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JAPAN'S HYDROGEN STRATEGY AND ITS ECONOMIC AND GEOPOLITICAL IMPLICATIONS

Monica NAGASHIMA

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Executive Summary

With the Basic Hydrogen Strategy (hereafter, the Strategy) released on December 26, 2017, Japan reiterated its commitment to pioneer the world's first "Hydrogen Society". The Strategy primarily aims to achieve the cost parity of hydrogen with competing fuels, such as gasoline in transport and Liquified Natural Gas (LNG) in power generation. The retail price of hydrogen is currently around 100 yen per normal cubic meter (yen/Nm^3)[1] (90 USD ($) cents/$Nm^3$) and the target is to reduce it to 30 yen/Nm^3 by 2030 and to 20 yen/Nm^3 (17 cents/Nm^3) in the long-term. Toward this end, over the past six years, the Japanese government has dedicated approximately $1.5 billion to technology Research and Development (R&D) and subsidies in support of:

- Achieving low cost, zero-emission hydrogen production from overseas fossil fuels + Carbon Capture and Storage (CCS), or from renewable energy electrolysis;
- Developing infrastructure for import and domestic distribution of hydrogen;
- Scaling up hydrogen use across various sectors, such as mobility, residential Combined Heat and Power (CHP), and power generation.

Japan's Strategy rests on the firm belief that hydrogen can be a decisive response to its energy and climate challenges. It could foster deep decarbonisation of the transport, power, industry and residential sectors while strengthening energy security. As such, it is a holistic, multi-sector strategy aimed to establish an integrated hydrogen economy. The Strategy encompasses the entire supply chain from production to downstream market applications. Success will primarily depend on the cost competitiveness and availability of carbon-free hydrogen fuel. Japan's state-backed approach is ambitious, as it involves domestic and overseas industry and government stakeholders on a number of cross-sectoral pilot projects.

At this stage, the economic and technical challenges and uncertainties have not been lifted. The government awaits the results of the ongoing pilot projects around 2020 before considering the integration of hydrogen into the wider economic and energy plans. While public funding is steadily

1. *Normal* referring to standard temperature and pressure.

increasing, it remains limited and reflective of caution against any long-term commitment. Decarbonization of Japan's energy sector still predominantly rests on nuclear, natural gas, energy efficiency and renewable energy sources (RES). The prospect of hydrogen playing an economy-wide role still meets considerable skepticism both in Japan and abroad. At present, nearly all hydrogen and fuel cell technology is still highly dependent on public financial backing.

Beyond transport, industry, and building sectors, the commercial adoption of hydrogen in power generation will be an indicator of the Strategy's success. Given that power plants would consume a lot of hydrogen fuel, an operation of several plants would indicate that the hydrogen fuel supply network is reaching price maturity. In addition to hydrogen, ammonia and methylcyclohexane (MCH) are also being studied for direct and co-fired thermal generation.

Japan's Strategy has global implications, including the potential to trigger a new area of international energy trade and industrial cooperation. Japan and its industry stakeholders are already engaging Australia, Brunei, Norway and Saudi Arabia on hydrogen fuel procurement. Overall, international cooperation will be crucial to scale-up industrial developments, improve technologies and reduce costs. As it forms partnerships on fossil fuel-based production of hydrogen, Japan is also heavily betting on carbon capture and storage (CCS) technology, which is key to reducing emissions but at a very early stage of deployment.

In the long-term, Japan must be mindful of the net cost-benefit and environmental footprint throughout the life-cycle of hydrogen production and use this metric for comparison with alternative energy sources. For instance, without CCS, the Australian coal gasification project is equally polluting as direct power generation using brown coal. The Japanese government remains adamant that it will pursue the hydrogen economy only if large volumes of zero-carbon hydrogen can be secured in the long-term. While CCS remains unproven and carbon pricing is hoped to emerge, countries with excess and cheap renewable electricity may soon be seen as key partners for hydrogen supply to Japan.

In addition to R&D, successful innovation will depend on policy direction and investment certainty. In the case of other previously doubted technologies like solar and wind power, global policy-backed action generated the economies of scale that decreased deployment costs by nearly 80% in roughly a decade. If Japan hopes for any comparable cost precipitation for hydrogen and fuel cells, it needs to be ready to fully commit to scale up hydrogen at home and abroad. If an 80% cost reduction and the full decarbonization of hydrogen fuel are to be achieved in the upcoming decades, the development of the hydrogen supply network will need to be handled with political vigor to unlock sufficient investment and encourage cooperation internationally.

Japan would further benefit from international cooperation in the midstream and downstream technologies. Even in the relatively mature residential CHP and fuel cell electric vehicles (FCV) segments where Japan aspires to become a global leader, nurturing an export market will be critical. The installation and operation of hydrogen and fuel cell technology requires highly advanced infrastructure and skilled technicians, not to mention affordability. Unless Japan achieves a breakthrough and convinces the world to invest in hydrogen, it risks losing a lot of money on Galapagos (isolationist) technology. For example, it took Toyota nine years to sell 500,000 hybrids worldwide in a market that enjoys a large network of filling stations.[2] 800,000 FCVs in twelve years in Japan alone appears ambitious without other countries' enthusiasm for cost reduction of infrastructure and fuel cells.

Global and coordinated action under a framework that secures fair rewards for developers could encourage technology development and accelerate its commercialization, which if done right, would benefit consumers worldwide and open new doors for businesses. Hence why international coordination of policies and cooperation among industries will also be increasingly necessary.

2. E. Brandt, "Japan Is Planning for 200,000 Hydrogen Cars by 2025," *The Drive*, April 24, 2017, available at: www.thedrive.com.

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Abbreviations

AIST	National Institute of Advanced Industrial Science and Technology
APERC	Asia Pacific Energy Research Center
BEV	Battery electric vehicle
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
EOR	Enhanced Oil Recovery
FCV	Fuel cell vehicle
H2	Hydrogen
IEEJ	Institute of Energy Economics, Japan
IGCC	Integration coal gasification combined cycle
JBIC	Japan Bank for International Cooperation
LH2	Liquefied hydrogen
LNG	Liquefied Natural Gas
MCH	Methylcyclohexane
METI	Ministry of Economy, Trade and Industry
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
NEDO	New Energy and Industrial Technology Development Organization
NeV	Next-Generation Vehicle Promotion Center
NEXI	Nippon Export and Import Insurance
NH_3	Ammonia
Nm^3	Normal cubic meter
NOx	Nitrogen oxide
PEFC	Polymer electrode fuel cell
PtG	Power to Gas
RES	Renewable energy sources
SIP	Cross-ministerial Strategic Innovation Promotion Program
SOFC	Solid oxide fuel cell

Introduction

Global hydrogen production and consumption is over 55 million tonnes per year.[3] The majority of hydrogen in the world is produced and used within industrial sites as captive hydrogen (used on site) or as industry feedstock. Of the annual 15 billion Nm^3 consumed by Japanese industries, oil refining accounts for nearly 70%, while the rest is consumed by ammonia and petrochemical industries (such as for methanol production). As for the commercial production of hydrogen, the caustic soda industry accounts for the largest share of by-product hydrogen sold off-site.[4]

Virtually all hydrogen is produced from fossil fuels without CCS, of which 48% comprises natural gas reforming, 30% is the by-product of petroleum refining, 18% is from coal gasification, and the remaining 4% is from electrolysis.[5] During this fossil-fuel based process, between 9 to 12 tonnes of CO_2 are emitted per every tonne of hydrogen, depending on the quality of feedstock.[6] Altogether, industrial hydrogen production is responsible for approximately 500 megatons of CO_2 annually.[7] Replacing fossil-fuel "extracted" hydrogen with hydrogen from zero-carbon energy sources could significantly reduce the carbon footprint of the industry today.

The potential usages of decarbonized hydrogen in energy systems are manifold, be it in the transport, industry, building and power sectors. As fuel, hydrogen can be used in electrochemical cells and internal combustion engines to power vehicles and electric devices. Hydrogen's high energy density allows it to fuel the propulsion of spacecraft. In commercial applications, it is emerging in fuel cell vehicles and buses. Hydrogen generates electricity inside fuel cells without emissions, leaving only water at the tailpipe. It can be used for micro-scale combined heat and power (CHP) generation in residential fuel cells.

3. Hydrogen Council. Hydrogen, Scaling Up. November 2017, available at: http://hydrogencouncil.com.
4. Agency for Natural Resources and Energy, "Hydrogen production, transportation and storage," April 4, 2014, available at: www.meti.go.jp.
5. B. Decourt *et al*., "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility", Paris, France: SBC Energy Institute, February 2014, available at: www.4is-cnmi.com.
6. G. Collodi, "Hydrogen Production via Steam Reforming with CO2 Capture" (Milan, Italy: Foster Wheeler, n.d.), available at: www.aidic.it.
7. IEA, "Technology Roadmap Hydrogen and Fuel Cells," 2015, available at: www.iea.org.

There are many ways to produce hydrogen, including electrolysis, in which an electric current splits water into oxygen and hydrogen molecules. Like natural gas, hydrogen can be compressed and shipped, which is the only way for an island nation like Japan to import large volumes of carbon-free energy. Moreover, surplus renewable electricity can be used to produce hydrogen (power to gas) for long term energy storage. This hydrogen can be blended into natural gas grid in certain proportions, or further transformed into methane or ammonia for combustion in thermal power generation.

If effectively electrolysed using RES, or produced from fossil fuels with CCS, hydrogen would dispel resource scarcity and atmospheric carbon as constraints on energy needs, by becoming the inexhaustible fuel that powers economic growth and contributes to the global fight against climate change and decarbonization of energy systems. Success in commercializing the related technologies would spell out a major global energy shift. As such, hydrogen can be a backbone of a low carbon energy system and its promise of providing secure and sustainable energy is spurring enthusiasm in Japan and abroad and leading industry stakeholders worldwide have established a Hydrogen Council to foster cooperation and coordination.[8]

However, hydrogen and fuel cell technologies, currently tested in pilot projects, are still heavily dependent on public financial support and will struggle to compete with other fuels for several decades. In order to achieve a "hydrogen society" with production and usage at the scale envisaged by the Japanese government, it is necessary to massively develop new infrastructure in order to produce, transport and use this fuel of the future. Moreover, hydrogen remains a secondary energy source, meaning that energy is required to produce hydrogen from a primary source of energy. Thus, the whole process will be dismissed due to inefficiency unless its life-cycle is carbon neutral.

For Japan, its attempt at the hydrogen economy is less of a gamble than a strategic bet. To understand why Japan's enthusiasm for hydrogen is second-to-none, it is important to contextualize the undertaking through the country's energy dilemma. An industrialized nation with the world's third largest Gross Domestic Product (GDP), Japan has the second highest dependence on foreign fuels among countries of the Organisation for Economic Cooperation and Development (OECD).[9] 93% of Japan's primary energy needs are covered by imports.[10] Beyond energy efficiency efforts,

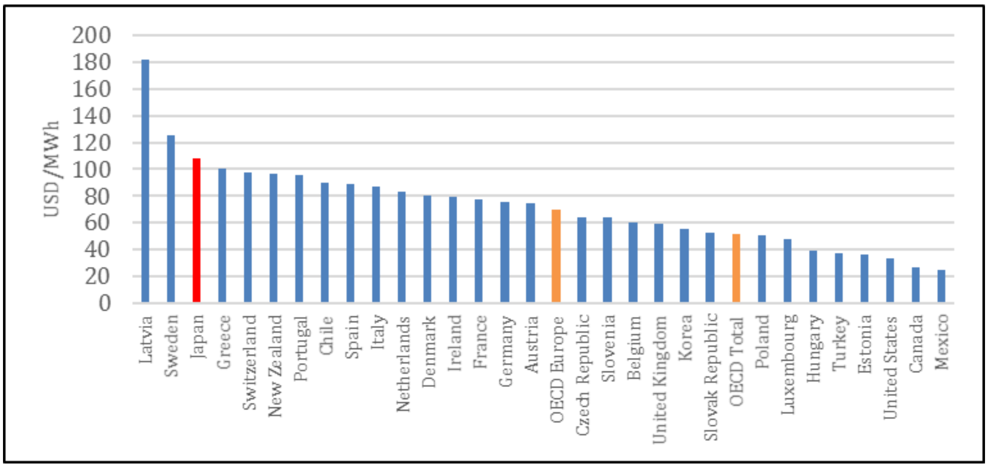
8. Hydrogen Council. Hydrogen, Scaling Up. November 2017, available at: http://hydrogencouncil.com.

9. METI, "Japan's Energy 20 Questions to Understand the Current Energy Situation," May 2018, available at: www.enecho.meti.go.jp.

10. METI.

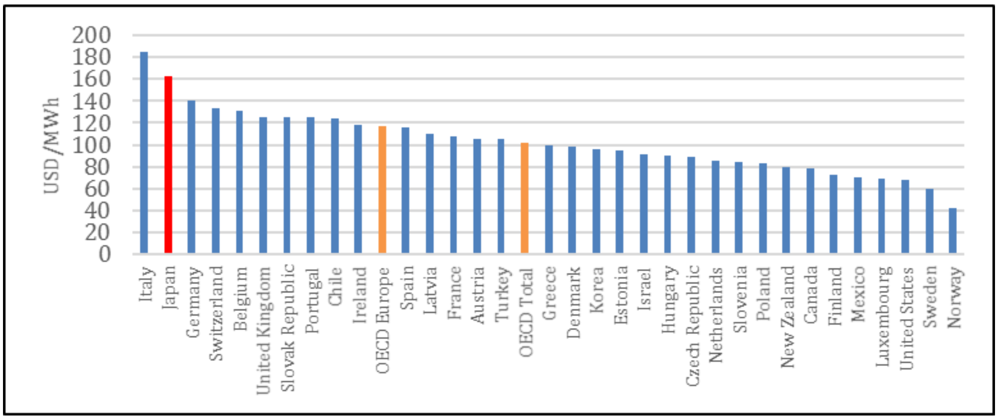
the nation's most viable option to improve energy self-sufficiency had been nuclear power, but most of its reactors remain idle due to the political aftermath of the Fukushima nuclear disaster in 2011.

OECD natural gas prices for households in $/MWh (2016)



Source: Adapted from the IEA 2018.

OECD electricity prices for industry in $/MWh (2016)



Source: Adapted from the IEA 2018.

The more immediate concerns are economic. Japan is the world's largest importer of LNG and pays the highest price per unit of import. Until the Fukushima accident in 2011, Japan recorded an almost consistent trade surplus, but the spike in fuel imports sent Japan's trade balance into the red nearly every year since. Domestic electricity tariffs increased by over 25 percent for households and 39 percent for industry since 2010.[11] Despite

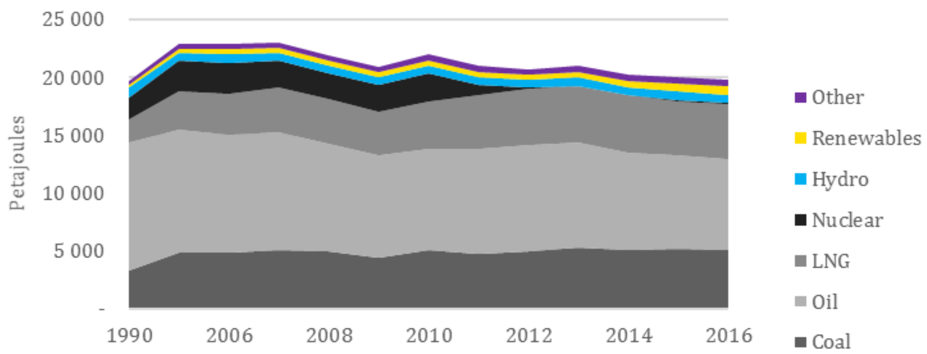
11. METI.

a recent price decrease, Japanese electricity and natural gas prices remain some of the highest in the OECD.[12]

Japan's energy mix and the potential role for hydrogen

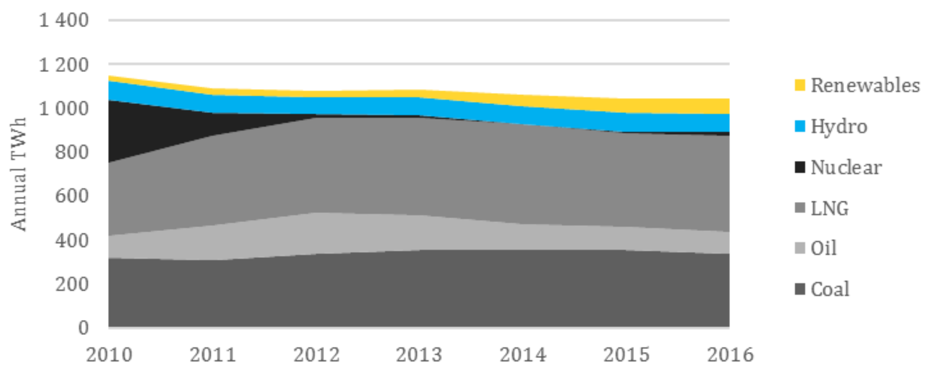
Taken together, LNG, coal and oil still account for 89% of Japan's primary energy today.[13] With its strong contribution to meeting the needs of the industrial and manufacturing sectors, oil holds the largest share (40%) in the primary energy mix, followed by coal (25%) and LNG (24%). Natural gas consumption saw a prominent rise in the recent years, especially in the power sector where it represents 42% of the total generation output in 2016. Large-scale hydro accounts for 8% of power generation, other RES for 7%, and nuclear for 2% that same year. After the post-Fukushima shut down of nuclear reactors, imports of fossil fuels, notably LNG increased and peaked in 2013. Fossil fuel use then declined following an overall decrease in energy consumption, the growing output from RES as well as the gradual and partial restarting of nuclear power. The progressive restart of nuclear power reactors is already reducing the country's LNG import needs by as much as 1 million tonne per reactor.[14]

Japan primary energy supply 1990, 2005-2016 (PJ)



12. IEA, "Energy Prices and Taxes" 2018, No. Q1 (April 7, 2018), available at : www.oecd-ilibrary.org.
13. METI, "2016 Energy Demand and Supply Statistics," April 2018, available at: www.enecho.meti.go.jp.
14. Reuters, "RPT-Japan's nuclear reboot gathers pace, set to curtail LNG demand", 3 September 2018.

