS: Deployment, targets, and policies

Currently, the fuel-cell vehicle population is only less than 0.05% of all registered vehicles in California, Germany, South Korea, and Japan. The FCEV numbers in these four geographies together account for nearly 60% of all on road fuel-cell vehicles and more than 60% of all installed hydrogen refueling stations across the globe.

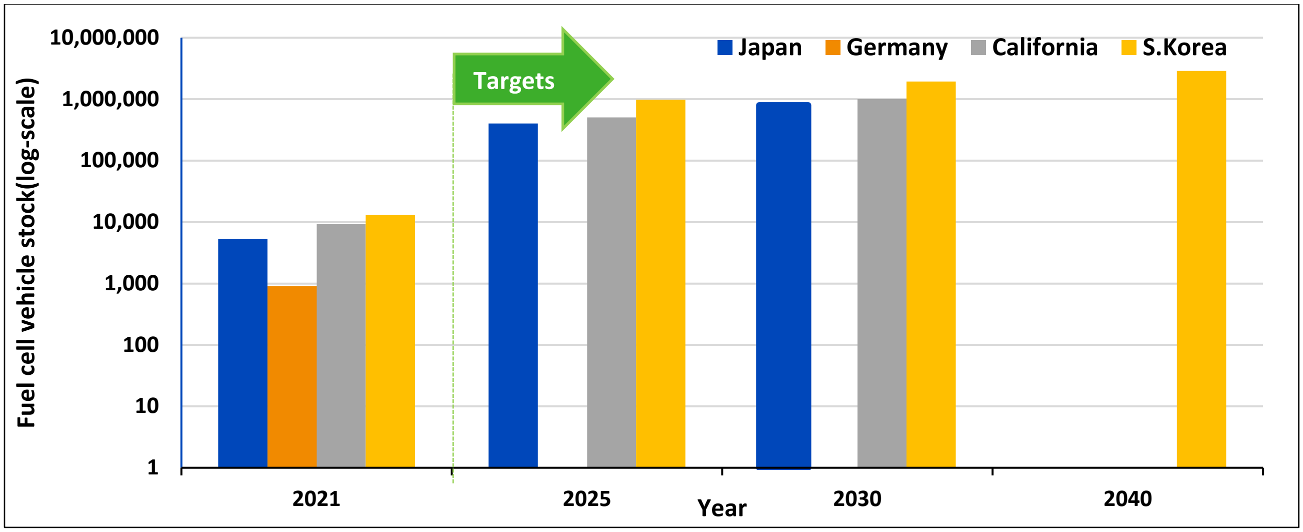

Figure 4 .Actual and projected FCEV stock(dominated by light duty vehicles) [29,36,37]

Figure 4 shows the fuel-cell vehicle population in the four jurisdictions as of 2021 and projections/targets thereafter. Japan's hydrogen strategy targets the FCEV population to reach 800,000 by 2030. The state of California does not have specific targets for FCEVs, though they are part of the state's goal of five million zero emission vehicles (ZEVs) on the road by 2030. California's Fuel Cell Partnership (CaFCP), an industry-government collaboration formed to commercialize FCEVs, targets 1 million FCEVs in California by 2030. That would represent 20% of all ZEVs if the state's broader ZEV target is also reached. Germany has not publicly announced any sales targets for FCEVs. By 2040, South Korea's hydrogen road map projects production of 2.9 million vehicles for domestic use. Each jurisdiction has implemented a set of policies to promote FCEVs, though these vary considerably.

Japan introduced subsidies for fuel-cell vehicle purchases in 2016, as part of the national budget for clean vehicles including BEVs, hybrids and clean diesel vehicles. The total budget for their national clean vehicle program in 2018 was $117 million, with additional subsidies being provided by prefectural governments for FCEVs and fuel-cell buses. The total subsidies in Japan reduced the retail price of a fuel-cell sedan by 38% as of 2017. Exemptions on the annual vehicle tax is an added incentive for FCEV buyers. For taxi operators the subsidies are slightly more generous. FCEVs in Japan are also looked upon as a potential off-grid power generator for homes and hospitals during blackouts. This adds to the appeal of FCEVs for Japan, which is highly conscious of the importance of disaster readiness. FCEVs have higher kWh in comparison to a similar sized BEV, which further espouses its use as an off-grid power generator [38].

