The Potential of Hydrogen Energy and Innovative Diffusion Models in Japan

Baizi Zeng and Wanglin Yan

Abstract Japan's energy system is vulnerable in terms of energy security and self-sufficiency, due to the nation's scarcity of fossil fuel resources and heavy reliance on imports, but the government sees promise in hydrogen energy. Hydrogen refueling stations and fuel cells are essential components in transportation and energy sectors, but several obstacles exist. This chapter looks at two applications for hydrogen. First it compares scenarios for introducing fuel cell vehicles and buses along with the required hydrogen refueling stations in Kanagawa Prefecture. Analysis shows that uneven user distribution will hinder the deployment of hydrogen refueling stations and negatively impact service equity due to challenges providing service where hydrogen demand is low. However, fuel cell buses could play a major role in reducing the financial risks of hydrogen stations and increasing service equity geographically. The second application examined is the concept of an integrated system built around fuel cell use to provide electricity, heat, and water to individual households and buildings, seen from the perspective of the food-energy-water (FEW) nexus. Such decentralized systems could form a complete cycle of resource collection, production, distribution, and recycling based on independent home systems. Combinations of systems offer even greater prospects for the future of hydrogen.

Keywords Hydrogen energy · Fuel cell vehicle · Route bus · Ene-Farm

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1 Introduction

To achieve carbon neutrality and address domestic energy challenges, Japan has been seeking a sustainable shift in the energy mix. Hydrogen energy has received increasing attention in recent years due to multiple benefits, including being clean, renewable, and highly efficient, and capable of being produced from numerous sources. The government has proposed the idea of building a “hydrogen society” and presented a detailed road map in 2014. Since then, the development of hydrogen energy has become a fundamental national policy and a series of related strategies have been formulated.

Among the many potential applications for hydrogen energy, fuel cell vehicles (FCVs) and home-use fuel cells would be the most closely associated with changes in the lifestyles of residents. Rather than the public transportation sector, Japan has chosen private-use FCVs as one area to seek breakthroughs to expand the use of hydrogen energy in the transportation sector. However, the high cost of building hydrogen refueling stations (HRSs) and the uncertain market penetration of FCVs have created somewhat of a “chicken-and-egg” situation. The scattered and limited demand for hydrogen in the private FCV market make the economics of HRSs a major challenge, while the lack of convenient HRSs also hinders the development of the FCV market. The Japanese government envisions the development of the FCV market in parallel with the construction of new HRSs, but data show that the current market penetration of fuel cell vehicles is far below targets.

Conversely there appears to be greater potential demand for hydrogen in public transportation systems, and it would be more stable and concentrated. In contrast to Japan’s development strategy, China has chosen public transportation as the breakthrough sector to expand the scale of hydrogen energy use. While building a network of HRSs, the government supports the introduction of fuel cell (FC) buses and creation of a hydrogen path to support HRS businesses in the early stages of the market.

Thus, to shine a light on the potential for such an approach in Japan, through the collection and calculation of traffic data in the study area of Kanagawa Prefecture, this chapter will compare the potential hydrogen demand from the public transportation system and private FCV market, and analyze the impacts of each on the spread of a network of hydrogen refueling stations.

On a separate but related line of pursuit, this chapter also looks at home-use fuel cell systems. Such systems use electrochemical cells designed with combined heat and power (CHP) technology, and use natural gas or hydrogen energy to produce electricity, heat, and hot water to supply homes. Due to the on-site production and co-generation technology, these systems have higher efficiency than traditional electricity production and can also reduce electrical transmission loss and heat loss. Another benefit is that home fuel cells can be configured to operate off-grid and provide continuous power and hot water for several days in the event of a natural disaster or power grid interruption. Taking this concept further, a domestic microgrid and a food-energy-water (FEW) nexus system could be built based on fuel cells, integrated with other power sources such as solar photovoltaic, as well as water tanks and storage batteries. The use of home fuel cells could transform the household of the future and have positive impacts on FEW nexus efficiency, safety, resiliency, and decarbonization.

Thus, to pursue this angle, this chapter also discusses the impacts of fuel cell technology on household power systems of the future and the FEW nexus at the household level.

2 Hydrogen Energy in Japan

2.1 Challenge of Japan's Energy Structure and Potential of Hydrogen

Energy challenges are serious for Japan because of the nation's resource scarcity. Japan's energy system is fundamentally vulnerable in terms of energy security and self-sufficiency because Japan is poor in fossil fuel resources and relies heavily on overseas imports. The energy self-sufficiency rate of Japan has remained extremely low, at about 6–7% in the past decade, due to the shutdown of nuclear power plants after the Great East Japan Earthquake in 2011, and it is the second-lowest among OECD countries. In 2020, Japan declared a goal of achieving carbon neutrality and building a decarbonized society. However, energy consumption still accounts for 84.2% of Japan's total CO_2 emissions (MOE 2021). Therefore, a structural shift and the large-scale introduction of clean and renewable alternative energy is essential to achieve these ambitious targets.

Hydrogen energy is a zero-emission energy (at least at the point of use) that can be produced from a variety of different primary resources, such as methane, natural gas, and coal. The diversity of production methods can contribute significantly to improving energy security and flexibility. Besides fossil fuel sources, hydrogen produced from renewable energy is considered a life-cycle carbon-free energy (Zhang et al. 2020). Hydrogen can also be used as an energy carrier to store and distribute an oversupply of renewable energy and play a key role in solving the issue of fluctuating output of renewable energy, and help to scale up the application of renewable energy. Combined with fuel cell plants, hydrogen energy can be used in a variety of ways, including electricity generation (hydrogen gas turbines), mobility (FCVs), and households (fuel cells) (Table 1).