Japan electricity generation mix 2010-2016 (TWh)



Source: Adapted from METI 2018.

Revealed in July 2018, the 5^{th} Strategic Energy Plan lays out the government's perspective on energy for 2030 and 2050.[15] Rooted in the 3E+S framework – energy security, environment, economic efficiency, and safety – and Japan's emission reduction targets of -26% by 2030 and -80% by 2050, the new document remains true to METI's firm ambition to increase RES and preserve nuclear power.

The share of fossil fuels is expected be reduced to 56% by 2030, while a long-term switch from coal to natural gas is to be implemented. RES are expected to amount to 22-24% of power generation by 2030. By 2050, they are to become *"the commercially viable principal electricity source"* with *"hydrogen, batteries and digital technologies"* enhancing energy stability. R&D on hydrogen will continue in the interim, so that by 2050 they could be used in the decarbonization of fossil and thermal power, and transportation sectors.

Nuclear power is to expand to 20-22% of electricity output by 2030 according to the 5^{th} Energy Plan. This equates to over 30 nuclear reactors. While *"the dependency on nuclear power will be reduced as much as possible"*, it will remain a long-term *"option for decarbonization"*. The government is indeed eager to revive nuclear power as the bedrock of baseload energy, with reassurances of high safety standards and its contribution to energy price reduction. For the first time the Strategic Energy Plan even mentions the intent to reduce Japan's stockpiles of plutonium, amid the mounting international and domestic criticism.

Of the country's 39 operable nuclear reactors, 9 have been restarted since August 2015 and 15 reactors are undergoing the process of restart

15. METI, "Cabinet Decision on the New Strategic Energy Plan," July 3, 2018, available at: www.meti.go.jp.

approval.[16] Currently, nuclear power accounts for roughly 3.6% of Japan's total power generation, which is significantly lower than the 30% share that nuclear held until 2011.[17] Before the Fukushima meltdown, the government was doubling down on efforts to increase the number of reactors. However, the accident drastically worsened the public sentiment towards nuclear power, not only impeding the government's still ongoing push to restart and build more reactors, but also intensifying the political environment for any major decisions on Japan's energy future.

Given the limited potential to expand further hydropower and geothermal resources in Japan, nuclear energy is presented as the only low-carbon, quasi-domestic source of stable power available. But the same arguments can be raised for hydrogen if it can be brought to commercialization. Specifying hydrogen targets in the power mix would signal the government's commitment and belief in the technology's long-term viability – which is essential for the colossal investment required to roll out the hydrogen vision. Yet, such determination would weaken the government's own argument that nuclear power is indispensable to the decarbonization of the power sector.

The government faces pressure to reduce domestic energy prices, and in particular to bring down the cost of its RES program which is entirely supported by consumers. Introduced in 2012, the feed-in-tariff system aimed to subsidize the installation of renewables like solar photovoltaics, wind, biomass and others, but it ballooned to a multi-trillion yen burden for the State.[18] Although RES now attract five times more investment than thermal and nuclear power combined, the success of Japan's renewable program appears subdued. The drop in renewable energy costs has not been rapid enough as the installation costs are two times higher than in the European Union,[19] while weak grid interconnectivity continues to pose balancing problems. The current struggle to justify the costly renewable energy program is likely to weigh on the government's approach towards the hydrogen program, resulting in a cautious funding strategy.

16. "Licensing Status for the Japanese Nuclear Facilities," Japan Nuclear Safety Institute, June 16, 2018, available at: www.genanshin.jp.

17. IAEA, "Country Statistics: Japan," IAEA Power Reactor Information System, July 24, 2018, available at: www.iaea.org.

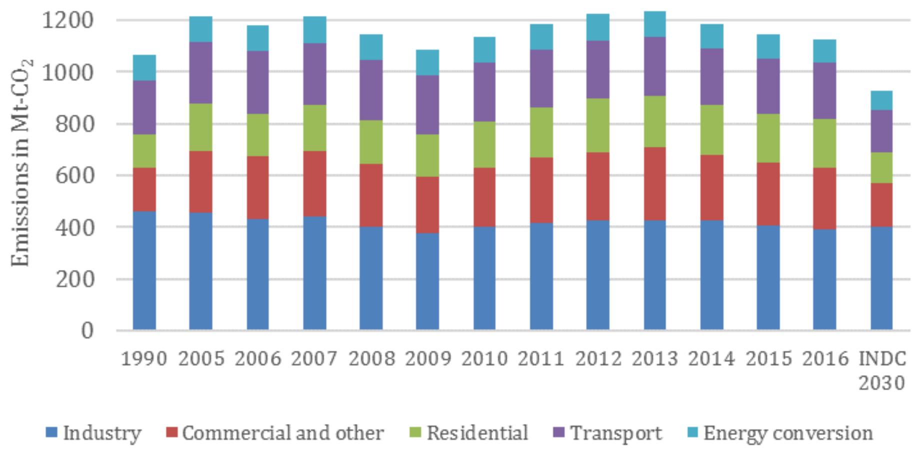
18. Y. Ito, "Brief History of Measures to Support Renewable Energy: Implications for Japan's FIT Review Obtained from Domestic and Foreign Cases of Support Measures" (Institute of Energy Economics Japan, October 2015), available at: https://eneken.ieej.or.jp.

19. Agency for Natural Resources and Energy, "Japan amidst Changes in Domestic & International Energy Environment," August 30, 2017, p. 7, available at: www.enecho.meti.

Carbon emissions and Paris commitments

Japan's carbon emissions peaked in 2013, reaching the historically highest level of 1,235 million tons of CO_2 following a 4% increase compared to 2011 levels (9% increase compared to 2010 levels).[20] This is in part due to the use of LNG and coal as substitutes to lost nuclear electricity generation, and a consequence of the steady economic recovery since 2009. The industrial, commercial and residential sectors are responsible for the highest surge. Since 2013, there has been a decoupling of economic growth and CO2 emissions, thanks to improved energy efficiency, the scale up of RES and partial reintroduction of nuclear power.

CO_2 emissions by sectoral energy use 1990, 2005-2016 and 2030 INDC targets under Paris Agreement (Mt-CO_2)



Source: METI, UNFCCC.

Ahead of the 2015 Paris Climate Agreement, Japan submitted its Intended Nationally Determined Contributions (INDC) in which it pledged to cut total greenhouse gas (GHG) emissions by 26% relative to 2013 emission levels, or 13% relative to 1990. It is worth noting that this is a weaker target than its 2008 Copenhagen pledge to cut overall emissions by 25% on 1990 levels by the year 2020. Japan backtracked on its original goals because emissions-free nuclear power is projected to play a lesser role in the power generation mix. Sectorally, the most significant decarbonization is expected in the commercial and residential sectors – roughly 40% each – and about 28% emission reduction in transport and

20. METI, "2016 Energy Demand and Supply Statistics."

energy conversion sectors. The most energy intensive industrial sector aims for a 7% reduction.

By 2050, Japan aims for an 80% reduction of GHG emissions (base year not stipulated). In 2012, the Cabinet approved the vision put forward by the Ministry of Environment (MoE) that aims to achieve emission reductions through energy demand efficiency and decarbonization of energy supply. While the government remains vocally committed to the target, it has not announced an implementation strategy or expected energy composition beyond 2030. The MoE and METI appear to be at odds with each other in their long-term reports released in 2017. The MoE focuses on strategies to achieve the 80% reduction domestically and emphasizes a need for the early introduction of a fully-fledged carbon pricing system. On the other hand, METI stresses the challenges of meeting the target domestically and instead promotes Japan's contribution to emission reductions through overseas programs. The METI report is also critical of introducing carbon pricing in the short term.[21]

Japanese 2030 GHG emissions and reduction commitments under Paris Agreement by sector (Mt-CO_2)

Year	Industry	Commercial and other	Residential	Transport	Energy conversion	Total
1990	462	169	130	207	97	1065
2005	457	239	180	240	101	1217
2006	431	244	165	242	97	1179
2007	442	253	176	239	103	1213
2008	403	240	171	232	99	1145
2009	375	219	165	228	98	1085
2010	404	228	177	229	98	1136
2011	417	253	192	225	100	1187
2012	429	261	206	227	102	1225
2013	429	279	201	225	101	1235
2014	425	256	192	219	95	1187
2015	406	244	187	217	93	1147
2016	392	240	188	215	93	1128

21. Climate Action Tracker, "Japan Country Summary," April 30, 2018, available at: https://climateactiontracker.org.

INDC 2030	401	168	122	163	73	927
INDC % reduction on 2013	-7%	-40%	-39%	-28%	-28%	-26%
INDC % reduction on 1990	-13%	-1%	-6%	-21%	-25%	-13%

Source: Japan's INDC.

Against the backdrop, this report aims to clarify the policy and economic context of Japan's hydrogen strategy and intitiatives, evaluating the progress made, describing its international implications and identifying future opportunities and challenges.

The Basic Hydrogen Strategy: Key Objectives

The Basic Hydrogen Strategy (herafter, the Strategy) was revealed at the Ministerial Council on Renewable Energy, Hydrogen and Related Issues on December 26, 2017.[22] It is a follow up of the Ministerial Council of April 2017, during which Prime Minister Abe officially requested the drafting of a plan to transform Japan into a world-leading "hydrogen society." The document was compiled with inputs from various ministries and agencies, academia and business players. It was issued by Japan's main energy authority, the Agency for Natural Resources and Energy (ANRE), under the heading of METI.

The *raison d'être* of the Strategy is the need to coordinate public and private hydrogen initiatives that have been ongoing in Japan since the 1970s. ANRE had issued a Strategic Roadmap for Hydrogen and Fuel Cells in June 2014, which outlined numerical targets for cost and scale of adoption in key application areas.[23] The new Basic Hydrogen Strategy introduces additional targets for 2020 and the *"long-term perspective of around 2050"*, and spells out the motivations and policy-details behind Japan's ambitions.

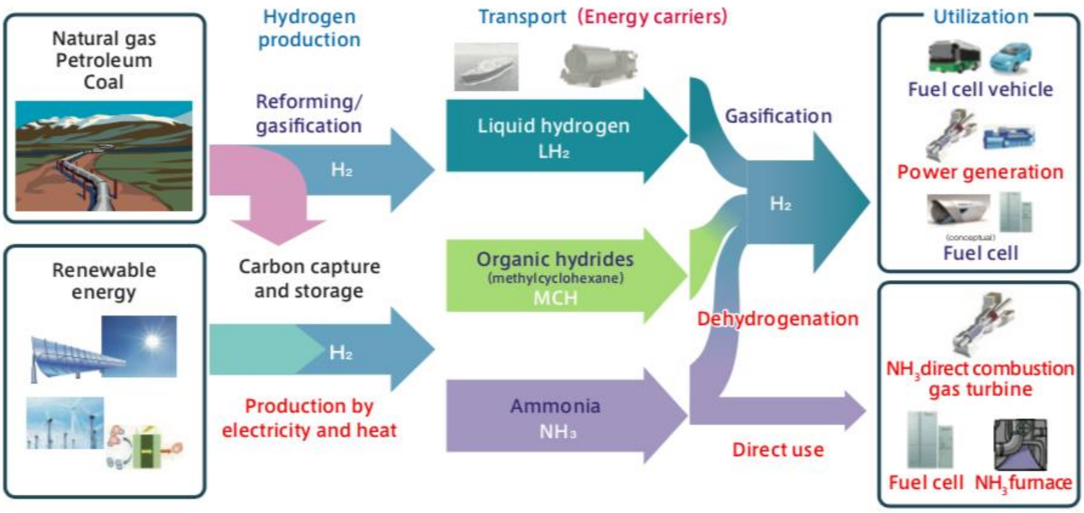
A key requirement for the success of the "hydrogen society" is to drive down the cost of hydrogen fuel and related technologies along the entire value chain. The strategy places heavy emphasis on reducing the cost of hydrogen production and procurement, with the goal of achieving an 80% cost reduction around 2050, which would make hydrogen fuel competitive with natural gas. The current price of 100 yen/Nm^3 is expected to be reduced to 20 yen/Nm^3 in the long-term (roughly from $ 90 cents/Nm^3 to 17 $ cents/Nm^3).

Japan also stresses that hydrogen must become carbon-free sometime after 2050. Current methods of production from fossil fuels are emissions intensive and thus need to be combined with carbon capture, utilization and storage (CCUS). Solutions for reducing the cost of renewable energy electrolysis are also being considered.

22. METI, "Basic Hydrogen Strategy Determined," December 26, 2017, available at: www.meti.go.jp.
23. METI, "METI Has Compiled a Strategic Road Map for Hydrogen and Fuel Cells," June 24, 2014, available at: www.meti.go.jp.

Towards these objectives, Japan aims to develop supply chain networks of zero-emissions, low-cost hydrogen. So far, in Australia, Saudi Arabia, Norway and Brunei, Japanese companies are working on hydrogen production from coal, oil and hydro power, and testing carrier technologies for shipping the hydrogen to Japan (see page 30). Carrier technologies examined under the strategy are liquid hydrogen, compressed hydrogen, methyl-hydrohexane, and ammonia. Renewable power-to-gas or power-to-fuel (power-to-X, denoting various possibilities of sector coupling) is also explored as a method of production with domestic renewable energy which could contribute to energy self-sufficiency and spur growth of local industries.[24]

The hydrogen supply chain network to be developed under the Hydrogen Strategy



Source: Cross-Ministerial Strategy Promotion Program (SIP), Energy Carriers 2016.

The last objective is to develop hydrogen and fuel cell applications in various sectors – mobility, power generation, residential CHP and industry – which implies the development of the related infrastructure. The 2020 Tokyo Olympics will be the first milestone to showcase the technical performance, marketability and scalability of on-going demonstration projects.

Japan is already one of the leaders in the deployment of fuel cell vehicles and fueling stations. As of 2018, there are over 100 fueling stations throughout Japan – more than double the 39 stations in the United States

24. SIP, "Cross-Ministerial Strategy Promotion Program (SIP) Energy Carriers," April 1, 2016, available at: www.jst.go.jp.

and 45 in Germany.[25] Yet, fulfilling the mobility sector targets will require many more stations, a reduction in manufacturing costs and an easing of regulations on the construction and operation of fueling stations (see page 45).

Power generation can become the most critical driver of hydrogen demand in the long-term. Based on the volume of fuel required by power plants, power generation can outweigh all other sectors and account for as much as 64% of Japan's hydrogen demand in 2050.[26] Yet in order to attract sufficient research efforts and investment, the government will need to show political determination and include energy mix targets in the long-term national energy plan.

According to the government, the Japanese market for hydrogen equipment and infrastructure may reach approximately 1 trillion yen in 2030 and 8 trillion yen – $ 75 billion – in 2050.[27]

25. METI, "One-Hundred Hydrogen Stations to Open as a World-Leading Initiative," March 23, 2018, available at: www.meti.go.jp; John Voelcker, "Germany's Hydrogen Stations Exceed US; California Beats Japan on Density," Green Car Reports, February 21, 2018, available at: www.greencarreports.com.
26. AIST and IEEJ, "Renewable Energy Storage and Transportation Technology Development; 2013 Scenario Research on Total System Installation" (National Institute of Advanced Industrial Science and Technology, March 31, 2014), p. 138.
27. METI, "METI Has Compiled a Strategic Road Map for Hydrogen and Fuel Cells."

Japan's Targets for the Hydrogen Economy (Cost in $)

	Present		2020 Target		2030 Target		Long term (After 2050)	Reference Data
	Scale	Cost	Scale	Cost	Scale	Cost		
SUPPLY								
	Hydrogen derived from fossil fuels without CCS (industrial by-product, natural gas reforming)				Develop international hydrogen supply chains and domestic production from renewables		Zero carbon H2 with CCS and renewables	
	200 ton/year	~10 USD/kg (Price at fueling stations)	4,000 ton	N.A.	300,000 ton	3 USD/kg	5-10 million ton 2 USD/kg	Annual LNG import 85 million ton
END-USE								
Power Generation	Under R&D		N.A.	N.A.	N.A.	Generation cost 17 cents/kWh	12 cents/kWh	LNG fired generation 12 cents/kWh Installed fossil fuel power generation capacity 132 GW
Mobility								
Fueling Stations	100	Construction cost: 4.5-5.4 million Annual operating cost: 450,000	160	Competitive without subsidies in second half 2020	900	N.A.	Replacing gasoline stations	31,500 gasoline stations Construction cost: 630,000-720,000
Fuel Cell Vehicles	2,000	Toyota Mirai: 66,000	40,000	Competitive without subsidies in second half 2020	800,000	N.A.	Replacing gasoline cars	62 million Passenger cars
FC Buses	~2 buses	~900,000	100	N.A.	1,200	N.A	Large FC vehicles	
Forklifts	40 forklifts	N.A.	500		10,000			
Home Fuel Cells	220,000	Rough cost estimate of Enefarm ~11,000	N.A.	Competitive in early 2020	5.3 million	N.A.	Replacing conventional residential energy systems	53 million households in Japan Cost of conventional heat and power systems: 5,400-6,300

Source: Adapted from METI Hydrogen Roadmap 2014, Hydrogen Strategy 2017.

Hydrogen Technology and Development Timeline in Japan

Towards CO_2-free hydrogen production

Hydrogen gas does not exist in large concentrations in nature and is therefore synthesized artificially through emissions-intensive processes. In the near term, hydrogen will be sourced domestically as a by-product of the refining and steam reforming of fossil fuels. In the longer term, Japan's policy roadmap towards commercialization aims to mass produce hydrogen from *"a combination of low cost unused energy from overseas and carbon capture and storage (CCS), as well as cheap renewable energy sources."* This points to three production methods:

- The first two involve extracting hydrogen from fossil fuels such as coal and oil, while carbon gas from the production process is captured and stored (or utilized, CCUS).
- Enhanced oil recovery (EOR) is being explored by Saudi Arabia as the more financially attractive alternative to CCS, as it allows to capture and re-use the gas for petroleum extraction;
- The third hydrogen production method electrolyzes water into oxygen and hydrogen gases using electricity generated from renewable energy sources.

Petroleum steam reforming + CCS

Hydrocarbons like natural gas and petroleum can be converted into hydrogen through the method of steam reforming. The process is based on a reaction between the hydrocarbon feedstock and high-temperature steam under 3-35 bar pressure in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Subsequently, the carbon monoxide and steam are reacted with a catalyst to produce more carbon dioxide and hydrogen. In the final step, carbon dioxide and other impurities should be filtered out, leaving pure hydrogen.[28] Although most commonly performed with natural gas, steam reforming also works with heavier fuels like oil and naphtha. Steam methane reforming is currently considered more practical than coal gasification for the higher density of resulting hydrogen.