Germany targets a 100% ZEV fleet by 2040[39], but unlike Japan does not have exclusive targets for fuel-cell vehicles. At the national level, since 2016 the German government grants a 2,000 EUR subsidy (Umweltbonus) for the purchase of BEVs and FCEVs. From January 2019, taxes were reduced for new EVs that are used as company cars (which constitute nearly 64% of all new passenger cars in Germany). Several German states and cities provide additional EV purchase incentives which have triggered new registrations (predominantly BEVs) that reached nearly 10,000 a month as of October 2019. For BEVs, the increase in registrations strongly correlates with the availability of a wider range of models offered by car manufacturers (VW, Renault, Hyundai, and Audi), unlike FCEVs. Germany's ZEV incentive program is unique because the auto industry contributes a significant portion of the incentives. Germany has further increased the electric vehicle incentives as part of their post-pandemic stimulus package. At present, the total subsidy for purchase of a BEV/FCEV costing less than 40,000 EUR is 9,000 EUR. For vehicles above 40,000 EUR the subsidy is 7500 EUR. In this, the manufacturer's share of incentives is 3000 and 2500 EUR respectively [40,41]. Clearly, the current set of incentives have not encouraged a significant roll out of fuel-cell vehicles in the German market as is evident from Figure 4, with less than 1000 FCEVs plying the road in 2021.

In South Korea, the central and local governments provide subsidies for consumer FCEVs, and while the incentives are available for any make, Hyundai provides nearly all FCEVs in Korea. Hyundai's most recent FCEV model, the 'Nexo,' has a starting price of 72 million Korean Won (57,000 US Dollars). The central government provides a 22.5 million KRW (18,000 USD) subsidy, while local governments provide subsidies ranging from 10 to 20 million KRW (8,000 to 16,000 USD). With all subsidies, Nexo model costs roughly KRW 32.5 million (26,000 USD) in Seoul[42]. Aside from end-user subsidies, the government offers additional incentives in the form of tax breaks. FCEVs are eligible for up to a 50% discount on public parking spaces as Type 1 low-emission vehicles. In addition, the Korea Expressway Corporation (KEC) offers a 50% discount on highway tolls to Battery Electric and Fuel-Cell electric vehicles. Thus, South Korea has the highest rates of subsidies for vehicle purchases among other jurisdictions compared here. This could be one reason why South Korea currently leads other jurisdictions in terms on FCEVs plying on road (more than 16,000 as on March 2022).

California has several important policies that directly or indirectly promote FCEVs. Its Low Carbon Fuel Standard (LCFS), and ZEV mandate are two critical policy interventions that have encouraged the adoption of zero emission vehicles in the state. The LCFS Program requires at least a 10% reduction in the carbon intensity of transportation fuels that are sold in the state by 2020, and an additional 10% by 2030. This is by far the most stringent requirement for transport fuels in the US[43]. As of 2020, the incentives include credits for low carbon electricity and hydrogen, as well as refueling infrastructure "capacity" credits for stations selling these. The ZEV sales mandate requires auto manufacturers to sell a certain number of ZEVs and plug-in hybrids each year, based on their total sales volumes. Requirements are in terms of percent credits, ranging from 4.5 percent in 2018 to 22 percent by 2025[10]. The credit requirements make it difficult to assess the exact number of FCEVs that will be produced through this regulation. But nevertheless, these policies seem to have triggered the initial market for fuel-cell vehicles in the state, accounting for almost the entire US market for fuel-cell vehicles. The Clean Vehicle Rebate Project (CVRP) is an income based clean vehicle adoption program by CARB that provides rebates of $4,500 for purchase of FCEVs, which is higher than the rebates offered to a similar sized BEV. For low income individuals an additional $2,500 of rebate is provided [13]. A federal tax credit of up to $8,000 is also available for FCEVs. In absolute money value, the total rebates/subsidies available for purchase of an FCEV in California is higher than in Germany but lower than in Japan.