2.2 Hydrogen Energy Strategies in Japan

Japan is the first country to have established a national strategy for hydrogen development, and its national energy strategies in recent years have emphasized

Table 1 Hydrogen strategies in Japan

Year	Policy	Description
2014	Fourth strategic energy plan	Introduces concept of a" hydrogen society"
	Hydrogen fuel cell road map	Describes road map to achieve a hydrogen society through three phases
2016	Hydrogen fuel cell road map (revised)	Sets clear targets for development of hydrogen use and supply
2017	Hydrogen basic strategy	Presents an action plan from the perspective of the entire energy system
2018	Fifth strategic energy basic plan	Presents fundamental reinforcement of measures for realizing a hydrogen society
2019	Hydrogen fuel cell road map (revised)	Revises targets revision and establishes a working group for follow-up in each sector
	Hydrogen and fuel cell technology development strategy	Sets targets for technology development
2020	Green growth strategy through achieving carbon neutrality in 2050	Sets hydrogen as a key method to achieve carbon neutrality

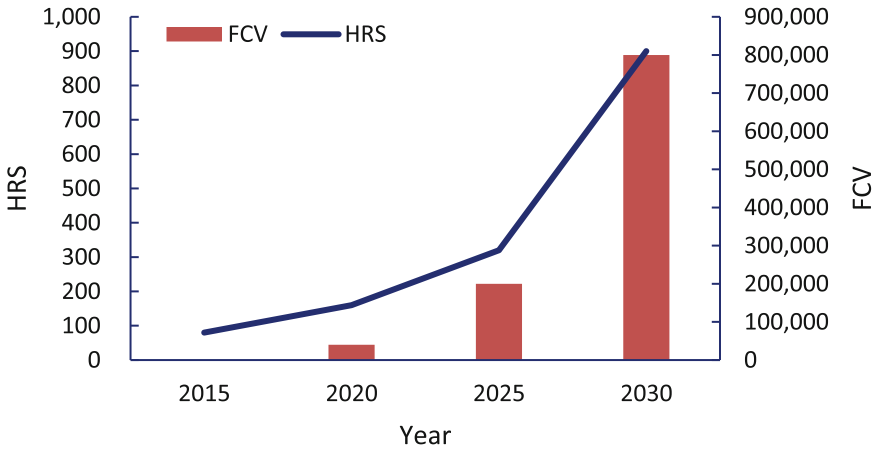


Fig. 1 Japan's hydrogen development targets (number of units) for hydrogen refueling stations and fuel cell vehicles. (Source: Ministry of Economy, Trade and Industry, 2019)

the significance of hydrogen. In 2014, the fourth Strategic Energy Plan proposed the idea of building a "hydrogen society." The same year, the Strategic Road Map for Hydrogen and Fuel Cells was released, and later revised in 2016 and 2019. It includes specific and detailed development targets for hydrogen utilization and supply, as shown in Fig. 1 and Table 2. Japan established the Basic Hydrogen Strategy in 2017 as an action plan for both the private and public sectors. In 2018, the Fifth Strategic Energy Plan again emphasized the importance of hydrogen energy and proposed the reinforcement of measures for realizing a hydrogen society. In 2019, a working group was established to evaluate targets for the road map. To

Table 2 Target achievement rates relative to hydrogen Fuel cell road map

Item and data year	HRS (2021)	Private FCV (2019)	FC bus (2019)	FC forklift (2019)
Achievement rate of 2020 target	157 (98.1%)	3,757 (9.4%)	57 (57%)	250 (50%)
Target (for 2020)	160	40,000	100	500
Target (for 2025)	320	200,000	–	–
Target (for 2030)	900	800,000	1,200	10,000

HRS hydrogen refueling station, *FCV* fuel cell vehicle, *FC* fuel cell
(Source: METI 2020a, b)

promote hydrogen energy technology innovation, the Hydrogen and Fuel Cell Technology Development Strategy was formulated, including clear targets for technological improvements. The Japanese government also established the Green Growth Strategy Through Achieving Carbon Neutrality in 2050, which focusses on three major industrial sectors that are all closely related to hydrogen energy (METI 2020a, b): energy; transportation and manufacturing; and construction. For example, in the construction sector, fuel cell systems can supply both electricity and heat for households and reduce the consumption of primary energy through co-generation. This could be an important step for next-generation housing. In the transportation and manufacturing sectors, Japan is targeting the development of hydrogen-powered fuel cell vehicles, fuel cell ships, aircraft, and machinery.

2.3 Current Development Status and Barriers

As of the most recent data, there were 157 hydrogen refueling stations in Japan (including 117 stationary and 40 mobile units), mainly in central areas of the Tokyo and Osaka metropolitan regions (Fig. 2). This number represents 98.1% of the target (2020) at that point under the Hydrogen Fuel Cell Road Map (Table 2). Generally, the supply capacity of a stationary and mobile HRS is 300 Nm^3/h and 100 Nm^3/h, respectively. More than 700 new hydrogen stations are planned for the future, which means that a rational and efficient deployment plan will be needed. Meanwhile, although the Basic Hydrogen Strategy indicates that FCVs and hydrogen station deployment are to be promoted in parallel, there is a significant gap between achievement rates for HRS and FCVs. Table 2 illustrates the achievement rates relative to target years in the road map. According to a METI report, the achievement rates in 2019 for FC bus and forklift targets were only about 50% of the 2020 targets, or 57 and 250, respectively. For private fuel cell vehicles, the number and targets achievement rate were even lower, at 3,757 units and 9.4%, respectively (METI 2019). The table suggests that development of hydrogen supply relative to market demand is extremely unbalanced.