Coal gasification + CCS

To produce hydrogen through coal gasification, coal is first partially oxidized and combined with steam under high temperature and pressure, to form synthetic gas consisting of hydrogen and carbon monoxide. Additional steam is applied to the synthetic gas to create more hydrogen and carbon dioxide. Hydrogen is collected through a separation system, while the CO_2 needs to be sequestered.[29]

Australian Victorian brown coal to hydrogen

In April 2018, a major Australian electricity producer AGL energy and Kawasaki Heavy Industries announced the construction of a coal gasification demonstration plant in Latrobe valley, Victoria. The pilot project will begin operation in 2020 and will run for about one year. It will test the viability of converting brown coal into hydrogen, which will then be liquefied for shipment to Japan. If proven successful, the parties will aim for large-scale commercialization in 2030. According to Kawasaki, the Latrobe Valley contains enough coal to create hydrogen that can power Japan for 240 years. Other Japanese participants are Marubeni Corp, J-Power Systems, and Iwatani Corp. Australian brown coal-based hydrogen reportedly costs 29.8 yen/Nm^3 (0.27 \$/Nm^3).[30]

Both governments are backing the project, with Australia contributing around $ 39 million and Japan contributing 7.4 billion yen in 2016 and 2017 ($ 67.4 million).[31] The total project cost is reported to be $ 496 million, half of which will be spent in Vitoria, while the other half will go towards infrastructure in Japan and shipping. At the end of the pilot period, the gasification and liquefaction facilities will be decommissioned.[32]

28. U.S. Department of Energy, "Hydrogen Production: Natural Gas Reforming," accessed May 28, 2018, available at: www.energy.gov.
29. U.S. Department of Energy, "Hydrogen Production: Coal Gasification," n.d., available at: www.energy.gov.
30. L. Karagiannopoulos, S. Paul, and A. Sheldrick, "Norway Races Australia to Fulfill Japan's Hydrogen Society Dream," *Reuters*, April 28, 2017, available at: www.reuters.com.
31. B. Kaye, "Australia's AGL to Host Coal-to-Liquid Hydrogen Export Trial For...," *Reuters*, April 12, 2018, available at: www.reuters.com.
32. C. Nadel, "Converting Brown Coal to Hydrogen? The Dirty Details on Another Coal Boondoggle," Environment Victoria, July 13, 2018, available at: https://environmentvictoria.org.au.

This project has been strongly criticized on both sides for poor economics and negative environmental footprint. In one year, 160 tons of coal will be used to produce 100 tons of atmospheric CO_2 and 3 tons of hydrogen, enough to fuel 33 FCVs annually. Hydrogen production from coal gasification is just as polluting as direct burning of coal for power generation unless it is coupled with CCS. This is a requirement for long-term project commercialization by the Japanese government, but so far CCS is both technologically and commercially not proven. In February 2018, the Victorian government finished seismic testing in the dried up oil wells off the coast of Golden Beach, Gippsland, which is viewed as the potential site for offshore carbon sequestration.[33]

The negotiations for this project started ten years ago, before the dramatic cost precipitation of solar PV and battery technology. Today, in Australia alone there are two projects under construction that use solar and wind power to produce hydrogen. Both reportedly produce more hydrogen at much cheaper cost than the Victorian coal gasification project.[34] To ensure public acceptance of its hydrogen strategy, Japan has to equally weigh both the long-term economic and environmental impact of the life-cycle of hydrogen production and choose the most sensible options.

Renewable power to gas (and beyond)

Power to Gas (PtG) refers to the process of creating a gas fuel from electricity. The first step of PtG is electrolysis where electricity is used to split water into oxygen and hydrogen. Hydrogen may then be converted into synthetic methane gas or ammonia. In the case of Japan's hydrogen strategy, PtG is explored as a solution for storage and load balancing of excess domestic electricity from RES.[35] In theory, PtG would act much like a battery system, where excess renewable power is transformed into hydrogen, which can be discharged in times of low power supply. Differently from electrical batteries, PtG could enable long-term stationary storage, following seasonal patterns for instance and thus support the rollout of RES.

Sector coupling: syngas and ammonia

Another appeal of PtG is the potential for decarbonization of the entire energy system through sector-coupling. Hydrogen can be injected into

33. K. Lazzaro, "World-First Coal to Hydrogen Plant Trial Launch in Victoria," ABC Gippsland, April 12, 2018, available at: www.abc.net.au.

34. C. Nadel, "Converting Brown Coal to Hydrogen? The Dirty Details on Another Coal Boondoggle."

35. METI, "The Basic Hydrogen Strategy", Agency for Natural Resources and Energy, December 26, 2017, available at: www.meti.go.jp.

natural gas pipelines in specific quantities. Hydrogen can even be further synthesized into methane through the process of methanation that combines hydrogen and CO_2 to create synthesized methane gas or syngas. Being structurally the same as natural gas, syngas is compatible with existing infrastructure and used in the same way as natural gas. Moreover, as syngas synthesis requires the input of carbon dioxide, the syngas life-cycle is in principle carbon neutral (although the combustion of syngas ultimately releases CO_2).

Alternatively, hydrogen can be further synthesized into ammonia. Both syngas and ammonia have longer storage time and can be widely applied in already established sectors. Therefore, PtG (or Power-to-X, to denote options for further conversion) offer possibilities for sector coupling, where renewables like solar, wind and hydropower may eventually power industry and heavy-duty transport, which are hard to electrify for the time being.

Production from renewable energy sources

Hydropower is the most common source of electrolysis, because solar and wind power are highly intermittent. In fact, throughout the 1900s hydroelectricity has powered electrolysis for the production of fertilizer ammonia, until natural gas became cheaper.[36]

The continued cost decline of solar and wind power, improvement of capacity load, and developments in electrolytic technology are gradually transforming large-scale renewable electrolysis into a viable option. Notably in electrolysis, the economies of scale are demonstrated in the compressors, gas holding tanks, transformers and balance plant of equipment.[37]

Domestic production of hydrogen would enhance Japan's energy security and reduce its exposure to import risks like price volatility, geopolitics and capital outflow. Local businesses can be expanded around hydrogen production, particularly in rural regions with the vast space for large renewable projects. The economic revival of depopulated rural regions is one of the most pressing social issues and a major investment priority for the Japanese government. For instance, the flagship Fukushima PtG project discussed below, is part of a series of clean energy initiatives aimed to bring economic revival to the region stricken by a tsunami and a nuclear accident in 2011.

36. R. Stevens, "Ammonia Future", June 2018.

37. C. Philibert, "Producing Ammonia and Fertilizers: New Opportunities from Renewables", Paris, France: IEA, October 2017, available at: www.iea.org.

Fukushima renewable power to gas

Construction of a large-scale demonstration project for solar-powered electrolysis with hydrogen storage will soon begin in the Fukushima Prefecture. The hydrogen electrolysis facility will have the world's largest 10 MW maximum electricity input capacity (minimum 1.5 MW) with maximum hydrogen production of 2,000 Nm^3/h (average 1,200 Nm^3/h), which is enough for at least 150 homes or 560 Fuel Cell Vehicles (FCVs). The facility will be powered predominantly by 20 MW of solar power constructed for this purpose and backed up by the grid. Annual production of hydrogen from solar power is estimated at 200t. The production capacity of the facility will be 900 t/year.[38]

Phase I testing of the system is scheduled for October 2019, and if successful, demonstration operations will commence in July 2020. The hope is to showcase the hydrogen produced in Fukushima at the 2020 Tokyo Olympics. Toshiba Corp, Tohoku Electric Power Company, and Iwatani Corp were selected by NEDO following the 2016 public tender called "Technology Development Project for Establishing Hydrogen Society/Hydrogen Energy System Technology Development".[39]

Challenges of PtG in Japan

Germany is ahead of Japan in PtG technology and there are several reasons why it will be difficult for Japan to catch up. The total length of the natural gas pipeline system in Japan is one half of the network in Germany and is much less interconnected across the nation. This means that even if hydrogen can be produced and methanized in sufficient quantities, it cannot be easily distributed. Hydrogen can also be mixed with natural gas, but the technical specifications of Japanese pipes allow for lower mixing concentrations compared to Europe, which is another limitation to the use of hydrogen in natural gas pipelines.[40]

Another challenge lies with using excess renewable power to produce hydrogen. Shibata has shown that relying on curtailed power for electrolysis renders production uneconomic even if the electricity is obtained for free.[41] Curtailment would need to be sufficiently large and frequent to meet production costs, but investment into renewable

38. Toshiba, Tohoku Electric Power Co., and Iwatani Corporation, "Fukushima New Energy Society Concept Realization Conference: Renewable Energy-Based Hydrogen Project Assessment Working Group," March 2, 2018, available at: www.meti.go.jp.

39. S. Kudou, "Japan to Build 20MW PV System to Produce Hydrogen in Fukushima," *Nikkei, Solar Power Plant Business*, March 10, 2017, available at: tech.nikkeibp.co.jp.

40. Y. Shibata, "Is Power to Gas Feasible in Japan?", Institute of Energy Economics Japan, January 2016, available at: https://eneken.ieej.or.jp.

41. Shibata.

electricity capacity that has no offtake seems highly improbable. The study thus called for the use of stable renewable power to actively produce hydrogen, a process which needs further R&D on cost reduction and scalability.

Import of PtG hydrogen: Hydropower from Norway

Hydrogen may offer the first opportunity for Japan to import electrical energy generated from RES. While renewables-based international supply chains are not addressed in the government's Strategy, a pilot project by Kawasaki Heavy Industries has already started. In 2017, Kawasaki formed a partnership with Norway's Nel Hydrogen, a maker of hydrogen plants, with the backing of Mitsubishi Corporation and Statoil (now Equinor). The companies will carry out a feasibility study for a demonstration project to produce hydrogen from hydroelectric power and eventually wind power in Norway, for delivery via liquid hydrogen tankers to Japan. In addition to renewable PtG, Norway is looking at the possibility of hydrogen production through natural gas reforming, a fossil fuel based method akin to petroleum reforming above that requires CCS.[42] The results of study are due to be completed in 2019.

Norway believes it can supply liquefied hydrogen to Japan for minimum 24 yen/Nm^3 ($ 21.7 cents/Nm^3). By comparison, hydrogen derived from Australian brown coal reportedly costs 29.8 yen/Nm^3 ($ 26.8 cents/Nm^3).[43]

Carriers: storage and transportation

Optimization of long distance transportation and long-term storage is an especially important task for Japanese research efforts given the limited potential for domestic production of carbon-free hydrogen. The cost structure of hydrogen supply chains – both international shipping and domestic distribution – is thus a critical determinant of the economic viability of hydrogen supply.

For transportation and most end-use application of hydrogen, the density of the gas needs to be increased either through compression, liquefaction, temporary adsorption to chemicals through hydrogenation, or conversion to other gases like ammonia (NH_3) and synthesized methane (syngas). Conversion not only raises the calorific value per mass of

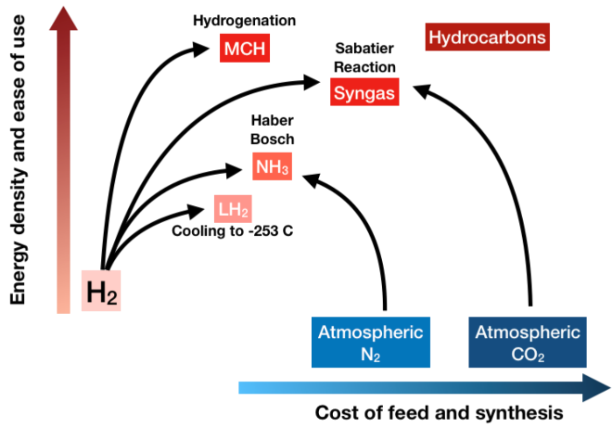
42. P. Nekså, D. Berstad and S. Størset, "Storskala Produksjon Og Distribusjon Av Hydrogen I Flytende Form", available at: http://gasskonferansen.com.

43. L. Karagiannopoulos, S. Paul and A. Sheldrick, "Norway Races Australia to Fulfill Japan's Hydrogen Society Dream", Reuters, April, 28, 2017.

hydrogen, but also raises the efficiency of long distance transportation and extends the storage time of the gas, which otherwise dissipates easily.

The type of carrier needs to be selected based on its physical properties and purpose.[44] For instance, liquefied hydrogen (LH_2) and organic hydrides like methylcyclohexane (MCH) were selected for pilot projects on long-distance shipping. LH_2 is well suited where high purity hydrogen is required, such as fuel for FCVs, but the cryogenic temperatures needed to keep hydrogen in liquid form pose numerous engineering challenges. In the case of hydride carriers, special facilities are required for the process of hydrogenation and dehydrogenation, which ultimately lower the purity of end-use hydrogen, but the mixture of hydrides is simpler to transport and store. Hydrogen can also be converted to ammonia and methane, which already have a diverse market and a well-established supply infrastructure. However, further research is needed to mitigate the toxic fumes of ammonia combustion.

Hydrogen energy carriers by density and the cost of feed and synthesis



Source: adapted from Gupta 2018.[45]

In terms of domestic distribution, supply networks for compressed and liquefied hydrogen exist for specific industrial use, but in order for hydrogen to play a role in nationwide energy transition, there is considerable need for scale up and innovation in methanation (also known as Sabatier Reaction) technology and increase in domestic pipeline networks.

44. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility.", *op. cit.*, p. 65.

45. N. Gupta, "Ammonia as a Renewable Energy Carrier. Opportunities & Challenges", June 21, 2018.

Presently, the research community is under the general consensus that individual properties of carrier technologies offer their own merits and further research and development should be continued for a more definitive comparison. Likewise, in its Strategy, the Japanese government considers each carrier by outlining their technical pros and cons, and by introducing the pilot projects that are being carried out domestically and abroad – which will also be done in the following chapters. The year 2020 is the first milestone for many of those projects to prove their economic viability and applicability.

Liquefied hydrogen

Both compression and liquefaction preserve the 99% purity of hydrogen, the highest among carriers, which makes them suitable for distribution and supply to sensitive fuel cell technologies like FCVs. Pure hydrogen can also be blended into natural gas pipeline networks, thus being compatible with existing infrastructure.

Hydrogen liquefaction (LH_2) takes place at -253°C, which condenses the volume to 1/800 of hydrogen gas.[46] The energy density is higher compared than compressed hydrogen, which allows fueling stations using LH_2 to serve more FCVs than compressed hydrogen stations. LH_2 can be transported internationally via tankers and distributed domestically with trucks.

The major downside of liquefaction is the 25-45% energy loss incurred during conversion. Maintenance and infrastructure costs for the cryogenic temperatures are high, while the daily loss of 0.5-1.0% due to boil-off, makes liquid hydrogen less efficient compared to other carriers for long-term storage.[47] In terms of regulatory hurdles for developers, the classification of liquefied hydrogen as a high-pressure industrial gas increases the compliance costs, including large space around fueling stations and high-grade material for facilities. Together with NEDO, the government is currently reviewing possibilities for deregulation that would remain safe and technically feasible.

Within the next couple of years, large-scale initiatives on transportation, loading, storage and import facilities for liquefied hydrogen are planned throughout the country.

46. METI, "The Basic Hydrogen Strategy."

47. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility.", *op. cit.*, p. 5; APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region", Asia Pacific Energy Research Centre, March 2018, p. 9.

A pilot project is being developed by Kawasaki Heavy Industries and Shell to supply liquid hydrogen produced from brown coal in Australia (see page 26). They aim to conclude preliminary demonstration by mid-2020 with the aim for commercial operation by 2030. Japan has so far backed the Australian initiative with 7.4 billion yen in 2016 and 2017 ($67.4 million).[48]

Hydrides – Methylcyclohexane (MCH)

Hydrogen can be transported and stored by hydrogenating (in mixing with hydrogen) organic aromatic compounds or metal hydrides, known as organic hydrides and metal hydrides respectively. For most end-use applications, the additional process of dehydrogenation (detachment) is required to disassociate hydrogen from the hydride. The advantage of hydrides is their reusability through repeated hydrogenation and dehydrogenation, and they are compatible with existing transportation methods as they can be handled at normal temperature and pressure, making hydrides also suitable for long-term storage. On the other hand, the disadvantages include the additional heat input required for dehydrogenation and the time required to carry out both reactions.[49]

When compressed with hydrides, 1/500 volume compression of hydrogen gas can be achieved. The hydride shipping and distribution infrastructure is to some extent established.[50]

SPERA Hydrogen (MCH) with Brunei

In July 2017, four major Japanese infrastructure and trading companies, Chiyoda Corporation, Mitsui Co., Mitsubishi Corporation, and Nippon Yusen, with support from NEDO, announced their partnership on the "Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD)", the world's first demonstration project on the international transport of hydrogen from Brunei to Japan.[51]

Hydrogen produced via steam reforming of processed gas, a by-product of a natural gas liquefaction plant in Brunei, will be transported

48. B. Kaye, "Australia's AGL to Host Coal-to-Liquid Hydrogen Export Trial for Japan's Kawasaki Heavy", April 12, 2018, Reuters, available at: www.reuters.com.

49. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility", *op. cit.*"; APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".

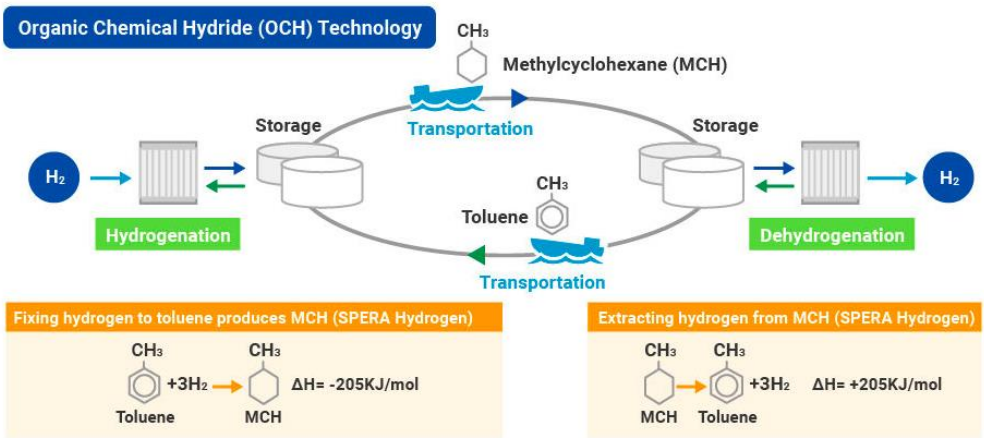
50. METI, "The Basic Hydrogen Strategy".