2.2.3.1 Medium- and Heavy-Duty FCEVs

While these jurisdictions have focused mainly on uptake of light-duty vehicle FCEVs, this is changing, particularly in California. In 2018, CARB awarded $41 million for the 'shore to shore' project, for developing 10 fuel-cell class 8 drayage trucks. More importantly, in June 2020, CARB passed the Advanced Clean Truck rule (ACT) which mandates that every new truck from Class 2b-8 sold in California to be zero-emission by 2045. CARB estimates CO_2e emissions reductions of 17.3 million -metric- tons by 2040, as a result of the ACT regulation enforced from 2024 [44]. The rule provides a schedule of increasing original equipment manufacturer (OEM) sales of ZEVs by truck class, with some classes (Class 4-8 straight trucks) required to reach 50% ZEV shares in 2030 and 75% in 2035.

South Korea's hydrogen road map projects 30,000 hydrogen trucks and 40,000 FCB to be produced by 2040. Hyundai's Xcient is marketed as the world's first mass produced fuel cell truck. These vehicles can travel 400 kilometres (250 mi) on a full tank and takes 8 to 20 minutes to refill. 56 (out of 1600) of these trucks have been exported to Switzerland starting in 2020 and have completed one million kilometers. The company plans to introduce different variants of these trucks globally and have initiated a demonstration project in California's Oakland port with 30 trucks (have a range of 500 miles). The project is funded jointly by CARB and CEC[45].

Medium- and heavy-duty vehicles(MHDV) population in Japan is close to 20%, but account for nearly 43% of GHG emissions from the transport sector[46]. Apart from the CO_2 emission regulations, there is no real policy push to roll out zero emission vehicles in this category. Incentives for fuel-cell based MHDV are still low, apart from a few instances, like the plans (in the Hydrogen strategy) to roll out 1,200 fuel-cell buses by 2030. Japanese OEMs like Toyota recently expanded its model range from light-duty FCEVs to FCBs and struck strategic partnerships for developing heavy-duty fuel-cell trucks but will require greater government support if these vehicles are to achieve significant market penetration.

Long-distance road-freight transport contributes nearly 20% of Germany's on road GHG emissions. Germany is part of the overall European plan to roll out 45,000 fuel-cell trucks and buses on road by 2030[47]. German OEMs, like Daimler, are also developing heavy duty fuel-cell vehicles, but like Japan, there are no specific policies for encouraging zero emission vehicles in this category.

With higher payload capacity and longer range, fuel-cell based MHDVs have some advantage over pure battery vehicles. But given the current high costs of these vehicles, greater government support is paramount and clear policy direction (like the ACT) will be required to successfully decarbonize this segment. Very few jurisdictions (like S.Korea and California) have targets set for this vehicle segment.

2.2.3.2 Hydrogen Refueling Station Deployment

A critical roadblock for the larger adoption of FCEVs is the unavailability of refueling infrastructure. Acknowledging this, all governments have taken steps to encourage buildout of a refueling station network to support growing fleets of FCEVs. Figure 5 depicts the current stations and the targets. All jurisdictions(except S.Korea) have very similar hydrogen station targets, between 900 and 1000 by 2030. South Korea's commitment for 2040, is far sighted and would incentivize the build out of upstream supply chain infrastructure to support these stations which is also very important to ensure uninterrupted operation of the stations.