From the perspective of investment in hydrogen energy in the mobility sector, the construction cost of an HRS has been reduced in recent years. According to the

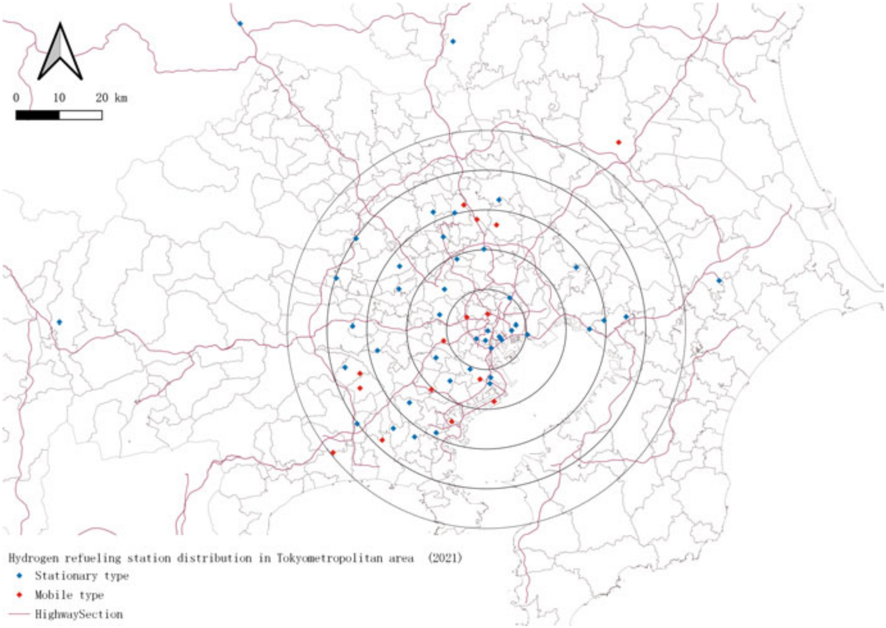


Fig 2 Hydrogen refueling station distribution in Tokyo metropolitan area (2021). (Source: Next Generation Vehicle Promotion Center: NeV, 2021)

METI report (METI 2020a, b), the average construction cost of an HRS remained at a level of 330 million yen in 2019, about 130 million yen reduced compared to the initial development period. Meanwhile, annual operating costs had decreased to about 20 million yen, down from 31 million yen per year in 2019. However, HRS construction and operating costs are still much higher than for the standard gasoline station. At the same time, low market penetration of FCVs makes it difficult for an HRS to be economically viable, and the cost of an FCV remains in the same price range as luxury cars. Taking the Toyota *Mirai* as an example, the selling price is 7.1 million to 8.6 million yen. The government offers about a three million yen subsidy per vehicle for FCV buyers, but even so, the price is still higher than most electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs).

Hydrogen refueling stations that can produce and distribute hydrogen energy to facilities and vehicles are an important part of infrastructure for the future large-scale utilization of hydrogen energy. However, there are several obstacles to the rapid spread of independent HRSs. Two obstacles are construction and operating costs, as mentioned above. Meanwhile, as mentioned, hydrogen demand is insufficient due to low market penetration and capacity utilization is not sufficient to be economically viable in the early stages of FCV market development. In addition, a mid-size stationary hydrogen station requires about 700 m^2 of space, and finding suitable land is a challenge, especially in urban areas.

The relationship between HRS promotion and FCV market development is often described as a "chicken and egg" situation. Consumers will have confidence to purchase an FCV only if adequate hydrogen stations are available to provide satisfactory service coverage, but investors will usually build hydrogen stations only if there is sufficient hydrogen demand to maintain high capacity utilization rates and achieve profitability (Li et al. 2020; Michalski et al. 2011; Zhang et al. 2020). From the point of view of Japan's strategic plan, it might be more difficult to solve this challenge since Japan's strategy is centered on the private vehicle market, which has considerable uncertainties and cannot guarantee stable and sufficient demand at the early transition stage. Also, private FCV users are sparsely distributed nationwide and cannot be centralized to support HRS demand. Hence, investors in HRS businesses would face significant financial risks, which may hinder their investment motivation. To address this challenge, a coordinated approach to the introduction of hydrogen demand and hydrogen station deployment could be a solution. This would mean that when decision makers create an HRS layout plan, they also need to give adequate consideration to promoting commensurate hydrogen demand from fuel cell vehicles (Li et al. 2020).

3 HRS Development Proposal Based on Public Route Buses

3.1 Methodology and Data Use

The private FCV market cannot guarantee the scaling up to the extent expected. Compared to the private FCV market, a strategy to introduce FC buses might make it easier to plan the layout of a network of HRSs and coordinate the hydrogen supply side with demand side, for a number of reasons. First, route buses have large potential hydrogen demand since the annual hydrogen consumption of one FC bus amounts to that of about 45 private FCVs. Second, hydrogen demand for route buses would be stable and centralized, since route length, operational frequency, and refueling locations are fixed. Third, bus transit centers, where buses assemble and are stored, typically serve as core locations for bus operations and maintenance facilities, and would likely have sufficient land area available for HRS construction. This chapter will consider transit centers as candidate locations to install HRSs and calculate potential hydrogen demand and regional distribution for both FCVs and FC buses, then compare the economic viability of HRSs in each scenario.

This analysis uses Kanagawa Prefecture as the study area because the Kanagawa government has made a detailed strategic road map of hydrogen energy and aims to achieve these development targets in 2025 (Kanagawa Next Generation Vehicle Promotion Council 2015). According to the strategic road map, the FCV targets for 2025 range from 20,000 to 100,000 vehicles, under three scenarios. Using those three market penetration scenarios (20,000, 50,000, and 100,000 vehicles), benchmarking with percentages of targets achieved, we estimate potential FCV users based on demographic data and vehicle ownership ratios. Future population projections by 1 km mesh are multiplied by household ratio to estimate regional distribution by household type in 2025. Then the numbers of households by 1 km mesh are multiplied by vehicle ratio and FCV market penetration in different scenarios to estimate the regional distribution of potential FCV users.