51. Mitsui & Co., "The World's First Global Hydrogen Supply Chain Demonstration Project," Press Release, July 27, 2017, available at: www.mitsui.com.

using Chiyoda's SPERA Hydrogen system shown below.[52] In the SPERA process, hydrogen is hydrogenated with toluene to produce liquid methylcylohexane (MCH) for easy storage and transportation at standard temperature and pressure. Once shipped to Japan, MCH is dehydrogenated, or broken down into the original toluene and hydrogen. Hydrogen will be used as fuel in another demonstration project for thermal power generation, while toluene is returned to Brunei to repeat the hydrogenation and transportation cycle. At the moment, MCH/toluene system is considered the most viable organic hydride carrier due to safety and availability of chemicals.[53]

The pilot project drew an investment of $ 100 million.[54] Construction begun in August 2017 and scheduled for completion by December 2019. The project will then run for a full year between January and December 2020, transporting 210 tons of hydrogen, in order to determine the commercial viability of the supply chain.[55]

SPERA Hydrogen System (MCH/toluene)



Source: Courtesy of Chiyoda Corporation.

52. Chiyoda Corporation, "What Is 'SPERA HYDROGEN' System?", accessed June 28, 2018, available at: www.chiyodacorp.com.
53. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".
54. A. Bandial, "Sg Liang Plant to Export Hydrogen to Japan by 2020", *The Scoop*, April 22, 2018, available at: https://thescoop.co.
55. Mitsui & Co., "The World's First Global Hydrogen Supply Chain Demonstration Project".

Chiyoda MCH fueling stations

By 2020, Chiyoda Corporation also plans to develop filling stations for FCVs that will use MCH. Nikkei Asian Review reported that the *"Processing capacity per unit of such equipment will be 30 cu. meters per hour. Chiyoda hopes to combine multiple units to process 300 cu. meters in the future. Filling a fuel cell vehicle requires 50 cu. meters of hydrogen"*. And Chiyoda announced its intention to *"spend 200 million yen to 300 million yen to install test equipment at a Yokohama R&D site"* in 2017.[56]

Ammonia

Ammonia is synthesized via the Haber Bosch process that catalytically combines hydrogen and air, made of 78% dinitrogen. Almost half of global hydrogen gas is used in the production of ammonia, a widely used chemical component of fertilizers, refrigerants and cleansers. Long-term storage and transportation of ammonia, both by pipeline and shipping, are much more convenient than hydrogen.[57] Therefore, given the technological maturity of the ammonia supply network and wide range of end-use sectors, ammonia has a good chance of catalyzing the onset of the hydrogen economy.

In 2014 energy carriers for hydrogen were selected as one of ten research themes by the Cross-ministerial Strategic Innovation Promotion Program (SIP) led by Japan's Council for Science, Technology and Innovation of the Cabinet Office. Six projects related to ammonia are being undertaken – ammonia as carrier for solar power-generated hydrogen; catalyst for ammonia synthesis; ammonia supply system for hydrogen fueling stations; ammonia fuel cells; and system for ammonia combustion.[58] Started in 2016, feasibility studies and demonstration projects are scheduled to take place in 2018.[59]

Production of carbon free ammonia

Currently, 95% of global ammonia is produced from fossil fuel hydrogen, and the rest is produced from electrolysis. The ammonia industry emits nearly 420 tons of CO_2 annually, over 1% of global energy-related CO_2

56. *Nikkei Asian Review*, "IHI, Chiyoda Developing Low-Cost Hydrogen Tech," March 4, 2017, available at: https://asia.nikkei.com.

57. C. Philibert, "Producing Ammonia and Fertilizers: New Opportunities from Renewables", IEA, updated October 1, 2017

58. SIP, "Cross-Ministerial Strategy Promotion Program (SIP) Energy Carriers."

59. Cross-ministerial Strategic Innovation Promotion Program, "Energy Carriers: Leading the World in Hydrogen Energy Utilization; Creating a Low-Carbon, Hydrogen-Based Society", accessed May 28, 2018, available at: www8.cao.go.jp.

emissions.[60] 70% of those emissions are said to be CCS ready.[61] Therefore, integrated ammonia plants with onsite CCS hydrogen supply stand to benefit from significant economies of scale.

However, as costs for solar and wind technologies are dropping, large-scale production of ammonia from renewable energy electrolysis is becoming competitive with ammonia production from natural gas. In addition to hydropower, regions with abundant solar and wind resources, where load factors can reach up to 3000 load hours for solar and up to 5000 load hours for wind power, can secure the stable power supply needed for economical hydrogen production.[62] Ammonia can therefore internationally transport carbon-free hydrogen from countries with abundant renewable resources to Japan.

Supply chain with Saudi Arabia

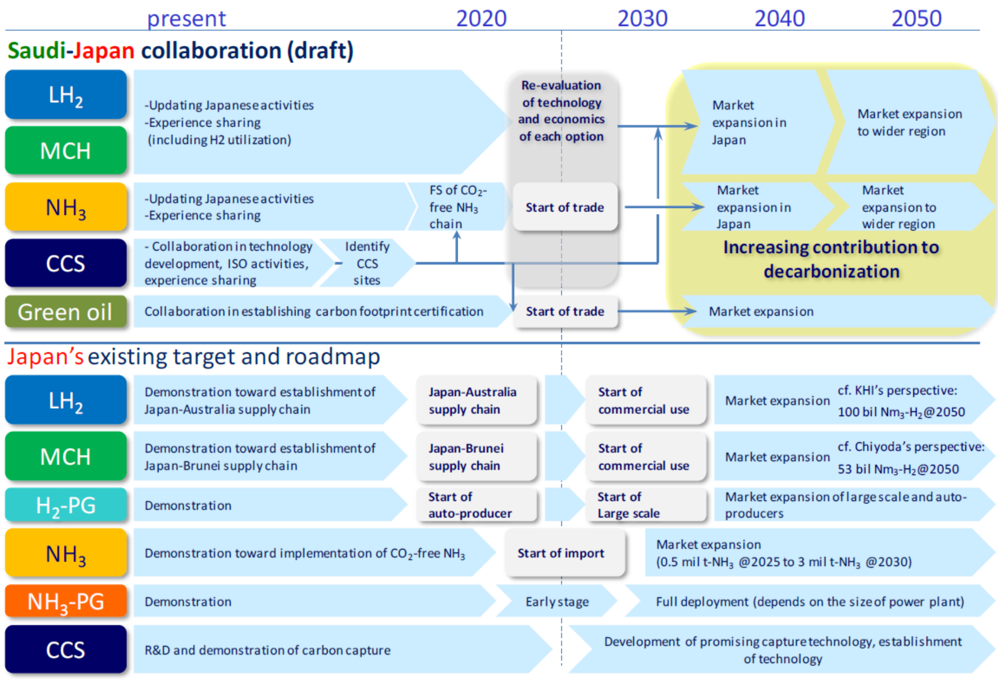
A delegation of Japanese companies and public officials, together with Saudi Arabian private and public counterparts are designing a joint demonstration project to produce and transport Saudi hydrogen to Japan. Two bilateral symposiums have been held in Tokyo (September 2017) and Riyadh (December 2017) to discuss potential areas of collaboration and challenges. Further shaping of the framework of cooperation, including financing schemes and technology sharing is expected.

60. Cédric Philibert, "Producing Ammonia and Fertilizers: New Opportunities from Renewables." IEA, Updated 01 October 2017.

61. Stevens, "Ammonia Future."

62. Cédric Philibert, "Producing Ammonia and Fertilizers: New Opportunities from Renewables." IEA, Updated 01 October 2017.

Roadmap for Japan-Saudi CO_2-free hydrogen/ammonia supply chain



Source: METI.

Note: "PG" refers to power generation.

After examining various energy carriers of hydrogen during the first symposium, Saudi Arabia expressed interest in ammonia given the maturity of production, transportation and use of this technology.[63] Ammonia demonstrates cost advantage over other hydrogen carriers because it can be combusted directly in power generation without regasification or dehydrogenation as required by alternatives. In order to achieve cost parity with LNG/coal fired power in Japan, the cost of ammonia supply has to be \$ 350/t-NH_3. It is already possible to source ammonia for \$ 250-350 /t-NH_3, but this ammonia is not CO_2-free. If the cost of CCS can be reduced to \$50/t-CO_2, carbon-free ammonia can be achieved at \$300-350/t-NH_3, well within the target for cost competitive power generation.[64]

Saudi Arabia suggested that private sectors in both countries form consortiums to explore CCS and EOR technologies. In addition to pursuing

63. METI and IEEJ, "2017 Research Report on the Possibility of Implementation of the Joint Credit Mechanism in Infrastructure. Report ahead of the Master Plan on Low Carbon Energy System Development in Saudi Arabia", 2018 March 15, p. 74, available at: www.meti.go.jp.
64. *Ibid.*, p. 63.

an in-depth feasibility study of this pilot on carbon-free ammonia, the parties agreed to make a wider assessment of the hydrogen economy, the carbon footprint certification scheme, and their links to climate change.

The Saudi delegation is led by Saudi Aramco, KAPSARC, while the Japanese side was led by officials from METI, 11 Japanese companies and the Institute of Energy Economics, Japan.

Saudi Arabia is Japan's biggest supplier of oil (33% of imports) and Japan has been one of the largest customers for Saudi Arabia. Saudi Arabia is also the ninth largest producer of ammonia.

This initiative emerges from a colossal bilateral effort, the *Joint Group for Saudi-Japan Vision 2030* established by Prime Minister Shinzo Abe and Deputy Crown Prince Mohammad bin Salman in September 2016. The Saudi Japan Vision 2030 consists of 3 pillars, 9 themes, 46 government projects by 44 ministries and institutions. Energy falls under one of the nine themes. It is led by the Ministry of Energy, Industry and Mineral Resources (MEIMR) on the Saudi side and METI on the Japanese side.[65]

Use: Ammonia co-fired coal power by Kansai Electric

By 2020, Kansai Electric Power and five other utilities are joining efforts to commercialize a technology for co-firing ammonia with coal in power generation, which could reduce CO_2 emissions by at least 20%. According to Nikkei Asian Review which reported on the story, *"adopting this technology at aging plants would bring emissions in line with those of newer facilities, reducing the need for new investment. If 70 plants switch to a coal-ammonia mix, CO_2 emissions would fall by an estimated 40 million tons a year, equivalent to about 3% of Japan's annual total"*.[66]

High electricity prices in the Japanese market make the project cost competitive. The cost of retrofitting coal plants with ammonia burning technology is estimated to increase the cost by 30% or 7 yen/kWh ($0.063 cents/kWh). This would still be cheaper than nuclear power which costs about 10 yen/kWh ($0.09 cents/kWh) and LNG power 14 yen/kWh ($0.126 cents/kWh).[67]

65. S. Crolius, "Japan, Saudi Arabia Explore Trade in Hydrogen, Ammonia", *Ammonia Energy* (blog), February 15, 2018, available at: www.ammoniaenergy.org.
66. *Nikkei Asian Review*, "Japanese Utilities Team on CO_2-Reducing Tech for Coal Plants", March 2, 2017, available at: asia.nikkei.com.
67. *Ibid.*

Use: Ammonia co-fired natural gas power by IHI

IHI Corporation aims to bring online an ammonia co-fired natural gas power plant by 2020. The system will directly burn ammonia with 20% methane gas, reducing the overall carbon dioxide emissions of the system by 20%. IHI spent roughly 1 billion yen ($9.1 million) in 2017 on a gas turbine, ammonia tank and other equipment at its research and development site in Yokohama. Trial operations are scheduled for 2018.[68]

Initial success in reducing NOx emissions

The challenge of introducing ammonia to power generation lies in curbing the highly toxic nitrogen oxide (NOx) emissions that are generated during the combustion of ammonia.

Chugoku Electric Power and the Japan Science and Technology Agency (JST) have successfully tested and patented the co-firing of ammonia with coal at Chugoku's Mizushima Power Plant Unit 2 in Okayama Prefecture.[69] Specifically, the experiment focused on whether all ammonia in the boiler was fully combusted, and to confirm that it contributed to power generation without significant NOx and other emissions. The facility was initially scheduled to operate at 155 MW with ammonia blended at 0.6%, but due to weather conditions, the output was reduced to 120 MW with 0.8% ammonia concentration (equivalent to 1 MW power). It is believed that concentrations can be increased further. The experiment showed how NOx emissions can be reduced under certain conditions, so the team has obtained a patent on the finding. The experiment was conducted between July 3 and July 9, 2017, as part of the "Ammonia Carrier" focus area under the Strategic Innovation Program (SIP).

If successfully brought to maturity, the ammonia co-firing technology can allow existing coal and natural gas fleets to be retrofitted at a reasonable cost while reducing carbon dioxide emissions in the fossil power sector. It is easier to secure investment for *"minor capital expenditures and take a small bump in operating costs, but it is a far harder choice to abandon those assets entirely and replace them with carbon-free technologies"*.[70]

68. *Nikkei Asian Review*, "IHI, Chiyoda Developing Low-Cost Hydrogen Tech".
69. "Result of Implementation of Ammonia Mixed Fire Test at Mizushima Power Station Unit 2 and Patent Application," Press Release, Energia the Chugoku Electric Power Co. Inc., September 8, 2017, available at: www.energia.co.jp.
70. T. Brown, "Industrial Demonstrations of Ammonia Fuel in Japan", Ammonia Industry, March 6, 2017, available at: https://ammoniaindustry.com.

Compressed hydrogen

Hydrogen is compressed at standard temperatures, filled in cylinders and transported or stored. This technology is in commercial use around the world for use in industries and FCVs. The energy loss of compressing hydrogen is 5-15% depending on pressure differentials.[71] While the technology is mature and reliable, the premium grade alloys required to hold the high pressure of storage tanks raise the costs of infrastructure. Depending on the pressure, the energy density per volume may be lower than other carrier technologies.[72]

Japan has recently raised its compression standards for fueling stations closer in line with the international practice. Previously, hydrogen fueling stations stored hydrogen at 35 MPa or 70 MPa, but internationally, the storage permit is 87.5 MPa for stations that fill FCVs at 70 MPa. Japan followed suit and, since 2016, facilities with such supply capacity have been permitted higher storage pressure of 82 MPa.[73]

For large scale dissemination of FCVs and fueling stations, it is necessary to reduce the cost of high pressure compressors and high pressure storage containers. Efforts are needed to reduce the weight of containers and their resiliency to high pressure. In addition to the aforementioned pressure deregulation, other regulatory steps are undertaken through the High-Pressure Gas Safety Act and the Fire Service Act to enable transport and storage of hydrogen in various forms.[74]

Domestic: pipeline transportation and trucks

The three options for on the ground distribution are high-pressure cylinders, tube trailers, and pipelines. The first two require high-pressure compression. The third is the most efficient option for delivering hydrogen gas, through a network of underground pipelines similar to those used for natural gas. Pipeline delivery of hydrogen gas has been used for decades in industrial parks both in Japan and abroad. Germany has been operating a 210 km hydrogen pipeline since 1939, while the world's longest hydrogen

71. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility", *op. cit.*
72. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".
73. METI, "Progress on Regulation etc of Fuel Cell Vehicles/Hydrogen Stations", August 2, 2017, available at: www.meti.go.jp.
74. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".

pipeline is 400 km long and is operated by Air Liquide between France and Belgium.[75]

Pipeline hydrogen delivery in Japan is explored in tandem with methanation PtG technologies where hydrogen is converted to synthetic methane for distribution or direct application. Due to the mountainous topography, the natural gas pipeline system in Japan is limited (one half of the network in Germany) and is much less interconnected across the nation. This means that even if hydrogen can be produced and methanized in sufficient quantities, it cannot be easily distributed via pipelines. Hydrogen can also be mixed with natural gas, but the technical specifications of Japanese pipes allow for lower mixing concentrations compared to European pipes.

The key to financing a pipeline project is to ensure a sufficient number of suppliers and users who can share the capital costs. As such, sites with large, concentrated demand for hydrogen are best suited for new projects.

Applications: hydrogen end-use and fuel cells

This chapter will explore the targets, demonstration projects and progress of end-use applications of hydrogen and fuel cells in Japan.

Highest market maturity is currently displayed by the residential CHP and mobility sectors. Residential CHPs have been on the market since 2009 and in the next couple years their consumption subsidies will be phased out. Subsidies are also driving FCVs and fuel cell buses onto roads, but sparse fueling infrastructure, inhibited by tight regulations and high construction costs, limits the spread of fuel cell transport. These are areas where Japan now demonstrates technology leadership and they are high profile segments of the hydrogen economy that could win over public acceptance in the near term, but they are not enough to realize the full potential of the hydrogen economy for Japan.

Power generation can be the single largest driver of new hydrogen capacity in the upcoming decades, accounting for up to 64% of annual hydrogen consumption.[76] At present the technology for large-scale power generation using hydrogen is still under research. The government has only set targets for the price reduction of hydrogen fuel to 17 cents/kWh in

75. S. Dunn, "Hydrogen Futures: Toward a More Sustainable Energy System," *International Journal of Hydrogen Energy*, No. 22, 2002, pp. 235–264.
76. AIST and IEEJ, "Renewable Energy Storage and Transportation Technology Development; 2013 Scenario Research on Total System Installation".

2030, and 12 cents/kWh in 2050 which would make it cost competitive with natural gas fired generation.

The chart below appeared in a 2014 report on the technologically feasible replacement of hydrogen in residential, commercial, transport, industrial and power sectors in Japan by 2050. By then, hydrogen could account for 28% of total primary energy supply. It must be stressed that these numbers do not account for the economic and policy factors that may influence market trajectory, while the technology outlook was extrapolated from the baseline at 2010. In other words, various end-use applications need to be backed up by a robust policy-framework and financial support, whilst achieving technical breakthroughs, in order to reach these levels of market penetration. Current targets under the Hydrogen Roadmap and Strategy are less ambitious.