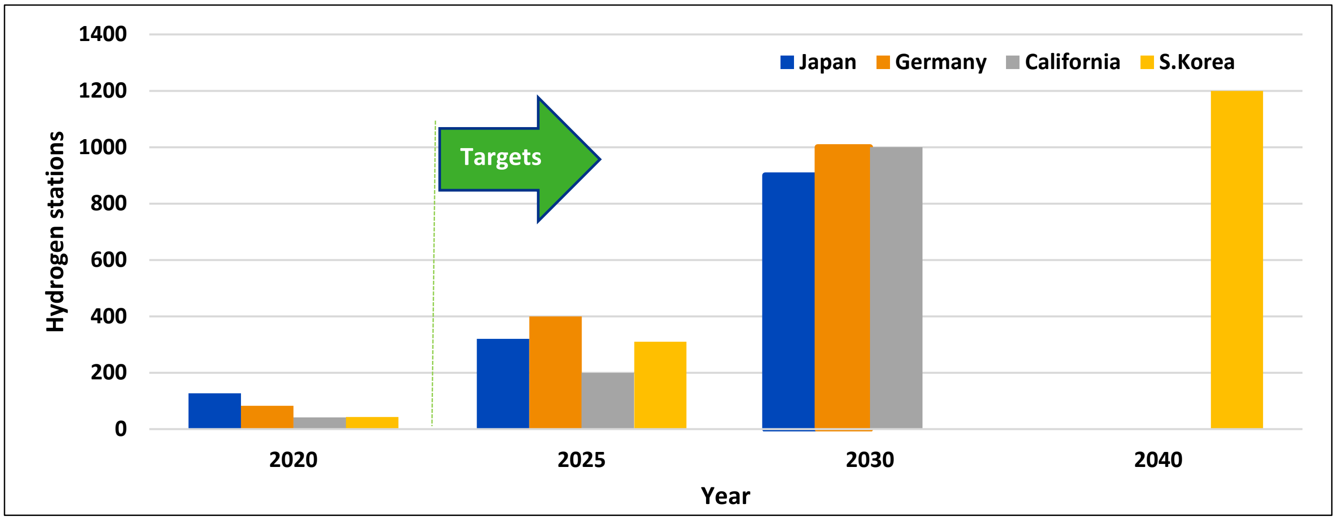

Figure 5. Current hydrogen refueling station deployment and government and industry projections through 2030

Like in other budding hydrogen economies, a major roadblock for the increase in the number of FCEVs in Japan is the lack of refueling infrastructure. But the situation in Japan is aggravated by very high costs of construction and operation of the refueling station. A hydrogen station in Japan is reported to cost two or three times the price as in Europe. The reasons for the high costs are twofold: hydrogen is a tightly regulated industrial gas, mandating high precision sensors and instrumentation (very expensive) use in the station. Manual refueling of cars by specialists licensed in handling high pressure gases (very few specialists available) limit the working hours of the fueling stations, drastically reducing the utilization rate of the station. A change in the existing law to allow automated fueling stations could go a long way in solving this problem. Of late, Japan has eased some of the regulatory roadblocks by allowing an increased storage pressure of hydrogen in refueling stations and modifying the High-Pressure Gas Safety Act and the Fire Service Act to enable transport and storage of hydrogen in various forms. By 2025, Japan is targeting to establish 320 hydrogen refueling stations [48]. To create a funding ecosystem, a consortium of 11 Japanese automakers, infrastructure developers and investors established the Japan H2 Mobility (JHyM), as a joint venture in February 2018. JHyM also helps to standardize equipment, optimize driver usability, and support the deregulation of industry standards.

Germany hopes to build an initial hydrogen system, including refueling infrastructure for vehicles which would then encourage adoption of fuel-cell vehicles. Germany is part of various European initiatives which promote hydrogen technologies in the transport sector. Fuel Cells and Hydrogen Joint Undertaking (FCH JU), European Hydrogen Initiative, German– French cooperation on energy transition are a few noteworthy ones. In 2009, Germany established the H2 Mobility partnership – a conglomeration of vehicle manufacturers, energy companies and government institutions for developing a nationwide network of hydrogen refueling stations[49]. H2 Mobility receives funding from the Federal Ministry of Transport (through NIP) and the European Commission (through FCH JU). At present, Germany has the second largest public hydrogen refueling infrastructure in the world, only surpassed by Japan[50] as shown in Figure 5.