This chapter then uses bus route data from National Land Information Division (2017) to calculate potential annual hydrogen demand on each bus route system for 1 year using the equation provided below. As bus frequency differs on weekdays versus weekends, potential annual hydrogen demand is calculated separately for each. The calculated potential hydrogen demand is doubled to account for the fact that route buses travel back following the same route. The results of potential hydrogen demand of each bus route are summed up and associated with their respective transit centers, to calculate the total potential hydrogen demand at each transit center. Transit center data is obtained from Google Earth, bus company data, and government reports. We start with Eq. (1):

$$\begin{aligned} D_{\mathrm{kbus}} = {} & E_{\mathrm{FC\ bus}} \times 2 \\ & \times \left\{ 244 \times \left(L_k \times F_{\mathrm{kweekdays}} \right) + 121 \times \left(L_k \times F_{\mathrm{kweekends}} \right) \right\} \end{aligned} \tag{1}$$

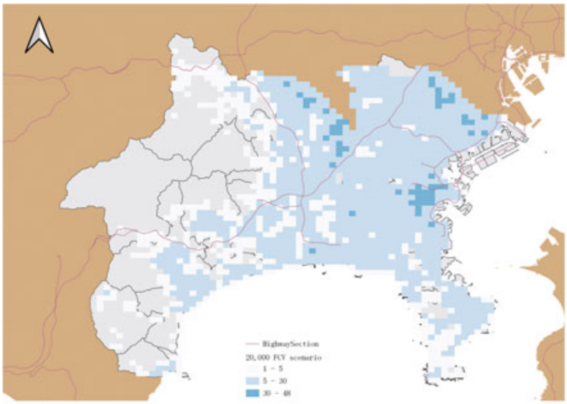
where D_{kbus} represents potential hydrogen demand of bus route system $k \in K$, and L_k is the length of bus route system $k \in K$. $E_{FC\ bus}$ is the fuel economy of an FC bus, which is 0.9 km/Nm^3. $F_{\mathrm{kweekdays}}$ and $F_{\mathrm{kweekends}}$ represents operational frequency of bus route $k \in K$ on weekdays and weekends (including public holidays), which are 244 days and 121 days, respectively. As mentioned, total one-way demand on each route system is multiplied by 2 to account for each bus's return trip.

Future population projections by 1 km mesh and household ratios are obtained from the National Land Information Division and the National Institute of Population and Social Security Research Center. To estimate the number and regional distribution of potential FCV users, it is crucial to take full account of future demographic changes and geographic characteristics, including population, household types, vehicle ownership rates, and location types. This chapter uses published research results of vehicle ownership rates by different mesh type (distance to station; within or outside trade area; mesh population size) and household type (single; nuclear; other) (Ariga and Matsuhashi 2013). Some of the transit center data is provided by the Kanagawa Chuo Kotsu Co. bus company, and the rest of the data is obtained from the official website of famous bus company in Kanagawa Prefecture. The total number of bus transit centers data collected is 71 and the number 1–71 will refer to each of bus transit center.

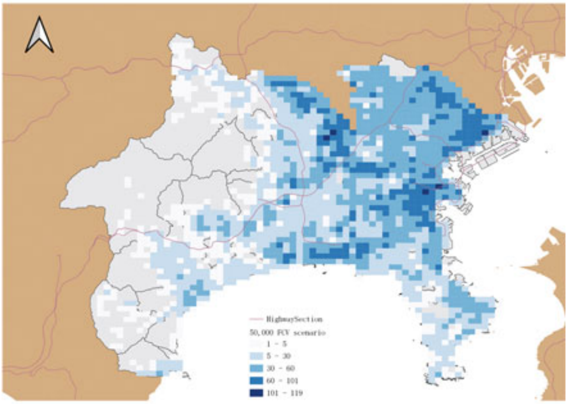
3.2 Regional Distribution and Hydrogen Demand of FCVs

Fig. 3 shows estimated regional distribution maps of FCV users by 1 km mesh, which vary significantly under different market penetration scenarios. As shown in

Fig. 3 Regional distribution of FCV users under three scenarios. (**a**) 20,000 FCV scenario. (**b**) 50,000 FCV scenario. (**c**) 100,000 FCV scenario



(a)



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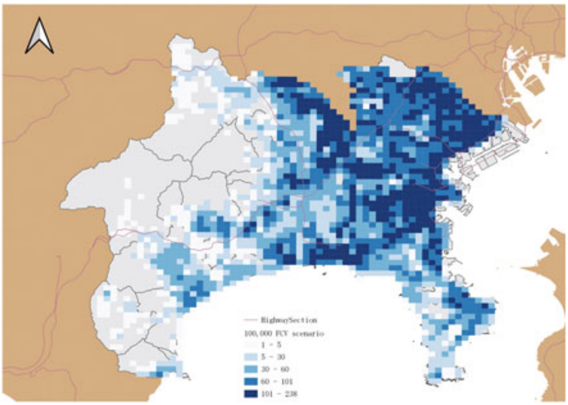

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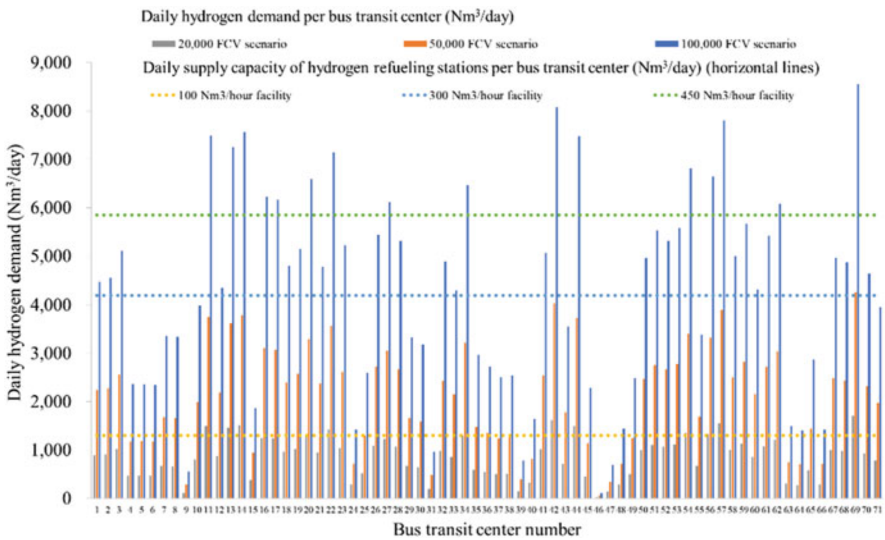