Technologically feasible hydrogen uptake in Japan, 2050

	Residential	Commercial	Mobility	Industry	Power Generation	Total
Technologically feasible supply in billion Nm^3-H_2	34	43	15	65	284	**441**
Percent share of H_2 uptake by sector	8%	10%	4%	15%	64%	**100%**
Share of total primary energy supply (TPES)	TPES in 2050 (in billion Nm^3-H_2 equivalent)					**1,556**
	% Share of Hydrogen					**28%**

Source: IEEJ/AIST 2014.

Japan's Targets for the Hydrogen Economy (cost in $)

	Present		2020 Target		2030 Target		Long term (After 2050)	Reference Data
	Scale	Cost	Scale	Cost	Scale	Cost		
SUPPLY								
	Hydrogen derived from fossil fuels without CCS (industrial by-product, natural gas reforming)				Develop international hydrogen supply chains and domestic production from renewables		Zero carbon H2 with CCS and renewables	
	200 ton/year	~10 USD/kg (Price at fueling stations)	4,000 ton	N.A.	300,000 ton	3 USD/kg	5-10 million ton 2 USD/kg	Annual LNG import 85 million ton
END-USE								
Power Generation	Under R&D		N.A.	N.A.	N.A.	Generation cost 17 cents/kWh	12 cents/kWh	LNG fired generation 12 cents/kWh Installed fossil fuel power generation capacity 132 GW
Mobility								
Fueling Stations	100	Construction cost: 4.5-5.4 million Annual operating cost: 450,000	160	Competitive without subsidies in second half 2020	900	N.A.	Replacing gasoline stations	31,500 gasoline stations Construction cost: 630,000-720,000
Fuel Cell Vehicles	2,000	Toyota Mirai: 66,000	40,000	Competitive without subsidies in second half 2020	800,000	N.A.	Replacing gasoline cars	62 million Passenger cars
FC Buses	~2 buses	~900,000	100	N.A.	1,200	N.A	Large FC vehicles	
Forklifts	40 forklifts	N.A.	500		10,000			
Home Fuel Cells	220,000	Rough cost estimate of Enefarm ~11,000	N.A.	Competitive in early 2020	5.3 million	N.A.	Replacing conventional residential energy systems	53 million households in Japan Cost of conventional heat and power systems: 5,400-6,300

Source: Adapted from METI Hydrogen Roadmap 2014, Hydrogen Strategy 2017.

Mobility

Fuel Cell Vehicles (FCV)

Toyota and Honda account for the nearly 2,500 commercial passenger FCVs on the road in Japan, with the largest share covered by Toyota.

In terms of mechanism, FCVs are similar to gasoline-electric hybrid cars with gasoline engines that power an electric motor. The difference lies in the fuel cell stack that replaces the internal combustion engine. An FCV runs on hydrogen fuel which is bought at hydrogen fueling stations much like gasoline is bought at gasoline stations. Being emissions-free at the tailpipe, FCVs are often compared to battery electric vehicles (BEVs) despite notable differences that make them complimentary in the fleet of cleaner alternatives to gasoline cars.

Quick refuel and longer range compared to BEVs

FCVs offer double driving range and significantly reduced filling time compared to BEVs. With high pressures used in the tanks of Toyota's Mirai, hydrogen has an energy density of about 1,500 Wh/l, about three times of today's batteries. The technical complexity of FCVs renders them more expensive, but there is scope for automakers to improve their performance in the future. Extending the range on FCVs remains likely by increasing the pressure at which hydrogen is stored inside the tank.[77] Thus, with sufficient R&D, their range can be extended closer to that of conventional vehicles without compromising usability.

Toyota launched the Mirai (meaning "future") model in December 2014. According to its brochure, Mirai's range is 650 km, which dips to 500 km under real driving conditions as estimated by the American EPA.[78] Honda's Clarity, launched in March 2016, has the optimal range of 750 km, or 590 km EPA range.

As a point of comparison with a BEV, the 2018 model of Japan's most common Nissan Leaf, takes 40 to 60 minutes to fill up 80% of the battery at fast charging stations, or 7.5 hours plugged in at home to reach the full "brochure range" of 270 km.[79] Even the Tesla Model S 100 kWh battery boasts a lower range of 632 km and takes at least 5 hours to charge. With near instant fueling time of 3 minutes and longer range, compared to BEVs, FCVs offer the driving experience closer to that of conventional vehicles. As a bonus, their fuel cells can act as off-grid power generators for homes and hospitals during blackouts.

Price and subsidies

The retail price of the Mirai is 7.24 million yen ($66,000). For private users, on top of the national subsidy of 2.02 million yen (offered by METI), each prefecture offers a subsidy of up to half of the national subsidy (the amount and the quota of subsidies vary according to provincial budgets).[80] The Tokyo government offers the full 1.01 million yen for all vehicles. Thus, for a Tokyoite a standard model with a navigation system would cost roughly 4.5 million yen ($41,000). Additionally, there is a five-year exemption on the annual vehicle tax of 13,000 yen. In terms of fuel cost, a

77. K. Inagaki and R. Harding, "Japan Gambles on Toyota's Hydrogen Powered Car", *Financial Times*, March 28, 2017, available at: www.ft.com.

78. EPA, "Compare Fuel Cell Vehicles," fueleconomy.gov, accessed May 19, 2018, available at: www.fueleconomy.gov.

79. Nissan, "Range & Charging | New Nissan LEAF Electric Car," Nissan, accessed May 19, 2018, available at: www.nissan.co.uk.

80. METI, "8th Hydrogen and Fuel Cell Strategy Council Meeting: Progress Status on the Strategic Roadmap", March 10, 2017, available at: www.meti.go.jp.

full tank on the Mirai is 5,000 ~ 6,000 yen ($46 ~ 55) per charge, a reasonable price in Japan where gasoline is on average 140 yen/L.

There are approximately 208 Honda Clarity's in Japan. The base price is 7.66 million yen ($69,000).[81] At the moment, the Clarity is available only for corporate lease for roughly 100,000 yen ($900) per month. Vehicles leased for minimum 4 years are eligible for the same national and prefectural rebates calculated on a monthly basis.

For taxi operators, the subsidies are slightly more generous. The national subsidy is 2.23 ~ 2.36 million yen (one third the cost of the car, offered by Ministry of Land, Infrastructure, Transport and Tourism, MLIT), and local subsidies between 1.11 ~ 1.18 million yen, bringing the unit cost to 3.36 ~ 3.55 million yen ($30,000 ~ 32,000). There are about 25 FCV taxis nationwide.[82]

Subsidies bring down the cost of FCVs to a competitive range, as seen in their steady, albeit slow uptake in Japan. Initial purchasers of the Mirai were mostly public bodies and corporations, but today about 40% of owners are private customers. Nevertheless, the current fleet of 2,500 FCVs has a long way to reach the 7 million BEVs, plug-in-hybrid vehicles (PHVs) and hybrid electric vehicles (HEVs) that are on the road, and they are a drop in the ocean of the 62 million passenger cars nationwide.[83]

Roadblocks

The biggest hurdle to buying a hydrogen vehicle is the lack of fueling infrastructure. Because charging outlets for BEVs can be installed anywhere with access to the power grid, say in homes and parking lots, BEV chargers are being deployed at a faster rate and are becoming readily available. On the other hand, the network of hydrogen fueling stations cannot be developed as quickly due to high costs imposed by regulatory and technical constraints.

Fueling stations

The dissemination of FCVs crucially depends on the number of accessible hydrogen fueling stations, which as of 2018 amounted to 100

81. Honda, "Clarity Fuel Cell," n.d., available at: www.honda.co.jp.
82. MoE and MLIT, "Supporting Policies for Fuel Cell Vehicles and Buses," April 16, 2018, available at: www.meti.go.jp.
83. NeV, "Statistical Data on Ownership of EVs, PHVs, FCVs and HEVs", Next-Generation Vehicle Promotion Center, accessed May 20, 2018, available at: www.cev-pc.or.jp; METI, "METI Has Compiled a Strategic Road Map for Hydrogen and Fuel Cells".

throughout Japan – more than double the 39 stations in the US and 45 in Germany.[84]

High costs and too few customers

The difference between Japan and other countries lies in the cripplingly high costs of construction and operation. A hydrogen station in Japan is reported to cost two or three times the price in Europe due to stricter regulations.[85] The costs amount to 500-600 million yen ($4.5 – 5.4 million) for construction and 50 million yen ($450,000) for annual operations. By contrast, the capital cost for a gasoline stand is 70-80 million yen (630,000 - $ 720,000), and even lower for fast charging EV stations at 3.3-16.5 million yen ($30,000 – 148,500).[86]

Capital subsidies and operational subsidies are calculated based on the characteristics of the station ranging 2/3 and 1/2 of the cost. Determining characteristics include size (medium: filling capacity over 300 Nm^3/h, or small: between 50-300 Nm^3/h, also whether it services buses), stationary or portable, "packaged" (where key equipment is bundled inside a facility) or regular, as well as if hydrogen is produced on-site and off-site.[87] As an example, the most common type is a mid-size stationary off-site station, whose capital cost is 350 million yen. The subsidy is 1/2 of the cost, bringing the capital costs down to 280 million yen ($2.5 million) for the developer.

Even with the subsidies, companies struggle to justify the investment into hydrogen infrastructure given the low number of FCVs on the road. For minimum profitability, each fueling station needs to service about 900 vehicles a year, a target that will hopefully be reached by 2030 as set out by the Hydrogen Strategy. If the government allows the subsidy program to expire in 2020, developers may have to run money-losing stations for about a decade before there is a self-sustaining number of FCVs.[88] So although FCVs depend on the number of fueling stations, fueling stations are not built because of high costs and uncertainty about the number of customers.

84. METI, "One-Hundred Hydrogen Stations to Open as a World-Leading Initiative"; Voelcker, "Germany's Hydrogen Stations Exceed US; California Beats Japan on Density".

85. R. Harding, "Japan Is Betting Future Cars Will Use Hydrogen Fuel Cells", *Financial Times*, October 23, 2017, available at: www.ft.com.

86. NeV and Mitsubishi UFJ Research & Consulting, "Fast Charging Stations for Electric Vehicles Estimation Document", 2015, available at: www.cev-pc.or.jp.

87. NeV, "2018 Outline of Construction Subsidies for Hydrogen Fueling Stations for FCVs", available at: www.cev-pc.or.jp.

88. R. Harding, "Japan Is Betting Future Cars Will Use Hydrogen Fuel Cells", *op. cit*.

Business consortium to pool funds

To address the financing problem, in February 2018, a consortium of 11 Japanese automakers, infrastructure developers and investors established the joint-venture, Japan H_2 Mobility (JHyM). It is the first of its kind in that it aims to pool private investment and government grants to finance the construction of hydrogen stations, which could achieve 10-20% cost reduction.[89] Nikkei newspaper reports that half of the cost will be covered by the government.[90] 80 stations are expected to be built in the next four years under this scheme. JHyM also aims to standardize equipment, optimize driver usability, and support the deregulation of industry standards.[91]

Regulatory roadblocks

Hydrogen is tightly regulated as an industrial gas, with standards intended for large-scale chemical plants with high explosive risks. The same standards are currently applied to fueling stations. As one example, fueling stations are required to be surrounded by much more space than a gasoline station, a considerable expense for cities with high property costs like Tokyo. In reality, it takes a lot to pool hydrogen because it dissipates quickly into the atmosphere. The stations are also equipped with sensors that immediately shut down the pump if any leaks are detected. These and other safety measures are currently reviewed by the government, which has been passing reforms on the fueling stations since June 2016.

By law, cars must be fueled by specialists licensed in handling high-pressure gases. Requirements for skilled manpower limit the working hours of the fueling stations, many of which close for weekends or in the afternoon before car users are off from work. Japan could follow in the footsteps of the U.S. and legalize self-service pumps, given that the process of filling a car is highly automated. That being said, the complexity of high pressure, cryogenic storage of hydrogen will continue to have trained personnel onsite to handle repairs and maintenance that are still frequently required.

89. H. Greimel, "Japan Group's Goal: 'Hydrogen Society'", *Automotive News*, March 19, 2018, available at: www.autonews.com.

90. S. Ibusuki, "Fuel Cell Cars in for a Lift as Japan Looks to Expand Infrastructure," *Nikkei Asian Review*, March 6, 2018, available at: https://asia.nikkei.com.

91. JHyM, "Accelerating the Construction of Hydrogen Stations to Promote Widespread Use of Fuel Cell Vehicles", March 5, 2018, available at: www.jhym.co.jp.

Fuel cell buses

In March 2018, Toyota began to sell its first fuel cell bus, the Sora, in Japan. The model is the first hydrogen fuel cell bus to receive vehicle type certification in the country. Toyota expects to introduce over 100 FC buses mainly within Tokyo ahead of the 2020 Olympics. The Sora can carry 79 passengers and run for 200 km on a full 600 L hydrogen tank. Two 114 kW fuel cell stacks are mounted on the roof, allowing the floor to be set lower for extra accessibility. The maximum external power supply capacity is 9 kW/235 kWh that allows the bus to act as a portable power generator.[92] Only a few units are currently leased to bus operators in Tokyo.[93]

The bus costs around 105 million yen ($945,000). The Ministry of Environment (MoE) offers a subsidy of 35 million yen (one third of the price), additionally local governments are expected to offer subsidies of 35 million ~ 50 million yen (tentative), which should eventually reduce the cost for operators to 20 million ~ 35 million yen ($180,000 ~ 315,000).[94]

Heavy-duty trucks

As for heavy-duty trucks, Toyota is testing its prototype Class 8 (36 ton capacity) "Alpha Truck" at its port facility in Los Angeles since October 2017. It combines two fuel cell components from the Mirai and a new motor designed specifically for the Alpha. So far, the truck reportedly outperforms its diesel counterparts with faster acceleration and off the line delivery.[95]

Later in June 2018, Toyota and the convenience store chain Seven-Eleven, unveiled Japan's first small fuel-cell truck with load capacity of 3 tons. The companies have joined forces to test the usability of fuel cell trucks in the store's operations, with hopes for eventual scale-up. Two trucks will be initially introduced in the spring of 2019 in Tokyo's Ota Ward. These trucks can cover 200 km per day.[96] The companies will also collaborate on implementing fuel cell stacks to generate power for refrigeration in the stores.

92. Toyota, "Toyota Launches Production Model 'Sora' FC Bus", March 28, 2018, available at: newsroom.toyota.co.jp.
93. S. Yamamoto, "100 million Yen Toyota Fuel Cell Bus, Sora Test Drive. Surprising Smoothness and Quietness," April 21, 2018, available at: https://clicccar.com.
94. MoE and MLIT, "Supporting Policies for Fuel Cell Vehicles and Buses," April 16, 2018, available at: www.meti.go.jp.
95. K. Field, "Toyota Explores the Potential of a Hydrogen Fuel Cell Powered Class 8 Truck," Clean Technica, April 27, 2018, available at: https://cleantechnica.com.
96. The Asahi Shimbun, "Seven-Eleven, Toyota Team up to Spread Use of Fuel Cell Vehicles," July 2, 2018, available at: www.asahi.com.

Fuel cell trucks are well suited for businesses with predetermined routes where refueling infrastructure can be set up – like from a production facility to a warehouse or an airport. Distance matters too. While higher in cost, fuel cell trucks can run longer distances than battery electric trucks. By 2030, the ICCT estimates the overhead cost of electric heavy-duty vehicles could be 25-30% less and hydrogen fuel cell at least 5-10% less than diesel vehicles to own, operate and fuel.[97]

Heavy-duty transport is of primary importance for decarbonization and it is vied by automakers offering different low carbon solutions. While heavy-duty freight represents only one-tenth of all vehicles, it accounts for 40% of carbon emissions in transport and its activity continues to increase.[98] As we look at the menu of emerging technologies – natural gas, battery electric, and fuel cell – there is a host of issues to consider from business and long-term policy planning perspectives.

The debate must be centered on the regional energy mix as that determines the life-cycle footprint of the technology. The battery electric truck is a carbon friendly solution where renewables and/or nuclear power make up a substantive share of the grid, but otherwise natural gas trucks may be the cheaper and less carbon intensive option. The California Air Resources Board has certified Cummins Westport natural gas engines as 'near zero'. This means that when powered by natural gas, or natural gas sourced from landfills or other biological means, the engines produce life cycle emissions equivalent to a 100% battery electric engine powered by a natural gas power plant.[99] Similar evaluations are needed in Japan to consider life cycle emissions of powering a truck from the grid (large surge in power demand will call for resilience measures and extra generation capacity), natural gas (although the potential for landfill biogas production in Japan is low), and the long-term potential for decarbonization of hydrogen fuel. While Japan awaits the commercialization of carbon-free hydrogen in the upcoming decades, FCVs and FC trucks will likely have a higher carbon footprint per kilowatt hour and kilometer traveled.[100]

97. M. Moultak, N. Lutsey, and D. Hall, "Transitioning to Zero-Emission Heavy-Duty Freight Vehicles", The International Council on Clean Transportation, September 29, 2017, available at: www.theicct.org.
98. *Ibid.*
99. M. Chatsko, "The Rise of the Electric (or Hydrogen Fuel Cell) Semi-Truck? Not So Fast", The Motley Fool, May 29, 2018, available at: www.fool.com.
100. Zach, "Hydrogen Fuel Cell Cars - #Fail, in Depth", EVObsession, June 28, 2015, available at: https://evobsession.com.

Fuel cell transport can also serve as portable power generators for emergency blackouts.[101] The graphic below illustrates power supply capacity of fuel cell vehicles and buses for disaster response facilities in Japan – hospitals, convenience stores and schools. Convenience stores are important supply bases for food and other essentials since they are open 24 hours and ubiquitous nationwide, even in remote regions.

FCV and Buses as Power Generators in Disaster Response

Facility	Power consumption in emergency operation	**FC Buses** needed per day for emergency operation (455 kWh/unit)	**FCVs** needed per day for emergency operation (120 kWh/unit)	**EVs** needed per day for emergency operation (24 kWh/unit)
Hospital	963 kWh/day at 10% capacity; emergency equipment only	2 buses	8 FCVs	40 EVs
Convenience Store	235 kWh/day at 47% capacity; refrigeration only	0.5 buses	2 FCVs	10 EVs
Evacuation Shelter (School)	100 kWh/day; Lighting, water supply for 200 people	0.22 buses	0.83 FCVs	4 EVs

Source: Adapted from METI.[102]

101. JapanGov, "Tokyo Aims to Realize 'Hydrogen Society' by 2020", 2016, available at: www.japan.go.jp.
102.Meti, "About Fuel Cell Vehicles", available at: www.meti.go.jp.