California started building its hydrogen refueling station network in 2005, based on the California Hydrogen Blueprint Plan [51], but could not achieve its initial targets. Of late, California has revived its focus on developing retail hydrogen refueling stations through legislations such as Assembly Bill 8 and amendments to LCFS. AB 8 dedicates up to $20 million per year to support construction of the first 100 hydrogen fuel stations in the state. The 2018 LCFS amendments allow for Hydrogen Refueling Infrastructure (HRI) credits, with the goal of reaching 200 hydrogen stations by 2025. Station owners can claim credits for 15 years, based on the difference between the station's installed capacity and the actual hydrogen throughput, which is very encouraging [52]. At present, California has 52 operational refueling stations, a number lower when compared to Japan and Germany. California Fuel Cell Partnership (CaFCP), an industry/government consortium, projects 1000 hydrogen refueling stations in the state by 2030. Further, in a more recent report by CaFCP, it envisions a roll out of 70,000 heavy-duty fuel cell electric trucks supported by 200 hydrogen stations in-state by 2035[53].

2.2.4 Where and how will the hydrogen be sourced and distributed?

"Green" hydrogen is produced from renewable sources (mostly through electrolysis using renewable electricity) and "blue" hydrogen is produced from fossil fuel sources in conjunction with carbon capture and sequestration CCS[54]. "Gray" hydrogen is produced using fossil natural gas without CCS. This is a mature technology and currently is the predominant method of producing hydrogen. But with increasing focus on decarbonization, much of the policy support and funding is directed towards developing either blue or green hydrogen pathways. Beyond hydrogen production, absence of a cheap and reliable distribution infrastructure remains a challenge, in all budding hydrogen economies.

Japan's hydrogen strategy identifies power to gas (PtG) as a solution for storage and load balancing of excess domestic electricity from renewable energy sources. Power to gas (PtG) refers to the process of creating a gas fuel from electricity. PtG offers possibilities for integrating different sectors. Power from renewables like solar and wind could be used to produce green hydrogen through the PtG route, which could eventually power heavy duty vehicles, shipping etc. Japan has also set out concrete cost and efficiency targets per application, targeting electrolyzer costs of $475/kW, efficiency of 70% or 4.3 kWh/Nm 3, and a production cost of $3.30/kg by 2030. The lack of large, non-intermittent renewable electricity supply, high cost of renewable electricity generation and the lack of gas infrastructure (both natural gas and hydrogen gas pipelines) dampens the prospects of a fully-fledged uptake of PtG in Japan, at least in the near future. This has prompted Japan to focus on developing a steady hydrogen supply chain through imports. Until 2040, these imports are likely to be mostly blue hydrogen, with the intent to eventually develop a domestic supply chain for green hydrogen. Japanese companies have struck strategic partnerships in Australia, Saudi Arabia, Norway, and Brunei for hydrogen production from coal, oil and hydro power, and are testing carrier technologies for shipping the hydrogen to Japan [28]. The first liquid hydrogen ship was delivered in December 2019, and the first blue ammonia (ammonia from gas reforming with carbon capture) shipment arrived in September 2020[55].

The German hydrogen strategy targets 14 TWh of green hydrogen production by 2030. The strategy has exclusively focused on electrolytic green hydrogen [17], due to strong public opposition to the implementation of CCS in Germany. The European Hydrogen strategy, released shortly after the German hydrogen strategy, targets to scale up green hydrogen production using wind and solar energy to up to 10 million- tons in the EU, and forecasts the ramping up of electrolyzer capacity to 40 GW by 2030[56]. Germany will leverage its EU presidency to enable a vibrant green hydrogen market across the EU member nations. As of 2019, Germany has more than 50 PtG projects in planning or operation (versus 3 in Japan) and plans to drastically increase the capacity during the next few years. One study has identified many scenarios where Germany could rely on imports to fulfill a majority of its future demands [57]. In the background of the ensuing Russia-Ukraine conflict and its implications on energy security, it is paramount that Germany expands its import baskets for hydrogen. We note that Germany is revisiting an agreement with Morocco for supply for green hydrogen[58].