Fig. 4 Daily hydrogen demand of FCVs in different scenarios

Fig. 3a, regional distribution of FCVs is relatively even and the number of FCVs within most of meshes is quite small, at only 5–30 in the 20,000 unit development scenario. In certain areas (including Minami ward of Yokohama City, east area of Kawasaki City, Minami ward and Chuo ward of Sagamihara City), there are only a few meshes where the number of FCVs is larger than 30. These three cities are government ordinance-designated (larger) cities with populations over 500,000. In the 50,000 FCV development scenario as shown in Fig. 3b, the number of meshes with 30–60 FCV users increases rapidly and is spread over into the east area. Four clusters of meshes with more than 60 FCV users appear, mainly in the government ordinance-designated cities mentioned above, and special cities with populations of more than 200,000 in southern areas of Kanagawa Prefecture. Finally, in the 100,000 FCV development scenario shown in Fig. 3c, the number of FCV users of meshes with more than 101 FCVs which are distributed in four clusters mentioned above has increased and is spread out along the railway lines. Meshes with 30 to 101 FCV users are mainly distributed around these four clusters. In western and southeastern Kanagawa Prefecture, the number of FCVs remains extremely low, at just 1–30 FCVs, due to low population density. The results of FCV user distribution show that even if the number of FCVs were to increase to 100,000 units as projected by government, meshes with a large number of potential FCV users will be mainly concentrated in three government ordinance-designated cities and the southern area of the prefecture where there is a high population density. However, in the west, central, and southeast areas, the number of FCV users is quite small and sparsely distributed.

Fig. 4 shows the potential hydrogen demand of FCVs in three different scenarios. The red, blue, green dotted lines (horizontal) represent the supply capacity of HRSs at 100 Nm^3/h, 300 Nm^3/h, and 450 Nm^3/h, which works out to supply capacity of 1,300 Nm^3/day, 4,200 Nm^3/day, and 5,850 Nm^3/day, respectively. In the 100,000 FCV scenario, maximum and minimum hydrogen demand for FCVs is 8,554.5 Nm^3/day and 116.98 Nm^3/day, respectively. Average daily demand is 4,257 Nm^3/day, and 40 HRS sites would have enough capacity for a 100% capacity utilization rate with mid-size HRSs. However, in the two scenarios below the 100,000 FCV level in Kanagawa Prefecture, the picture changes. In the 50,000 FCV scenario, average demand is 2,128.7 Nm^3/day, only enough to justify mid-scale HRS facilities at a 50.6% utilization rate. Only one site would have enough demand to support a 100% utilization rate of a mid-sized HRS. Finally, in the 20,000 FCV scenario, hydrogen demand is extremely low and average hydrogen demand across all HRS locations is only 852.1 Nm^3/day. The hydrogen demand at most bus transit centers is below the capacity of even a small-scale HRS.

3.3 Hydrogen Demand for Route Buses

Figure 5 shows the potential daily hydrogen demand of FC buses and FCVs separately, and the sum of both. Hydrogen demand for FCVs is calculated using the 100,000 vehicle scenario. Comparing demand of FC buses versus FCVs, it is apparent from Fig. 5 that even if the target for FCV development was 100% achieved, which means sales of 100,000 FCVs, hydrogen demand for FC buses would still be two to four times larger. Maximum and minimum hydrogen demand for FC buses are calculated at 24,638.5 Nm^3/day and 990.2 Nm^3/day, respectively. The average daily demand for FC buses is calculated at 10,963.9 Nm^3/day, about two times larger than supply capacity of a large-scale HRS.

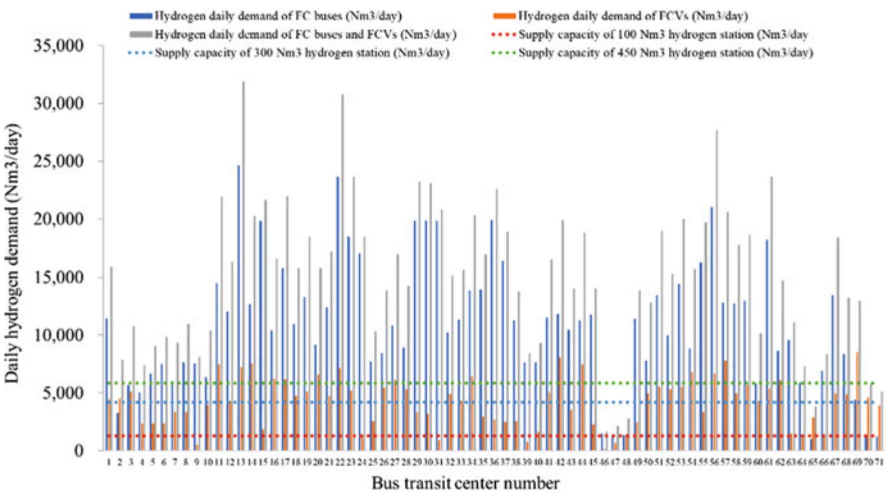

Fig. 5 Comparison of daily hydrogen demand of FC buses, FCVs, and the sum of both

For FC buses, there are 64 transit centers and 60 transit centers of which daily hydrogen demand is larger than 4,200 Nm^3/day and 5,850 Nm^3/day, which means that demand of almost all transit centers is quite enough to support a mid- or large-scale hydrogen station operating at 100% of capacity. Only three transit centers would not have enough hydrogen demand to support 100% capacity utilization rate for a mid-scale hydrogen station and four transit centers not enough hydrogen demand to justify a small HRS. For these seven transit centers (Sugita, Miyano, Yugawara, Sekimoto, Yokohama, Kugenuma, and Daishinto) the average hydrogen demand is about 1,574.5 Nm^3/day. However, if these they could also provide public refueling services for FCV users, the Sugita, Kugenuma, and Daishinto transit centers could have enough hydrogen demand to support a 100% capacity utilization rate for a mid-scale HRS. The other four transit centers could have enough demand to support a small-scale HRS at a 100% operating ratio. Another benefit of this scenario is that the estimated hydrogen demand is stable and predictable since bus routes and operational frequencies are fixed and well known.