Box 1: Japanese Automakers in the global competition for FCVs

Two out of three automakers with commercialized FCVs are Japanese (the third is South Korean Hyundai), but Japan is not the biggest consumer of fuel cell transport. California, which accounts for almost the entire US market, has 4,926 FCVs, 21 fuel cell buses, 35 hydrogen stations, and 32 buses in development as of July 2018.[103] California's market is larger than Japan's, where there are only about 2,500 FCVs, less than 10 buses, although roughly triple the number of hydrogen stations. Specific details on California's incentives, including rebates of $5,000 and three-year free hydrogen fuel refills, can be found on the website of California Fuel Cell Partnership. Other markets for FCVs are also budding in Europe (predominantly Germany) as well as South Korea. Although global automakers are cautiously teaming up to explore fuel cells amidst their uncertain outlook, they are accelerating the development of battery electric vehicles with greater confidence.

In 2013 Nissan formed a research partnership with Daimler and Ford to advance the commercialization of FCVs by tapping into "*more than 60 years of [their] cumulative experience*".[104] Daimler pulled out of the project in 2017 and was followed by Nissan in June 2018, with both companies pledging instead to focus more on battery cars.[105] Mercedes-Benz, owned by Daimler, has since unveiled its new Concept Sprinter fuel cell van in June 2018 with plans for limited production, while already committing to put the battery-powered eSprinter into mass production.[106] Audi also has an FCV prototype and signed a multi-year patent cross-licensing agreement with Hyundai.[107] Even Toyota (partnered with BMW in 2013 to develop an FCV by 2021)[108] and Honda (teamed up with

103. "By The Numbers: FCEV Sales, FCEB, & Hydrogen Station Data", California Fuel Cell Partnership, July 12, 2018, available at: https://cafcp.org.

104. "The Strategic Cooperation between Daimler and the Renault-Nissan Alliance Forms Agreement with Ford to Accelerate Commercialization of Fuel Cell Electric Vehicle Technology", Press Release, Nissan Motor Corporation, January 27, 2013, available at: https://newsroom.nissan-global.com.

105. D. Z. Morris, "Daimler Steps Back From Fuel-Cell Car Development", *Fortune*, April 2, 2017, available at: http://fortune.com; "Fuel Cell Cars Hit Roadblock as Nissan-Renault Pulls out", *Nikkei Asian Review*, June 16, 2018, available at: https://asia.nikkei.com.

106. S. Edelstein, "Mercedes-Benz Unveils Fuel-Cell Sprinter Van Concept", *The Drive*, July 2, 2018, available at: www.thedrive.com.

107. "Audi, Hyundai to Cooperate on Fuel Cell Vehicles", *Automotive News Europe*, June 20, 2018, available at: europe.autoanews.com.

108. "BMW Group and Toyota Motor Corporation Deepen Collaboration by Signing Binding Agreements", Press Release, BMW Group, January 24, 2013, available at: https://ngtnews.com;

General Motors in 2018 to release the successor to the Clarity by 2020)[109] while pushing for FCVs, are keeping their portfolios diverse with other low emission and regular cars.

Meanwhile, China is on its way to become the world's champion of fuel cell buses. The city of Zhangjiakou has reportedly ordered 74 units before the Beijing 2022 Olympics. Half of the fleet was expected to be operational in the first half of 2018, which would make China's fuel cell bus fleet the largest in the world. 49 of those units will be made by China's Beiqi Foton Motor Co., which will deliver the Foton AUV 10.5-meter fuel cell bus. The other 25 will be made by Zhengzhou Yutong Group Co. Ltd. These buses will use 60 kW fuel cell systems and a battery hybrid system, giving a range of up to 500 km.[110]

Another fuel cell bus developer in China, Wuhan Tiger Fuel Cell Vehicle unveiled its 56 passenger, 450 km fuel cell bus last December. They signed an agreement with Wuhan Skywell to produce 3,000 buses in the next two years.[111] In May 2018, China's battery electric vehicle developer BYD partnered with US Hybrid Corporation to develop a hydrogen fuel cell battery electric bus. The buses will first be tested in Honolulu's Daniel K. Inouye International Airport.[112]

So far, these efforts are emerging from uncoordinated technology development by the private sector, without concrete public support. "The government has outlined plans to encourage the development of hydrogen energy and fuel cell vehicles, but the national and local policies aren't specific or strong enough to give the industry clear guidance and greater confidence" said Liu Jihong, director of the Foton AUV Bus Research Institute.[113]

It is tempting to draw a parallel between China's solar PV strategy and their outlook on fuel cells and hydrogen. In the early 2000s German and Japanese firms had nursed photovoltaic technology at its infancy, until they found themselves outcompeted by Chinese manufacturers that

H. Boeriu, "BMW to Produce a Low-Volume Hydrogen Fuel-Cell Car in 2021", *BMW Blog* (blog), March 29, 2017, available at:www.bmwblog.com.

109. "GM, Honda to Collaborate on Next-Generationn Fuel Cell Technologies", Press Release, Honda, n.d., available at: www.honda.ca.

110. "Largest Chinese Fuel Cell Bus Order Issued for 2022 Winter Olympics", *Fuel Cells Works*, February 5, 2018, available at: https://fuelcellsworks.com.

111. "Hydrogen-Powered Bus Unveiled in Central China", *Xinhua*, December 28, 2017, available at: www.xinhuanet.com.

112. "China's BYD, US Hybrid to Develop First-Ever Hydrogen Electric Bus", *Xinhua*, May 4, 2018, available at: www.xinhuanet.com.

113. K. Wang, "Hydrogen on Track to Drive China's Development", *China Daily*, June 5, 2018, available at: www.chinadaily.com.cn.

drove down costs and brought the technology to maturity. The key to China's leverage is large scale industrial capacity – the result of steadfast policy and financial coordination between the central government that set solar technology as the national industrial and clean energy priority, and the local governments that were excited to see businesses grow in their jurisdictions. Such government support emerged after years of successful solar panel exports to Europe by private companies, much like other export-based manufacturers in China at the time. Recently the nation has been evolving from a manufacturing powerhouse towards an innovation hub that serves the ever growing and richer domestic market.

The question is, how much can this tell us about the future of fuel cells? China's large industrial might and consumer base offer the advantage of scale. China's "run, then plan" approach is reflective of high risk tolerance that greatly contrasts with the measured pace of Japanese governance and industries. That being said, there is too much uncertainty surrounding hydrogen that initial success is almost entirely dependent on technology breakthrough in the lab. China does not currently have enough fuel cell specialists and few universities offer relevant courses. According to Mr. Liu, while it is not unusual for electric vehicle companies to employ more than 100 experts and researchers with doctorates, it would be difficult to find 10 equally qualified people in an FCV company.[114] It's also fair to assume that (although statistics are missing) a similar disparity could also exist in Japan.

China's public support for hydrogen will likely depend on hydrogen's contribution to its domestic energy system. Currently there are no plans for the decarbonization of production. China has sizeable potential for CCS and renewable energy to make it happen, but there are more direct uses – such as power generation with CCS or powering electric vehicles with renewables from the grid – that are more efficient. The greatest potential for switching lies in sectors that are hard to electrify, like heavy-duty transport and buses, where we are seeing China take the first steps.

Stationary fuel cells: Residential CHP

There are various types of fuel cell, each named according to the electrolyte that is used in the system. The two most commercially advanced options are the polymer electrode cell (PEFC) and solid oxide fuel cell (SOFC).

114. *Ibid.*

They generally run on either natural gas or propane with primary application in heat and power co-generation (CHP).

In 2009, a consortium of major Japanese energy suppliers and fuel cell manufacturers launched co-branded stationary fuel cell units for households, called Enefarm. Enefarm is a micro co-generation system for heating and distributed power that comes in PEFC and SOFC types, with PEFC model covering 90% share of sales. With electricity output of 700 W and 1,000 W, Enefarm is not designed to meet the entire power demand of a house, rather it covers a portion of the power demand and the entire demand for hot water.[115]

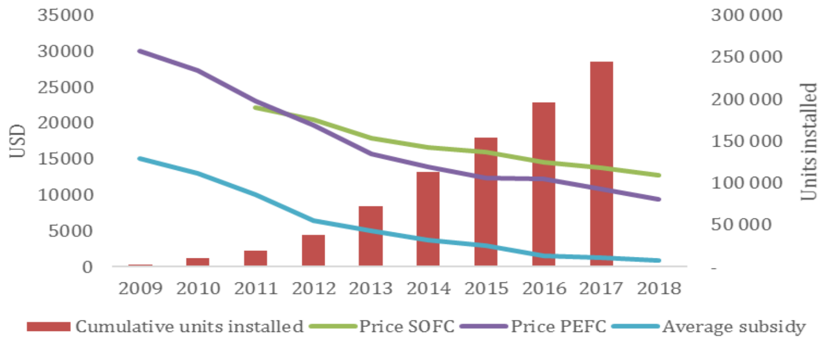
Currently the government offers sliding subsidies based on the type of fuel cell used in the system (PEFC or SOFC), price (must fall within the tiered pricing limit) and variable factors, such as the type of fuel gas or whether a building is retrofitted. Customers are incentivized with higher subsidies to purchase and install cheaper systems, which aims to increase cost competitiveness and improvement of performance among the equipment producers. Higher subsidies are granted to SOFCs which show better technical performance, but due to higher cost they make up a smaller share of sales. Additional subsidy of 30,000 yen is given to installations in existing buildings to encourage the emerging trend of retrofitting.

The average price of a PEFC in 2018 is around 1.04 million yen ($ 9,360), or a little under 1 million yen ($ 9,000) with a subsidy. A SOFC system can be purchased for around 1.4 million yen ($ 12,600), or 1.28 million yen ($ 11,500) with a subsidy.[116]

Compared to conventional electricity and heating systems, the capital cost for a PEFC or SOFC enefarm system is 2.5 to 3.5 times higher but with potential annual saving of roughly 50,000 yen on energy bills, owners can recoup their investment in about 12 to 13 years without subsidy.[117]

115. IEA, "Technology Roadmap Hydrogen and Fuel Cells."
116. METI, "8th Hydrogen and Fuel Cell Strategy Council Meeting: Progress Status on the Strategic Roadmap"; FCA, "Changes to subsidies since the previous year (2018, 2017)," Fuel Cell Association, 2018, http://www.fca-enefarm.org/subsidy30/change.html; ACEJ, "Enefarm sales," Advanced cogeneration and energy utilization center, Japan, March 2018, https://www.ace.or.jp/web/works/works_0090.html.
117. Katsuyuki Okawara, "At 1.6 million yen, Panasonic residential enefarm is less than half of the price of the first enefarm," *Kaden watch*, February 5, 2015, https://kaden.watch.impress.co.jp/docs/news/686923.html.

Enefarm fuel cell micro co-generation cumulative installation, prices and subsidies, 2009-2018 ($)



Source: Adapted from METI, IEA, ACEJ, FCA.

By 2020, the government hopes to reduce the retail cost for PEFC systems to 800,000 yen ($ 7,200) and for SOFC system to 1 million yen ($ 9,000) (cost recoupment in 7 to 8 years) and achieve cumulative installation of 1.4 million units. If cost reduction continues at current 12% annual decline, it appears plausible to hit the price target by the end of this decade. On the other hand, the installation target requires more units installed per year than the combined total of the past nine years, which is an ambitious growth rate. By 2050, METI hopes to see 5.3 million units nationwide, or in about 10% of Japanese households.

Prices have fallen by about 43% for SOFCs and 70% for PEFCs since their introduction to the market. However further cost cuts will be needed to achieve installations in the millions hoped by METI. So far there has been a reduction in cost and size of the residential CHP systems, leading to increased usability. Progress includes the reduction in the number of fuel cell stacks by 10-30% (reducing the amount of platinum used by PEFCs), 10% reduction of components with each new fuel cell type, 40-60% reduction in size of the equipment, and the frequency of maintenance has been reduced from once every five years to over ten years.[118]

The fuel cell stack accounts for only 15% of the cost of the PEFC system. Larger cost share is covered by the water tank (30%) and the BOP (25%), with the fuel-processing unit (15%) and packaging (15%) accounting for the rest. This means that further cost decreases will be more difficult to

118. METI, "8th Hydrogen and Fuel Cell Strategy Council Meeting: Progress Status on the Strategic Roadmap".

achieve because the fuel stack is a relatively small share of the overall cost of the system.[119]

The IEA estimates that replacing 10% of heating systems with fuel cells in Japan would reduce the total residential energy demand by 3% resulting in 4% reduction of carbon emissions compared to gas boilers and grid electricity for residential energy supply.[120]

Two brands of Enefarm are available on the market – Panasonic and Aisin. The Aisin Type S SOFC Enefarm has 52% power generation efficiency, and 87% combined heat cycle efficiency.[121] Earlier manufacturers Eneos and Toshiba have seized production.[122] Panasonic began to enter the European Enefarm market as well.[123] The challenge of entering the European market lies in the difference of gas quality, with higher variability in constituents and presence of potentially poisonous chemicals in the European gas requires the redesign of the gas processing unit for PEFC systems.[124]

Power Generation

Power generation using ammonia was discussed earlier in the section on energy carriers. This part will focus on the development of hydrogen fueled thermal power generation, which can become the single largest driver of the hydrogen market by 2050 if brought to full technical potential, accounting for 64% of new hydrogen demand.[125] By fuel consumption, 1 GW power generation capacity requires roughly 3 million Nm^3/year of hydrogen fuel while a single FCV requires roughly 1,000 Nm^3/year. At peak number of FCVs expected on the road by 2030, fuel demand of the entire national fleet would equal a fraction of demand of a single power plant. Hydrogen power generation is still in infancy, as combustion technology is undergoing research and development. Its future commercialization and mass market introduction is contingent on the government's willingness to back-up this power source and clarity on the role of nuclear power in the energy mix.

119. IEA, "Technology Roadmap Hydrogen and Fuel Cells".
120. *Ibid.*
121. Aisin, "Enerfarm", available at: www.aisin.co.jp.
122. Toshiba, "About Production and Sales Termination of Domestic Fuel Cell System (Enefarm)", available at: www.toshiba.co.jp.
123. METI, "8th Hydrogen and Fuel Cell Strategy Council Meeting: Progress Status on the Strategic Roadmap".
124. IEA, "Technology Roadmap Hydrogen and Fuel Cells".
125. National Institute of Advanced Industrial Science and Technology (AIST), March 31, 2014 "Renewable Energy Storage and Transportation Technology Development; 2013 Scenario Research on Total System Installation", p. 138.

Electricity can be generated through the combustion of hydrogen, both as pure hydrogen and as a mixture of natural gas or coal. In general, existing natural gas power plants are adapted for hydrogen co-firing and these possibilities are explored in Japan and overseas. Turbines with up to 50% mixing in the integrated coal gasification combined cycle (IGCC) have already been commercialized.[126] A pure hydrogen combustion plant has been operating in Italy since 2010.[127] Japanese companies like Mitsubishi Hitachi Power Systems (MHPS) and Kawasaki Heavy Industries are also working on both direct and co-fired combustion technologies.

Although there are no CO_2 emissions, hydrogen combustion emits nitrogen oxide (NOx), an air pollutant and a greenhouse gas. Natural gas co-firing can be doubly polluting when a too rapid reaction results in unstable combustion and high temperatures of the flame. To counter this, measures such as injections of water to cool the flame and dilution of the fuel with inert gases are being studied.[128] However, water injection worsens the fuel economy, so Kawasaki developed an alternative technology that supplies hydrogen in small doses that burn in microflames, a method the company dubs the "Micromix" technology. The Micromix can be used for 100% hydrogen combustion while suppressing NOx emissions.[129]

On a larger-scale, MHPS developed a turbine combustor that uses a mix of LNG and 30% hydrogen, while suppressing NOx emissions to the level of gas-fired power. This allows output of 700 MW (with internal temperature of 1,600°C) and offers around 10% CO_2 emission reduction compared to regular gas turbines.[130]

Power generation from hydrogen combustion is expected to be more cost effective than electricity production by stationary fuel cells due to scalability. While fuel cell stacks are bound by requirements of the number and size of stacks, hydrogen power plants can be expanded much more easily.[131] Conversely this means that power generation becomes less advantageous in small-scale distributed power generator. To benefit from

126. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility", *op. cit.*
127. Enel, "Enel: At Fusina (Venice), Inauguration of First Industrial-Scale Hydrogen Plant in the World", July 12, 2010, available at: www.enel.com.
128. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".
129. Motohiko Nishimura, Kawasaki Heavy Industries, "In the Near Future, Hydrogen Power Generation Will be a Trump Card in Reducing CO_2 Emissions", September 2017, available at: https://global.kawasaki.com.
130. MHPS, "The Hydrogen Gas Turbine, Successfully Fired with a 30% Fuel Mix, Is a Major Step Towards a Carbon-Free Society", April 26, 2018, available at: www.mhps.com.
131. B. Decourt *et al.*, "Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility", *op. cit.*

operation as a large-scale plant, it must also secure sufficient volumes of hydrogen fuel.[132]

Industry

Virtually all hydrogen consumed by Japanese industries today has been emitted as by-product of an industrial process. In oil refining, by-product hydrogen is reused within the same facility as feed in oil desulfurization. Recently given the rising demand for higher grades of petrochemicals, refineries in Japan and elsewhere in the world began to buy hydrogen from other plants as they can no longer meet their own demand. Currently in Japan, the largest supplier of hydrogen is the caustic soda industry, which sells high-purity by-product hydrogen to filling stations and other factories. However, caustic soda production is switching to the more energy efficient gas diffusion electrode method that emits no hydrogen, so it cannot be relied upon for hydrogen supply in the future.[133] Steelmaking produces by-product hydrogen too, of which some is sold externally, as in the Kitakyushu Hydrogen Town (HyTown) demonstration project described below. The volume and quality of by-product hydrogen may be variable to the type of feed and the manufacturing process. This can raise costs if poor quality hydrogen needs additional refining, while supply inconsistency complicates procurement for the off-taker.