Germany's gas grid covers a total of 511,000 kilometers which can be leveraged for distribution and storage of hydrogen produced through the PtG route [56]. The largest PtG plant with hydrogen injection into the gas grid (6 MW) has been operational in Germany since 2015 [59]. At present, hydrogen is being blended into Germany's natural gas pipelines for use in power plants as well as heating applications. Germany's pipelines handle blends close to 10% of hydrogen and the plan is to extend this to 20%[60]. Pipeline safety studies indicate a safe blending window ranging from 5% to 20% by volume of hydrogen, depending on the specific design and age of the pipeline [61]. Apart from blending, Germany has been promoting other hydrogen distribution techniques like Liquid Organic Hydrogen Carriers(LOHC)[62] and also developing cross country hydrogen pipeline network across Europe [16].

In the backdrop of favorable policies such as SB 1369 (for renewable hydrogen production using electrolysis) and the recently passed Carbon Capture and Storage Protocol under LCFS, California is poised to become an early producer of both blue and green hydrogen. The production of green hydrogen using electricity grid connected electrolyzers might be expensive, given the high industrial electricity rates in California. This could prompt some regional imports (mostly green hydrogen) from neighbouring states. Additionally, California has been trying to forge partnerships for possible low-cost hydrogen imports, for example with Chile[63] . Also, the definition of green hydrogen is broader in the Californian context with substantial amount of green hydrogen that could be produced from landfill and dairy biomethane.

California’s natural gas utilities have more than 100,000 miles of gas transmission and distribution pipelines. A first step towards establishing a hydrogen distribution network would be to enact policies (by the California Public Utilities Commission) to allow blending of hydrogen into the existing natural gas pipelines, much like in Germany. However, in the long-term dedicated hydrogen pipelines need to be constructed to serve the demands of industry, power plants, and hydrogen-refueling stations.

Currently, South Korea's hydrogen demands are met mostly by the petrochemical industry [29]. The government and industry regard renewable energy powered electrolysis as a key component of their long-term hydrogen production strategy. The Korean hydrogen roadmap also envisages imports of renewable hydrogen by 2030, but the global partners have not yet been identified. To meet growing demands in the early stages of market growth, South Korea would produce hydrogen using natural gas that is imported in the liquid form. It is not clear now, whether those production capacities would be coupled with some form of CCS or not. Recently, South Korean Ministry of Trade, Industry and Energy (MOTIE) announced reduced feed stock pricing for natural gas that would be employed for producing hydrogen needed by the transportation sector. The Korea Gas Corporation (KOGAS) is expected to spearhead plans to establish a steady supply of hydrogen for meeting future demands [64]. KOGAS is considering building new hydrogen pipelines (in addition to using existing natural gas pipelines) at the point of import to facilitate the domestic shipment of imported hydrogen. These and other proposed pipeline projects would be in addition to South Korea's existing 200-kilometer hydrogen pipeline.

At present, the majority of the global hydrogen production stems from CO_2-intensive processes based on fossil fuels. Capturing those CO_2 emissions (to make blue hydrogen) adds cost but may still be economically attractive in many situations. The long-term cost competitiveness of green hydrogen (electrolytic) over blue hydrogen largely depends on the capital cost reduction of electrolyzers coupled with very low electricity rates. Proponents of green hydrogen foresee such scenarios, by the end of the decade, when green hydrogen reaches cost parity (or even lower) with blue hydrogen. For blue hydrogen, the cost of carbon capture and the feasibility of geological storage of CO_2 is the key for cost reduction. Almost all future low carbon scenarios for Japan, South Korea and Germany assume most of the hydrogen demand to be fulfilled by imports, unlike for California where a vast majority of hydrogen demand could be satisfied through instate production or with regional imports. The availability of a low cost and reliable hydrogen distribution network is a challenge in all jurisdictions.