4 Role of Fuel Cell Technology in the Food-Energy-Water Nexus

4.1 Development Status of Fuel Cells in Japan

Currently, commercial fuel cell systems can be classified into three types from the perspective of energy production method: indirect (reformed); indirect (water electrolysis); and hydrogen consuming fuel cell. Ene-Farm is the brand name in Japan for a household use indirect fuel cell system that operates through fuel (natural gas) reforming to produce hydrogen and supply power to individual households. Panasonic and Kyocera launched the Ene-Farm system in 2009, and sales for household use nationwide exceed 400,000 units so far (Fig. 6). H2One by Toshiba is a stand-alone indirect fuel cell that can be integrated with renewable energy to produce hydrogen on-site through the electrolysis of water. This system is designed to provide power for large facilities and communities, and has been installed in several Japan Rail (JR) stations, as well as office buildings and stadiums.

A hydrogen consuming fuel cell is directly charged with hydrogen gas produced separately, to produce power and heat. This type of fuel cell could be installed in locations where there is enough hydrogen production nearby, such as a factory.

Indirect (reformed) fuel cells are the type mainly introduced for use in households and small buildings as they can use existing infrastructure, such as pipelines that deliver natural gas to the home to produce hydrogen on-site, and supply power and heat. Currently, for households or small buildings, it is still difficult to directly deliver hydrogen from outside sources or to install renewable energy facilities on-site at sufficient scale to power fuel cells.

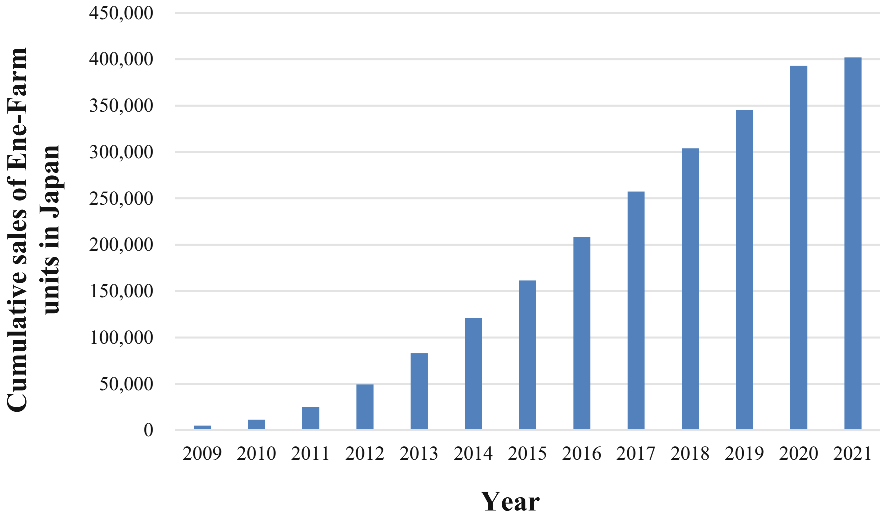

Fig. 6 Cumulative sales of Ene-Farm fuel cell units in Japan. (Source: Ene-Farm Partners)

4.2 Advantages and Significance of Introducing Fuel Cell Systems

The Ene-Farm system can extract hydrogen from liquefied petroleum gas (LPG) to generate electricity, while capturing surplus thermal energy to heat water and space in households. It has generally found applications in individual households and can be integrated with solar panels and battery to supply and storage electricity to the home. The energy management system can be configured to preferentially consume electricity from the Ene-Farm system, and users can sell the excess electricity to the power grid. In a sense, this system could also be considered as a "virtual" power plant in the future. From the perspective of energy saving, Ene-Farm can reduce power loss and heat loss in the process of production and distribution, because power is produced locally, and the co-generation technology can capture surplus heat from household components. According to data from Toshiba, this fuel cell system can reduce fossil fuel consumption in the household by more than 40%, and the savings could be even higher if the home is equipped with a solar photovoltaic system. This system can provide heat and electricity during power outages in the main grid for up to 8 days to maintain basic living (500w–700w). The system is also configured to connect to the family's fuel cell-equipped FCV to supply electricity to the home in the event of a grid interruption or natural disaster. In fact, two FCV vehicles could supply enough electricity for a small hospital or community shelters for up to 1.1 days of normal operation (Horikawa et al. 2015). The Ene-Farm is typically also equipped with a water tank as an emergency backup to supply domestic hot water. In summary, the development of fuel cell systems such as is significant for the water-energy nexus, in terms of security, efficiency, and decarbonization.

For the utilization of fuel cell technology in large facilities, Toshiba has developed a stand-alone indirect fuel cell system called H2One. Basically, this is a decentralized micro power grid that can produce, store, and distribute electricity. While the Ene-Farm still relies on a centralized gas supply, H2One is more independent and environmentally friendly, because it can be configured to be equipped with a renewable energy plant or connected to a renewable power network, and it can use excess renewable energy to manufacture hydrogen through water electrolysis. This, this system is like a micro power grid, and even without an LPG supply, this system can still produce hydrogen and distribute electricity, heat, and hot water to supply a large building or facility. According to recent simulations, this type of fuel cell combined with a solar photovoltaic micro-power grid could meet the needs of 150 households in terms of daily electricity demand, and could offer low cost of energy, zero carbon emissions, and promote the expanded use of renewable resources (Ghenai et al. 2020). And according to information from Toshiba's official website, H2One, has already been installed in Kawasaki city, can supply electricity and hot water for approximately 1 week for 300 people. It can also be used as a small-scale hydrogen station to refuel FCVs, which could reduce construction and operating costs by maintaining a relatively high capacity utilization rate, providing hydrogen for both buildings and FCVs. Actually, this kind of joint supplying system has already been put into use. Toshiba has introduced the first H2One Multi Station to fill FCVs and supply electricity to local food market in Tsuruga City, Japan.