There are no decarbonization targets for industrial hydrogen in Japan, unlike in France that chose industrial hydrogen as the first step towards its green hydrogen market. Under the French strategy, 10% of industrial hydrogen (100,000 t-H_2) will be sourced from zero-emission electrolysis by 2023, and 20-40% by 2028.

Japan instead chose to focus on new hydrogen production technologies that should eventually become carbon free and cost-competitive, as well as on new end-use markets like FCVs, enefarm and power generation. These new markets are projected to consume 300,000 t-H_2 per year in 2030, and 10 million t-H_2 after 2050. While the current annual market of 1.3 million t-H_2 is large, 98% is the by-product of chemical and steel production mentioned above. High energy prices and import dependency for energy in Japan have led to high optimization of factories, and any further requirements for emission control are believed to harm their competitiveness.

132. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region."
133. *Ibid.*

Like France, Japan is advancing hydrogen production through electrolysis but a major difference lies in the high cost of renewable energy. While tender-based pricing is emerging, many projects are priced according to the FiT scheme. In 2018, solar (between 10 kW and 2,000 kW) costs 18 cents/KWh and 21 cents/KWh for onshore wind (over 20 kW).[134] In addition to high electricity cost, the intermittency of renewables reduces the capacity factor of electrolysis thereby raising marginal costs of hydrogen production. Therefore as explained in the chapter on hydrogen supply chains in the Asia Pacific Economic Cooperation (APEC) region, even in 2030, domestic hydrogen from solar and wind power are projected to cost close to \$ 1.00/Nm^3-H_2 and may remain more expensive than imported hydrogen made from natural gas + CCS and hydropower.

While industrial demand will not drive the hydrogen economy in Japan, it will stand to benefit from cost reductions in green hydrogen. Industrial parks are excellent testing grounds for hydrogen pilot projects thanks to established distribution and storage infrastructure. In the long-term, the industrial application may go beyond feedstock, as hydrogen has potential to replace fossil fuels in boilers, cogeneration and direct heating. As such, industries will be able to reduce their emissions by switching to green hydrogen once it becomes cheaper.

The technical feasibility of switching to hydrogen (regardless of whether it is decarbonized) in the industry was estimated by IEEJ in a report commissioned by the National Institute for Advanced Industrial Science and Technology (AIST).[135] By 2050, industries in Japan could in theory consume 645 billion Nm^3 or 58 million t-H_2 per year. The largest uptake can be expected in chemicals (37% of total hydrogen uptake by industry), pulp and paper (25%) and steel (13%).[136]

134. METI, "2018 Renewable Energy FIT and Levies" (between 2017 and 2019). Updated March 23, 2018, available at: www.meti.go.jp.

135. The study evaluated a sample of representative technology in 2010 and projected its development by 2050 based on literature reviews and hearings with manufacturers. The price of competing fuels, policy support or environmental costs were not accounted for. Sectors like "Ceramics" and "Steel" have a large share of coal that cannot be substituted because it is the main material. Oil in "Oil refining" was excluded for the same reason.

136. AIST and IEEJ, "Renewable Energy Storage and Transportation Technology Development; 2013 Scenario Research on Total System Installation", p. 127.

Hydrogen uptake potential by industrial sectors, 2050

Industrial sector	Billion Nm^3-H_2	% share of hydrogen in industry	% share within sector's total energy demand
Pulp, paper	159	25%	40%
Chemical fiber	53	8%	90%
Glass	8	1%	40%
Ceramics	55	9%	20%
Non-ferrous metal	15	2%	70%
Machinery	34	5%	30%
Chemicals	239	37%	14%
Steel	82	13%	5%
Industry Total	**645**	**100%**	-

Source: AIST/IEEJ 2014.

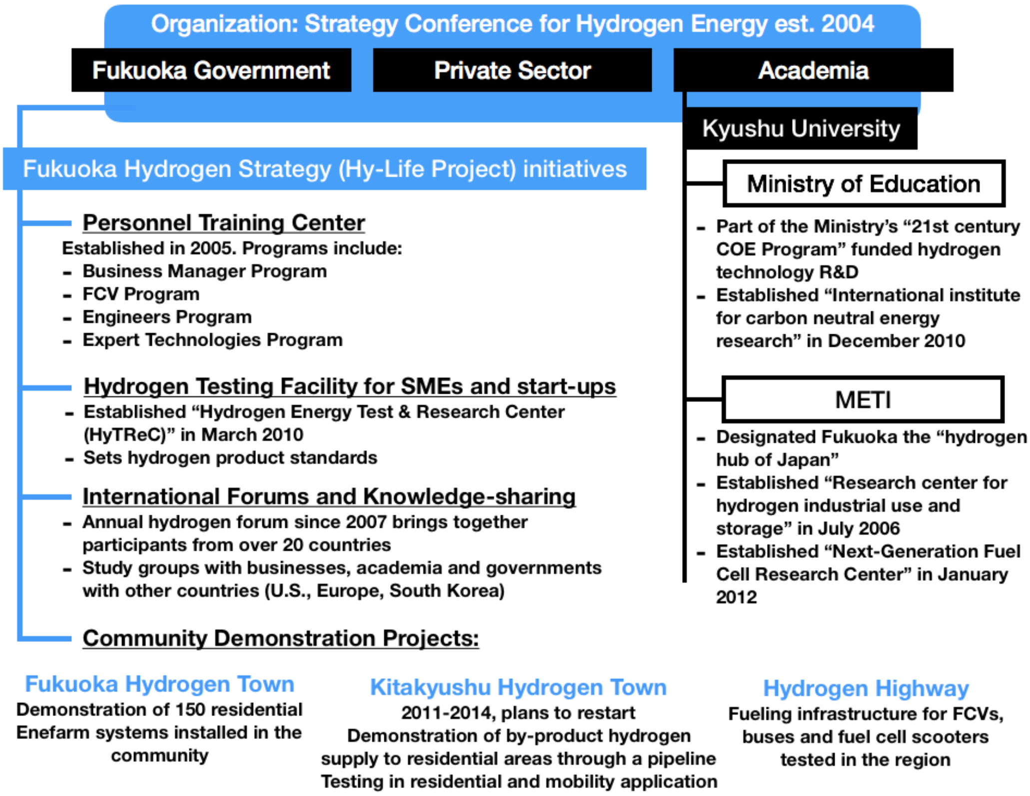
Hydrogen Town (Kitakyushu City, Fukuoka Prefecture)

Kitakyushu city in Fukuoka Prefecture has been recognized by the OECD as the first green growth model city in Asia for its many innovative and international efforts on sustainability. In 2004, the Fukuoka prefectural government co-founded the Strategy Conference for Hydrogen Energy, an organization comprising 672 members from Japan's private, academic and public sectors.[137] Together, they established the Fukuoka Hydrogen Strategy (Hy-Life Project) focused on R&D and commercialization of hydrogen and fuel cells, and human resource development.[138]

137. 144 members when launched in 2004 (Corporations: 63, universities: 64, government/research/sponsoring institutions: 17). By 2013, grew into 672 members (corporations: 523, universities 112, government/research/sponsoring institutions: 17). The executive board comprises: governor of Fukuoka Prefecture, former director general of Kyushu bureau of METI, mayor of Kitakyushu City, mayor of Fukuoka City, etc. Executive members from the following private sector members: Nippon Steel & Sumitomo Metal Corporation, Iwatani Corporation, JX Nippon Oil & Energy, Toyota, Kyushu Electric Power, Saibu Gas, Nissan, Honda, etc. Source: Wataru Aso, 2013.

138. W. Aso, "Fukuoka Hydrogen Strategy Hy-Life Project", April 12, 2013, available at: https://tapahtumat.tekes.fi.

Hydrogen initiatives in Fukuoka Prefecture

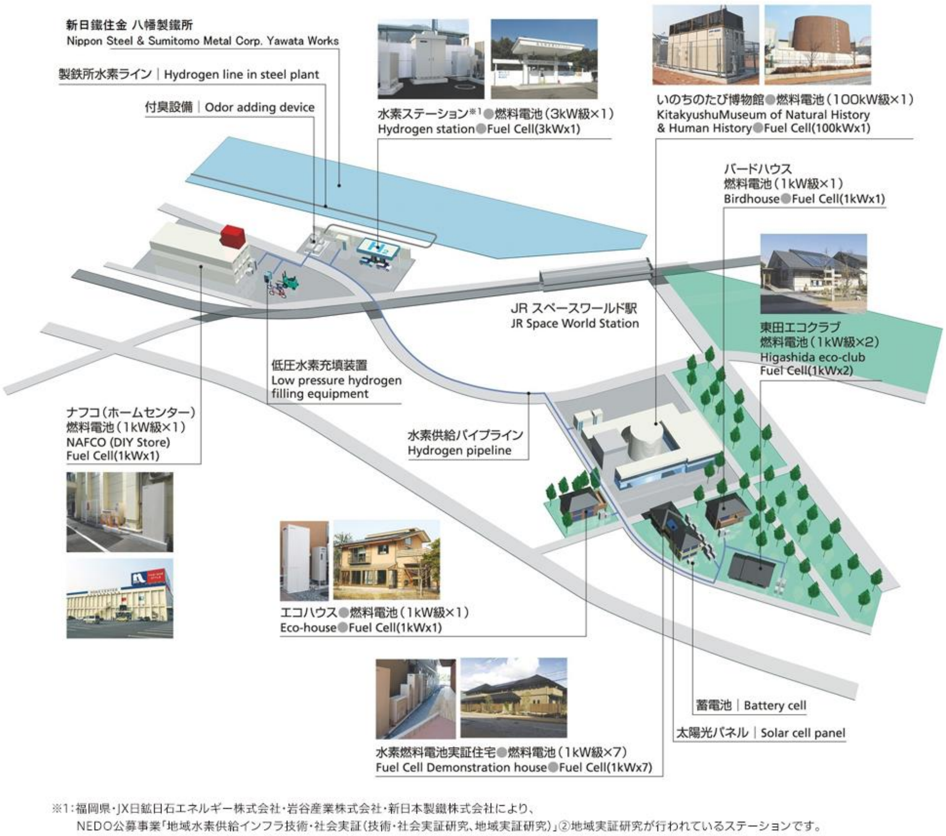


Source: Adapted from Wataru Aso 2013.

One of the Hy-Life Project initiatives is the Kitakyushu Hydrogen Town, the world's first community-level hydrogen demonstration project that ran between 2011 and 2014. Its aim was to test the supply of by-product hydrogen from a nearby steel factory to residential, commercial and public facilities using a pipeline, as seen in the figure below.[139]

139. The steel factory is owned by Nippon Steel & Sumitomo Metal, which has been operating as a state-owned steel factory since 1901. Part of the original factory is registered as a World Heritage site as "Site of Japan's Meiji Industrial Revolution: Iron and Steel, Shipbuilding and Coal Mining".

Kitakyushu Hydrogen Town



Source: HySUT Kitakyushu Hydrogen Town Demonstration Project with partial edits by Saibu Gas.

Specifically, the project tested the following: (1) hydrogen supply using a pipeline, (2) operability of fuel cells across multiple applications, (3) fuel cell powered vehicles, small forklifts and bicycles (the project ran before FCVs appeared on the market), (4) the supply of electricity from FCVs to households, and (5) smart community power sharing. Further details on each demonstration below.[140]

(1) Hydrogen pipeline
- 1.2 km hydrogen pipeline was laid from the steel factory to a residential neighborhood.
- Meetings were held with the residents to ease their fears about hydrogen safety and use.
- Opportunity to identify operational challenges of hydrogen supply using a pipeline.

140. City of Kyushu, "Kitakyushu City Hydrogen Society Vision", March 2017, available at: www.city.kitakyushu.lg.jp.

(2) Operability of fuel cells across multiple applications
   - Stationary fuel cells were installed in apartments, business facilities and hydrogen fueling stations.
   - Demonstration of pure hydrogen fuel cells and storage batteries connected to solar panels.

(3) Fuel cell powered cars, small forklifts and bicycles

(4) Supplying electricity from fuel cell vehicles to residential and public facilities
   - Demonstration of electricity supply from FCVs to houses.
   - Examined possibilities of power balancing systems to level peak load.
   - Tested emergency power supply to public facilities (Kitakyushu Museum of Natural and Human History) designated as evacuation shelters for disaster response.

(5) Smart community power sharing
   - Joint effort of community energy management system (CEMS) and building energy management system (BEMS) in the "Higashida no Aikouen", a home for the elderly.
   - Excess electricity was converted into hydrogen and stored in tanks. When power demand increased, hydrogen was discharged into fuel cells to generate electricity.

Although testing in the Kitakyushu Hydrogen Town was completed in 2014, in 2016 the Fukuoka Prefecture and Kitakyushu City announced their intention to restart the project. The aim is to further reduce costs of hydrogen technology.[141]

Last year, the city also announced the "Kitakyushu City Vision for Hydrogen Society", which aims to establish a hydrogen supply chain by 2030.[142] In addition to the Higashida district that hosted the Kitakyushu Hydrogen Town, the Vision also selected Hibikinada as a "leading area" where many energy facilities and port infrastructure are based. That area is to become key to the import of hydrogen from overseas, the production of hydrogen from LNG reforming, and as a base for hydrogen storage and supply for Kyushu and the rest of Japan.[143]

141. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".

142. City of Kyushu, "Kitakyushu City Hydrogen Society Vision".

143. APERC, "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".

Cost and Funding

Supply chain cost modeling in the APEC region

The Asia Pacific Energy Research Center (APERC) and the Institute of Energy Economics, Japan (IEEJ) have modeled and compared the cost of hydrogen supply for the Japanese power generation and mobility sectors from APEC economies under a 2030 scenario.[144] The region wide scope used in the study is especially important in estimating the feasibility of international trade networks on which Japan is likely to rely given its limited capacity for domestic hydrogen production.

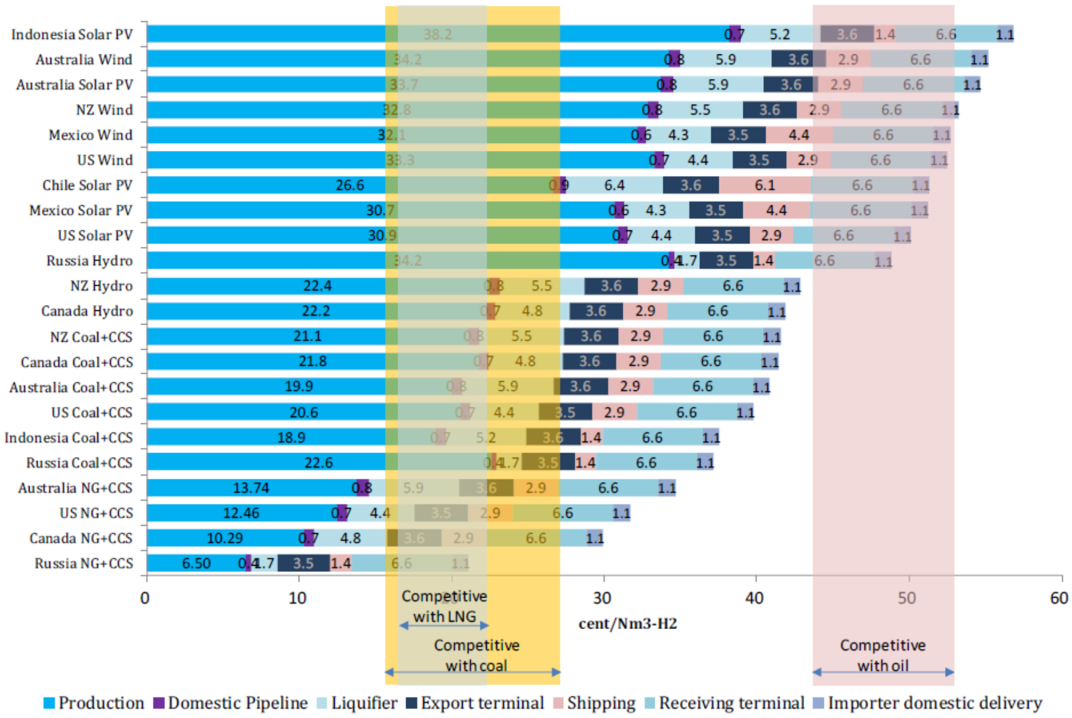
The chart below shows the projected cost of hydrogen supply chains for power generation in 2030. The horizontal bars represent import costs of emissions-free hydrogen by export country and production fuel (renewables or fossil fuels + CCS). Import costs are composed of cumulative costs of production, transport and storage in the exporting country, international transportation (energy carrier assumed to be liquefied hydrogen), and the cost of domestic receiving terminals and distribution.[145] The import costs are then compared to the price of competing power generation fuels (coal, gas and oil) in Japan represented by the vertical bars on the chart. The price range of the competing fuels reflects a potential carbon price – the lower end is a scenario where no carbon price is included in the cost of fossil fuels and the upper end represents a carbon price of \$100/t-CO_2. According to APERC/IEEJ's estimates, the cost of hydrogen supply must be less than \$16-27 cents/Nm^3 to be cost competitive with coal fired-power, \$17-22 cents/Nm^3 with LNG, and \$44-53 cents/Nm^3 with oil. In other words, in order to compete with thermal power generation without carbon pricing, emissions-free hydrogen must be imported at below \$17 cents/Nm^3, and it will take a while before any supplier can achieve such level of competitiveness. For comparison, the

144. APERC/IEEJ. March 2018 "FY2017 APERC Research Cooperation Project Perspectives of Hydrogen in the APEC Region".

145. Domestic production of hydrogen for power generation is omitted on the premise that it is much more energy efficient to feed the renewable electricity into the grid rather than using it for electrolysis to produce hydrogen for power generation. It is even more unlikely that Japan will import fossil fuels for the production of hydrogen given virtually no space for CCS in the country.

current retail price of hydrogen in fueling stations in Japan is roughly 100 yen, or about $ 90 cents/Nm3.

Hydrogen supply cost for power generation in Japan by country of production and the cost of competing fuels in 2030 ($ cents)



Source: APERC/IEEJ 2018.