3 Policy and Strategy Summary

Table 2 attempts to summarize the relative level of effort or focus on different areas of the hydrogen market by the different countries, and the emphasis and priority that each places on a range of strategies. The figure is subjective and uses a simple low, medium, and high classification for each indicator listed, pertaining to the development of the hydrogen economy. These ratings are not all encompassing and are likely to change into the future (owing to the dynamic nature of the hydrogen market) but are meant to provide some sense on how the jurisdictions are similar and different from each other based on the data and discussions in the preceding sections.

Table 2. Summary of present status and future drivers of the hydrogen economy in the four jurisdiction

S.No	Attribute	Japan	Germany	S.Korea	California
1	GHG reduction targets for 2030	△	●	◆	△
2	Drivers of future hydrogen demand				
	• Power generation	●	◆	△	△
	• Transportation	△	●	●	●
	• Industry	◆	●	△	△
3	Market penetration/ Present status of hydrogen technologies				
	• Fuel Cell vehicles	△	◆	●	●
	• Hydrogen refuelling stations	●	△	◆	◆
	• Stationary power generation units	●	△	△	◆
	• Power-to-gas (PtG) projects	◆	●	◆	◆
4	Policy emphasis for hydrogen production				
	• Blue hydrogen	●	◆	△	△
	• Green hydrogen	△	●	△	△
5	Domestic feasibility for cost effective hydrogen production	◆	△	◆	●
6	Potential to employ existing gas infrastructure for hydrogen distribution	◆	●	△	●

Legend	
●	High
△	Medium
◆	Low

4 Conclusions

Enacting measures to keep global temperatures from increasing beyond 1.5 degrees Celsius requires immediate and unprecedented action. Hydrogen is increasingly attractive as a feasible decarbonizing energy carrier by major economies. We reviewed hydrogen-related activities, policy, present status, and targets in major economies around the world, with a focus on Japan, Germany, South Korea, and California. Achieving GHG emission reduction targets and ensuring economic and energy stability is what is driving these jurisdictions towards greater adoption of hydrogen. But the approach followed by every region is succinctly different.

Japan, South Korea, and Germany have an overarching “hydrogen strategy”, unlike California which has focused more on technology neutral zero-emission policies that could encourage hydrogen-based technologies. Japan’s efforts have focused more on stationary demand-side applications such as fuel-cell based off-grid power generation. Germany has been the most proactive on developing hydrogen supply systems, mostly through the green hydrogen (electrolysis) route. South Korea is poised to become a global leader in the production and deployment of fuel cell electric vehicles and large-scale stationary fuel cells for power generation and has the third-largest public investment in hydrogen after Germany and Japan. California’s hydrogen strategy has centered primarily around the demand side, specifically the transportation sector, by promoting fuel-cell vehicle sales.

We identify specific challenges for each of these jurisdictions, as they expand their hydrogen ecosystem. The lack of supporting infrastructure (hydrogen distribution in particular) to meet projected growth in hydrogen demand is a common challenge for all jurisdictions. A major challenge for Japan will be to develop a cost-effective and self-reliant domestic hydrogen supply chain. Germany will need to incentivize a larger adoption of fuel-cell vehicles and diversify its low-carbon hydrogen import basket. California should aim to increase the role of hydrogen beyond transportation, such as in various industries and buildings. Policy directives encouraging hydrogen-based power generation (using fuel cells or in gas turbines) and permitting blending of hydrogen into existing natural gas pipelines can help incentivize investments in hydrogen supply and some of the hydrogen markets outside of transportation. Ushing hydrogen in hard-to-decarbonize sectors (such as steelmaking, shipping, cement, etc.) appears a potentially important direction for all jurisdictions, given their ambitious GHG reduction goals.

Overall, to be successful in rolling out a large hydrogen system, all these economies will need to develop a balanced approach, incentivizing both supply and demand of hydrogen, and prioritizing the infrastructure needs to make the system work. Strong communication and sharing of experiences, both successes and failures, is critical at this stage as these and other countries start to make major investments in hydrogen systems. Hydrogen’s true potential is its versatility, and its ability to decarbonize sectors that are very carbon intensive. An integrated and holistic policy focus with a steady funding mechanism to promote hydrogen is paramount if regions are to achieve their deep decarbonization plans.

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