The third type of fuel cell product directly consumes hydrogen from an external source to produce and supply electricity and heat. It could be set up near a factory or other facility that produces hydrogen (even as a by-product). Even if electricity and LP gas supplies are cut off in the event of an emergency, fuel cell systems can still generate electricity and heat by consuming hydrogen from any outside source to supply a factory, building, or single household. The H2Rex system developed by Toshiba has a typical hydrogen consuming fuel cell. More than 100 units have been sold in Japan, mainly for convenience stores, heated swimming pools, and hotels. Also, it can be used to supply hydrogen for both FCVs and fuel cell in building. Compared to conventional hydrogen energy distribution systems that only distribute hydrogen to FCVs, this type of simultaneous supply system that could have greater benefits in terms of CO_2 emission reductions and reduce primary energy consumption because of the higher operation rate and efficiency of hydrogen production. (Pak et al. 2006).

4.3 Proposal of FEW Nexus System Based on Fuel Cells

From the point of view of the FEW nexus, fuel cell can play an important role in developing the independent household FEW nexus in combination with other technologies and power sources. The M-NEX Tokyo team has proposed a FEW system which might be a feasible solution to build an independent, energy saving, low emission household FEW system, as shown in Fig. 7. This system includes

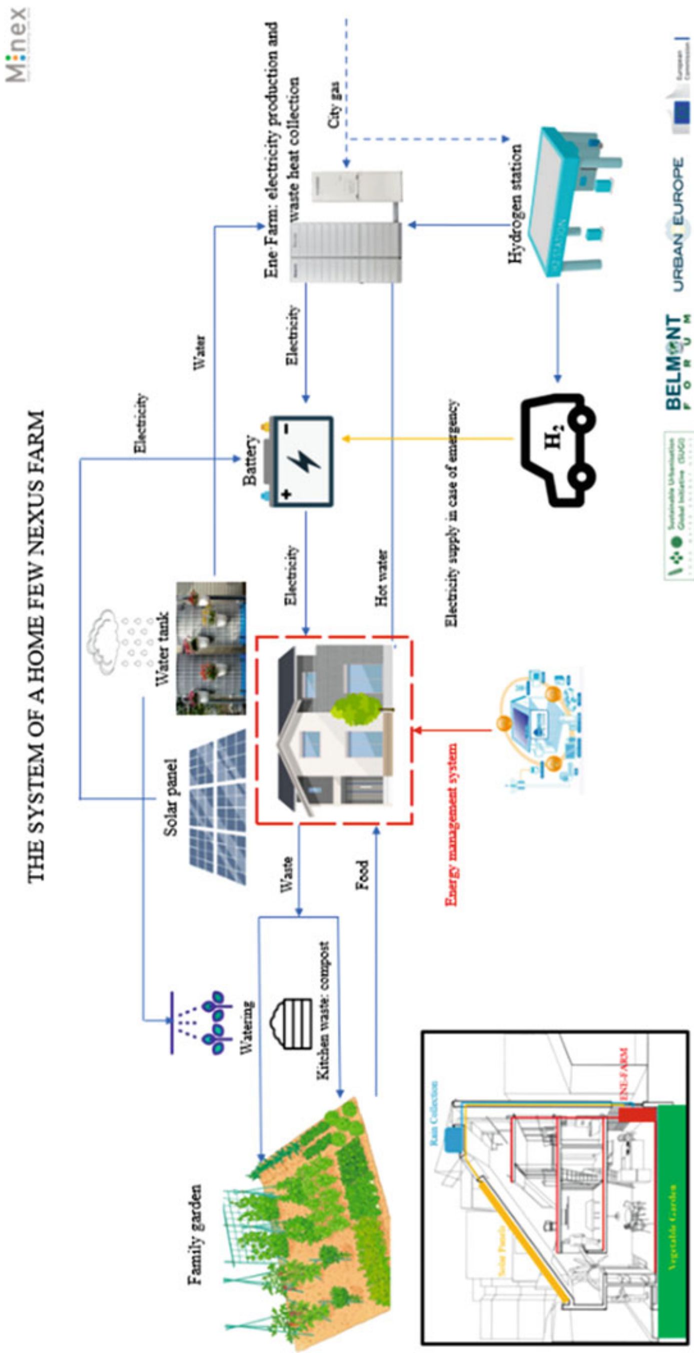

Fig. 7 Conceptual design of a home food-energy-water (FEW) nexus system. (Source: M-NEX project)

multiple processes of production, storage, distribution, consumption, and recycling, in terms of food, energy, and water. Combined with a solar panel and energy storage battery system, a fuel cell could be a core component to improve energy efficiency and reduce GHG emissions and primary energy consumption, and maintain a relatively independent energy-water nexus. Solar panels and fuel cells could generate electricity to supply to a household and reduce reliance on the power grid. Excess electricity could be stored in batteries or sold to the grid thus having this system serve as a virtual power plant on the regional grid. Using an energy management system, the whole system could preferentially consume electricity from solar panels (instead of the grid) in the daytime and use the grid to replenish insufficient power demand in night, if needed. This system would result in a smoother power supply curve and could be a feasible solution to address the problem of fluctuating output from renewable power. By-product water and heat generated in the process of power generation could be recycled and used to supply heat and hot water to a household.