The largest and most variable price determinant is the fuel source (coal, gas or renewables), country and the method of production. Hydrogen from Russian natural gas coupled with CCS offers the lowest import cost at around 22 cents/Nm3, followed by natural gas from Canada, the U.S. and Australia. Russian supply noticeably benefits from lower cost of liquefaction and shipping to Japan in comparison to other exporters. Canadian hydropower is the best priced renewable source of hydrogen at 42 cents/Nm3, but in the Japanese power generation market it would remain more expensive than coal and LNG even if carbon pricing would be introduced in the future.

The next figure shows the supply cost of CO_2-free hydrogen to FCVs in fueling stations, which is added to the hydrogen import cost calculated above.[146] Similarly, the most competitive price is offered by Russian natural

146. According to the levelized facility cost of a small fueling station with a hydrogen supply capacity of up to 300 Nm3/h is about 60 yen/Nm3 (energy carriers include liquefied hydrogen and domestic

gas-based hydrogen. For large-scale stations with fueling capacity of at least 1200 Nm^3/h (yellow bars on the chart) the supply cost ranges $36-72 cents/$Nm^3$. The cost increases to $69-105 cents/$Nm^3$ for small fueling stations with capacity of up to 300 Nm^3/h (red bars). The current retail price of hydrogen fuel for FCVs in Japan is roughly $90 cents/$Nm^3$.

Domestic hydrogen is more expensive than hydrogen from foreign fossil fuels with CCS. The higher LCOE of renewable energy in Japan (assumed to be 7 yen/kWh in 2030) has contributed to the markedly higher cost of domestic hydrogen production, but it is offset by avoidance of liquefaction, transportation and regasification costs incurred by import hydrogen, making the overall domestic supply comparable to some imported renewable hydrogen.

Hydrogen fuel cost at FCV filling stations in Japan by country of hydrogen production in 2030 ($ cents)

Source: APERC/IEEJ 2018.

It is worth noting that the study presented here is the first attempt at economic assessment of the hydrogen supply potential across the wide APEC region. By pointing out the limitations and variability of data across the examined economies, authors acknowledge that the estimates will need to be updated when more data becomes available. Any shift in policy direction, technology breakthrough, and adjustment in the model's

distribution). The supply cost for large fueling stations with supply capacity of at least 1,200 Nm^3/h is estimated to be 20 yen/Nm^3.

assumptions will influence the cost structure of the supply chains. A contributing factor to the higher cost of renewables-based production is the low capacity factor, or operation time of production facilities. Due to the intermittency of solar and wind power, production facilities remain idle for long periods of time, so a 20% capacity factor is assumed in the calculation. If power supply can be stabilized by incorporating a combined solar and wind system for example, the output efficiency will improve, thereby lowering the marginal cost of production from renewables.

Public funding

Over six years, nearly $ 1.5 billion has been spent on hydrogen programs by the Japanese government, primarily by the Ministry of Economy Trade and Industry (METI). In 2018, the ministry plans to allocate a record $ 272 million to hydrogen research and subsidies, or 3.5% of its energy budget.[147] Research and development (R&D) has been the focus of METI's funding to date, which is channeled through the governmental research institution the New Energy and Industrial Technology Development Organization (NEDO) that oversees national programs on new technology development.

R&D support continues to be strong for energy carriers. Since 2013, NEDO has spent about $ 321 million on supply chain R&D spanning production, transportation and application of hydrogen. In addition to NEDO's research on supply chains and energy carriers, the Strategic Innovation Program (SIP) under the Prime Minister's Cabinet selected hydrogen energy carriers like ammonia as one of 10 strategic areas for a five-year research program from 2014 to 2018, which totals $ 150 million.[148]

Although the R&D budget for power to gas (PtG) has expanded from $ 100,000 in 2014 to $ 12 million in 2017, it remains modest compared to other technologies.[149] As discussed earlier, the lack of large, non-intermittent renewable electricity supply and the lack of gas infrastructure (both natural gas and hydrogen gas pipelines) dampens the prospects of fully-fledged uptake of PtG in Japan.

147. METI, "2018 Summary of Resource/Energy Related Budget Request", August 2017, available at: www.meti.go.jp.

148. NEDO, "Hydrogen Use Advanced R&D Project Register [Carrier Technology]", page 6, November 11, 2017, available at: www.nedo.go.jp; Cross-ministerial Strategic Innovation Promotion Program, "Research and Development Plan for Energy Carriers (Towards the realization of a new energy society)" pp. 11-13, Cabinet Office, Government of Japan, April 1, 2018, available at: www8.cao.go.jp.

149. NEDO, "Hydrogen Society/Hydrogen Energy System Technology Research and Development Project Register [Power to Gas]", December 6, 2017, available at: www.nedo.go.jp.

With the aim of improving cost, durability and achieving 65% power generation efficiency in next generation fuel cells, NEDO is involved in basic research on catalysts and electrolytes, in addition to applied technology development with the annual budget of $ 26 million.

Public budget for hydrogen R&D and subsidies ($ million)

Public Body	Budget type	Sector	Project description	2013	2014	2015	2016	2017	2018	Total
METI	R&D	Power to Gas	Power to Gas, including Renewables to Gas	-	0.1	14	8	12	-	34
METI	R&D	Supply Chain	Development of supply chains for hydrogen production, import and application	18	44	107	25	42	85	321
Cabinet	R&D	Supply Chain	Technology development for H2 production from solar power; transportation and application of ammonia; organic hydride; liquid hydrogen	-	30	30	32	33	26	150
METI	R&D	Fuel Cells	R&D on durability and cost reduction of "next generation fuel cells"	40	-	-	33	28	26	127
METI	Subsidy/ R&D	Enefarm	Subsidies for residential enefarm; and since 2017, R&D budget and subsidy for commercial and industrial CHP	156	153	135	86	84	80	385
METI	R&D	Fueling Stations	Fueling stations R&D, e.g. automation, safety	-	29	37	-	-	22	88
METI/ MoE	Subsidy	Fueling Stations	Fueling station construction and operation	41	65	123	114	90	106	539
METI	Subsidy	Mobility	FCV subsidies as part of clean vehicle program (BEVs, hybrids included)	-	-	-	123	111	117	351
METI	R&D	Power generati on	Improvement of thermal power generation, including Integrated Gasification Fuel cell Cycle (IGFC)	63	56	-	108	119	129	475
Ministry of Economy, Trade and Industry (METI)				106	149	107	237	241	272	1,112
Ministry of Environment (MoE)				-	-	24	59	49	63	195
Prime Minister's Cabinet				-	30	30	32	33	26	150
Total				**106**	**178**	**161**	**327**	**324**	**361**	**1,458**

(For reference) Other energy related expenditure ($ million)

Public Body	Budget type	Sector	Project description	2013	2014	2015	2016	2017	2018	Total
METI/MoE	R&D	CCS	Carbon capture and storage	106	109	153	135	145	153	802
METI	Subsidy/ R&D	Renewables	R&D and installation subsidies for solar, wind, biomass, geothermal, and hydrogen power	1,099	1,228	1,179	1,203	929	988	6,625
METI	Subsidy/ R&D	All Energy	Overall annual energy budget	7,050	7,854	7,169	7,546	7,627	7,759	45,004

Source: METI, NEDO, SIP, MoE.

As certain technologies began to transition from lab to market in recent years, financial support was extended to consumer subsidies. Fueling station construction and operation are jointly subsidized by METI and the Ministry of Environment at roughly $ 106 million in 2018. Subsidies for FCVs were introduced in 2016 as a share of the national budget for clean vehicles like BEVs, plug-in-hybrids and clean diesel cars; the 2018 national clean vehicle budget is $ 117 million and with additional subsidies for FCVs and FC buses offered by prefectural governments. Subsidies for residential enefarm systems (majority PEFCs) will be phased out in the coming years as the technology reaches maturity and competitiveness with alternatives. However, support will continue for industrial and commercial fuel cells, such as SOFCs which were introduced to the market in 2017.[150]

Both METI and MoE also allocate around $ 150 million annually to R&D on carbon, capture and storage (CCS), which is indispensable for zero-emission hydrogen production from fossil fuels. The results of the demonstration projects are expected by 2020.

The market for hydrogen equipment and infrastructure business is forecast to reach 1 trillion yen in 2030 and 8 trillion yen – or $ 75 billion – by 2050.[151]

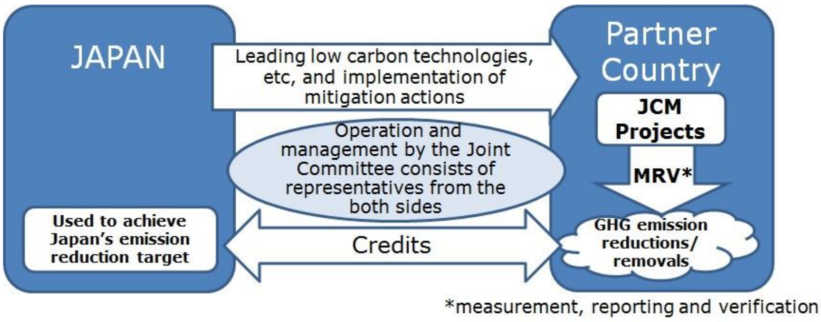
Funding for overseas hydrogen projects

Public funding for overseas projects, including financing options under consideration for the ammonia demonstration project in Saudi Arabia, may involve the following institutions and mechanisms.[152]

150. NEDO, "Promoting the Technology for Solid Oxide Fuel Cells [SOFC]", p. 8, 2018, available at: www.nedo.go.jp.
151. METI, "Basic Hydrogen Strategy Determined".

At the demonstration phase, the New Energy and Industrial Technology Development Organization (NEDO) sponsors projects under the Joint Crediting Mechanism (JCM) or under the scheme for technology transfer related to energy reduction and efficiency. The JCM was developed by the Japanese government to compliment the UN's Clean Development Mechanism (CDM). It allows Japan to account for its emission reductions by transferring low carbon technology, services and products to developing countries whilst contributing to their sustainable development. Japan has engaged 19 countries under the JCM since its launch in 2013.[153]

JCM scheme between Japan and Partner Country



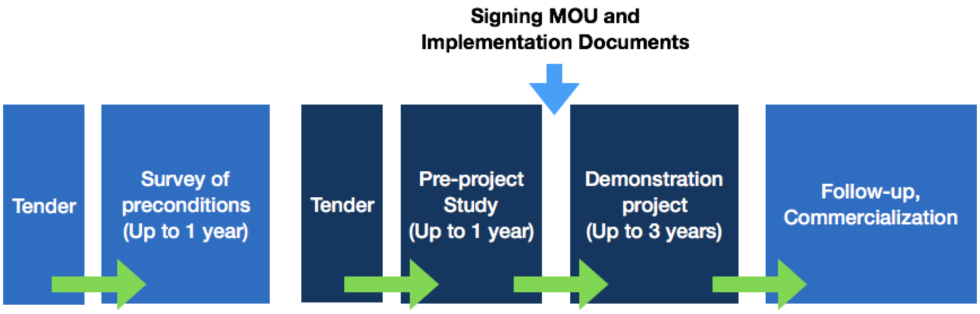
Source: The Joint Crediting Mechanism.

Between 2011 and 2016, the total worth of JCM projects was 8.9 billion yen ($ 80 million), and the proposed budget for 2017 was 1.9 billion yen ($ 17.1 million). Among them was a feasibility study of carbon capture, utilization and storage (CCUS) in Saudi Arabia using Japanese CO_2 separation and collection technology. The scope of evaluation includes the potential of greenhouse gas mitigation, commercial viability, types of financing options, and economic performance. The study was carried out between 2015 and 2017, and it will likely be renewed from 2018 onwards under the JCM scheme.[154]

NEDO can also provide funding for demonstration projects of Japanese energy technology and know-how overseas.[155] The aim is to promote Japanese industries while also contributing to the sustainable development of the partner country and reduction in global greenhouse gas emissions.

152. METI and IEEJ, "2017 Research Report on the Possibility of Implementation of the Joint Credit Mechanism in Infrastructure. Report ahead of the Master Plan on Low Carbon Energy System Development in Saudi Arabia".
153. GEC, "Overview", The Joint Crediting Mechanism, n.d., available at: http://gec.jp.
154. METI and IEEJ, "2017 Research Report on the Possibility of Implementation of the Joint Credit Mechanism in Infrastructure. Report ahead of the Master Plan on Low Carbon Energy System Development in Saudi Arabia".
155. NEDO, "NEDO International Projects; Addressing International Energy and Environmental Issues with Japanese Technology", n.d., available at: www.nedo.go.jp.

NEDO International Demonstration Project Implementation



Source: Adapted from NEDO.

Before the project can be initiated, NEDO may call for a tender on the feasibility survey of preconditions. This is a general country report outlining energy statistics of the partner country and possible areas for collaboration. Once complete, a second tender is initiated for the actual demonstration which consists of a pre-project study (up to 1 year) and the demonstration project (up to 3 years). With the tender, NEDO selects a Japanese company to conduct hearings with the partner government and private sector in order to develop a concrete demonstration proposal. Once approved, NEDO signs an MOU with the partner government, while the designated Japanese company and its counterpart sign the Implementation Document on specific operational details. The demonstration project is carried out for up to 3 years. Finally, the process is capped off with a series of project evaluations and follow-up initiatives aimed to eventually scale-up and commercialize the technology in the country.[156]

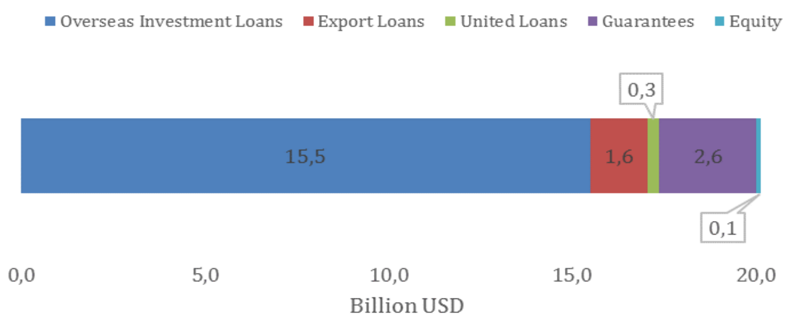
NEDO's budget for demonstrations in 2017 was roughly 14 billion yen ($ 126 million). Traditionally, NEDO took on full project funding, but recently it shifted to partial support. For subsidized projects, NEDO covers 1/2 of the cost for large companies and 2/3 of the cost of small-to-midsize enterprises (SMEs). For the pre-project study NEDO offers up to 2 million yen ($ 18,000) for large companies and up to 3 million yen ($ 27,000) for SMEs.[157]

Having proven commercial viability in the demonstration phase, projects can then apply for funding from the Japan Bank for International Cooperation (JBIC). The state-owned JBIC complements private banking institutions with policy-driven financing solutions. In addition to

156. NEDO, "International Energy Consumption Efficiency Technology/Ssytem Demonstration Project Tenders", April 2016, available at: www.nedo.go.jp.
157. METI and IEEJ, "2017 Research Report on the Possibility of Implementation of the Joint Credit Mechanism in Infrastructure. Report ahead of the Master Plan on Low Carbon Energy System Development in Saudi Arabia".

maintaining and improving global competitiveness of Japanese industries, the bank aims to uphold the following pillars: international development and securing upstream resources critical to Japan; international business development for environmental protection; and prevention and resilience to global financial disruptions.

JBIC's operations in 2016 (billion $)



Source: JBIC Annual Report 2017.

JBIC's operations can be divided into overseas investment loans, export loans, united loans, guarantees and equity finance. In 2016, JBIC's operations totaled 2.2 trillion yen ($ 20 billion), with overseas investment accounting for 77% share.[158] In terms of regions, the strongest presence is seen in Europe, followed by the Middle East, Central and South America, and North America. In July 2014, JBIC issued a loan for an EOR project to capture carbon emissions from a coal power plant in Texas, the U.S., operated by JX Nippon Oil & Gas Exploration company and American utility NRG Energy.[159]

The third Japanese institution key to overseas infrastructure development is the state-owned Nippon Export and Import Insurance agency (NEXI). It protects investment and trade from geopolitical risks (e.g. wars, natural disasters) and commercial risks (e.g. default or non-repayment by foreign business counterpart) that cannot be insured by private companies. In 2016, NEXI's operations amounted to roughly 7 trillion yen ($ 63 billion).[160]

158. JBIC, "Annual Report" (Japan Bank for International Cooperation, 2017), p. 14, available at: www.jbic.go.jp.
159. METI and IEEJ, "2017 Research Report on the Possibility of Implementation of the Joint Credit Mechanism in Infrastructure. Report ahead of the Master Plan on Low Carbon Energy System Development in Saudi Arabia".
160. *Ibid*.

Conclusion

As a resource-poor but economically and technologically advanced nation, Japan is uniquely compelled to undertake the development of hydrogen in its energy system in the coming decades as a response to energy and climate challenges. The government has its sights on the entire supply chain of zero-carbon hydrogen, from its production to transportation and application in various sectors.

Japan's Strategy is ambitious, involving domestic and overseas industry and government stakeholders on a number of cross-sectoral pilot projects. At this stage, the economic and technical challenges and uncertainties have not been lifted. The government awaits the results of the ongoing pilot projects around 2020 before considering the integration of hydrogen into the wider economic and energy plans. While public funding is steadily increasing, it remains limited and reflective of the government's caution against any long-term commitment. Decarbonization of Japan's energy sector still rests on nuclear, natural gas, energy efficiency and RES.

Success will depend on Japan's ability to produce, procure and use large volumes of zero-carbon hydrogen at a cost that is competitive with alternative fuels. Reaching cost parity is also significantly dependent on the emergence of effective carbon pricing.

Moreover, a domestic scale up will have to be paired with an international push for hydrogen. Hence why a global coordination of policies and cooperation among industries will also be increasingly needed.

METI and NEDO will host the Hydrogen Energy Ministerial Meeting on October 23, 2018 in Tokyo. The meeting will bring together ministers of major countries committed to hydrogen-related efforts worldwide, representatives of private companies and stakeholders.[161] The aim is to enhance cooperation and to harmonize efforts on a global level by exchanging best practices, hold discussions on future directions of policies for global utilization of hydrogen, while maintaining the focus on the 2019 G20 summit meeting to be held in Japan.[162]

161. ANRE, "Hydrogen Energy Ministerial Meeting to Be Held", Release, METI, May 8, 2018, available at: www.meti.go.jp.

162. The Hydrogen Energy Ministerial is timed to coincide with the LNG Producer-Consumer Conference which will be held on October 22, 2018 in Nagoya.

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