Such a system can also improve resilience and safety thanks to the water storage in a tank (separate water storage tank in the fuel cell package), while electricity from the fuel cell and battery system could continue to sustain normal daily functioning of a household for serval days. The system can be configured for the fuel cell in an FCV to supply electricity for the household during an emergency, as mentioned above. Hydrogen from an external hydrogen station could also be supplied to a household fuel cell system, and this could have the benefit of improving the capacity utilization rate of hydrogen stations in the community and lower risks for the household. Also, according to the current research, from the energy consumption point of view, hydrogen provision system for a combined FCV and a household fuel cell system with combined heat and power (CHP) designs is better than distributing hydrogen only for FCVs (Pak et al. 2005).

5 Discussion

5.1 Uneven Regional Distribution and Initial Small Demand in FCV Market

This chapter examined the regional distribution of potential future FCV users in Kanagawa Prefecture and found that potential users are unevenly distributed in geographically and mainly concentrated in three cities (Yokohama, Kawasaki, and Sagamihara) and the southern part of the prefecture. This uneven distribution will hinder future deployment plans for hydrogen refueling stations (HRSs) and have negative impacts on service equity, since it will be difficult to maintain HRS services in the regions that have low hydrogen demand. According to Kanagawa's strategic road map, even under the optimal scenario with 100% of FCV unit targets (100,000 units) being reached, still half of the transit centers would not see enough hydrogen demand to support a 100% capacity utilization rate at mid- and large-scale

HRS facilities. In the 50,000 FCV scenario, almost all sites would not see enough hydrogen demand to keep a mid-scale HRS going at a 100% operating rate. In the 20,000 FCV scenario, more than 60 HRS sites would not even support a small HRS. In conclusion, even in the best-case FCV deployment scenario there is still a gap between targets and HRS deployment based on Kanagawa's road map, and this means that it is essential to introduce new and additional hydrogen demand if the prefecture wishes to promote the development of the hydrogen energy infrastructure.

5.2 Potential of Fuel Cell Buses to Induce Hydrogen Infrastructure Development

We have seen that demand for FCV cars is small and unevenly distributed in the study region, but hydrogen demand to power fuel cell route buses in Kanagawa would be much larger, and sufficient to justify mid- or large-scale hydrogen refueling stations at most transit centers. Hydrogen demand for FC buses would be more balanced than for FCV passenger cars alone, meaning that HRSs could be deployed even in areas with relatively low population density, and still maintain sufficient operation rates to be economically viable. The introduction of FC buses could play a significant role in reducing financial risks of hydrogen station operations and help increase service equity in specific areas of the region that have lower hydrogen demand. Our calculations showed only seven transit centers to have relatively low hydrogen demand. However, if those transit centers could be configured to provide hydrogen refueling services for private FCV users, hydrogen demand would be sufficient to justify small- or mid-sized HRS facilities.

5.3 Impacts of Fuel Cell Plants on Future Household FEW Nexus

Systems designed to incorporate fuel cell equipment, solar panels and co-generation technology could reduce primary energy consumption, energy loss, and CO_2 emissions arising in the process of electricity production and distribution compared to conventional electricity supplies that depend entirely on a centralized power grid. For individual households or buildings, this chapter has proposed the concept of the FEW nexus system based on fuel cells configured with other equipment. Such a system could incorporate the whole flow of FEW processes, from resource collection, production, storage, and management to final use, and independently supply electricity, hot water, and heat for several days, even during an emergency. Such a design could reduce reliance on the centralized power grid, improve resilience to disasters, and boost adaptive capacity.

Using hydrogen as a clean and potentially abundant source of renewable energy, Japan's concept of creating a hydrogen society, if realized on a large scale, could exert a significant influence on the FEW nexus. Hydrogen could play a major role in Japan's future energy structure if hydrogen-based energy consumption and demand were both to increase dramatically. In order to achieve carbon neutrality, green hydrogen produced by water electrolysis technology could become an important resource for hydrogen production. Water itself could become an energy production resource. Fuel cell systems can supply electricity, heat, and water to buildings and backup the energy-water nexus even in an emergency. As we have seen, fuel cell technology and hydrogen energy could efficiently lower risks in the FEW nexus. Decentralized energy systems like on-site hydrogen production could more fully utilize local resources to increase local energy supply potential through multiple overlapping hydrogen production methods. Scaling up hydrogen energy utilization could be an effective method to reduce dependence on a single type of energy and diversify the energy structure.

6 Conclusion

This chapter first examined the potential regional distribution of future FCV users in the study area of Kanagawa Prefecture and showed that potential users would be unevenly distributed geographically and demand relatively small. The uneven distribution of FCV users will hinder the deployment of hydrogen refueling stations and have negative impacts on service equity, since stations would not be economically viable in areas that have low demand for hydrogen. A gap still exists between FCV development targets and HRS deployment based on the prefecture's hydrogen road map.

While FCV passenger car demand is still small and unevenly distributed in the region, demand for FC buses has the potential to be considerably greater, enough to justify mid- or large-scale HRS facilities and have them operating at high utilization rates. With adequate deployment of FC buses, hydrogen demand at each refueling site would be more balanced which, means that HRSs could be deployed even in areas with low population density. Hence, the introduction of FC buses can play a significant role in reducing financial risks inherent in hydrogen station operations and help increase service equity in regions with small hydrogen demand. Some bus transit centers that have low hydrogen demand could also have extra capacity to provide refueling services for private FCV users. By doing so, those centers could have enough demand to justify small- or mid-scale HRS facilities.

In terms of fuel cell technology other than for vehicles and buses, this chapter mainly introduced two types of fuel cell products designed for household and commercial building use. Fuel cells could have positive effects on reducing the consumption of primary energy, increasing energy efficiency, and improving resilience and energy security. This chapter then proposed a possible scenario for a FEW circulation system that combines fuel cell technologies with other components, and discussed how such systems could improve the FEW nexus and increase security and resilience. Combined with other technologies, a fuel cell based decentralized FEW nexus system could cover the entire process from resource collection and recycling, production, distribution, management to final use, functioning as independent FEW-based plants for individual households or buildings. Though further advances are still needed, these concepts show the great potential for such systems to improve safety, efficiency, independence and sustainability of the FEW nexus.

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