NEAR-TERM LOCATION OF HYDROGEN REFUELING STATIONS IN YOKOHAMA CITY FROM THE PERSPECTIVE OF SAFETY

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ABSTRACT

The roll-out of hydrogen refueling stations is a key step in the transition to a hydrogen economy. Since Japan has been shifting from the demonstration stage to the implementation stage of a hydrogen economy, a near-term, city-level roll-out plan is required. The aim of this study is to plan near-term locations for building hydrogen refueling stations in Yokohama City, from a safety perspective. Our planning provides location information for hydrogen refueling stations in Yokohama City, for the period 2020–2030. Mobile type and parallel siting type refueling stations have been considered in our planning, and locations were determined by matching supply and demand to safety concerns. Supply and demand were estimated from hybrid vehicle ownership data, and from space availability in existing gas stations. The results reaffirmed the importance of hydrogen station location planning, and showed that use of mobile type stations is a suitable solution in response to the uncertain fuel cell vehicle fuel demand level during the implementation stage of a hydrogen economy.

1 INTRODUCTION

In Japan, industry, government, and academia have collaborated to pursue research into, and development of, a hydrogen economy, where fuel cell vehicles become the primary mode of transportation. This is a desirable forward direction from the perspectives of reducing carbon emissions, improving air pollution, and ensuring resource security [1]. The widespread adoption of fuel cell vehicles requires the roll out of hydrogen refueling stations; however, the relationship between them is the typical “chicken and egg” problem [2-4]. Hence, it is important to roll out hydrogen stations systematically in the near term, before full-scale adoption of fuel cell vehicles occurs [5]. In Japan, where the development of a hydrogen economy is a high priority, 100 hydrogen stations have been established, as of 2019 [6]. Japan's Ministry of Economy, Trade, and Industry has created a hydrogen economy road map with the aim of rolling out 200,000 fuel cell vehicles and 320 hydrogen stations by 2025 [7]. Hence, Japan is promoting the near-term roll out of hydrogen stations at the national level, and the next step is to plan hydrogen station locations at the city level.

Previous studies on the deployment of hydrogen refueling stations can be divided into three approaches [5, 8-19]. The first approach focuses on demand from fuel cell vehicle users, and seeks the optimal locations of hydrogen stations to satisfy that demand. This includes (i) studies based on the P-median model [8-10], which targets regional demand; (ii) the flow interception model [11-14], which targets inter-regional demand, and (iii) research that considers travel time to hydrogen stations [15]. The second approach focuses on the supply of hydrogen stations, and seeks to identify optimal locations by minimizing hydrogen supply life cycle costs [16, 17]. The third approach, which considers both supply and demand, develops multiple criteria related to supply and demand, and subsequently seeks the optimal locations of hydrogen stations by maximizing those criteria [18, 19]. Studies have also been conducted to estimate demand from regional characteristics, where supply costs are imposed as a supply constraint, and the locations of hydrogen stations that balance supply and demand are considered [5].

Our research can be classified as an approach that considers both supply and demand, and also considers the planning of hydrogen station locations from the additional perspective of station safety. The purpose of this study has been to plan the locations for the near-term roll out of hydrogen stations over the years 2020–2030 in Yokohama City, which is a city at the forefront of Japan's push toward a hydrogen economy.

2. METHODOLOGY

2.1 General Overview

The location of Yokohama City, which is the focus of this study, is shown in Fig. 1, while Fig. 2 shows the overall flow of our approach to planning hydrogen station locations. The background maps shown in Fig.1 can be obtained by the national land numerical-information data-download service provided by the Ministry of Land Infrastructure, Transport and Tourism (MLIT) [20]. To consider the relationship between demand from fuel cell vehicles and supply of hydrogen stations, our approach includes a demand model, supply model, and a supply–demand matching process.

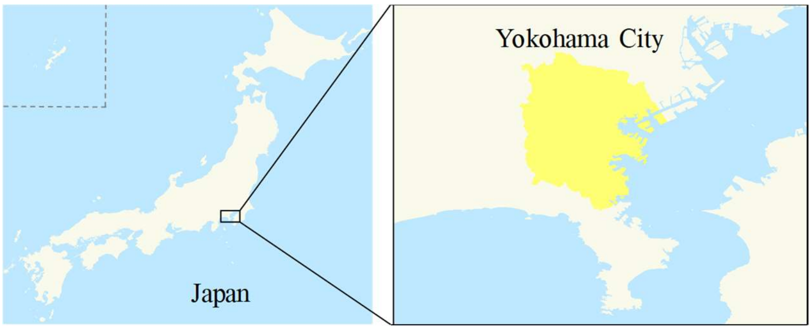


Figure 1. Target city for this study

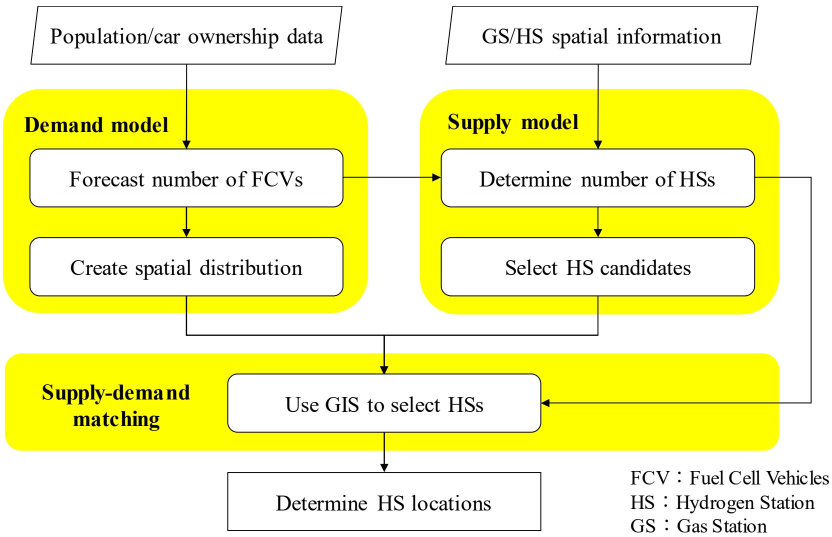


Figure 2. Overall flow of our approach in planning hydrogen station locations

The demand model predicts the number of fuel cell vehicles in Yokohama City, from 2020–2030, using population and automobile ownership data [21, 22]. It also estimates the spatial distribution of fuel cell vehicle ownership at the neighborhood level. To accommodate the uncertainty about the adoption of fuel cell vehicles, we prepared three scenarios: optimistic, intermediate, and pessimistic [5].

The supply model considers the safety of the hydrogen stations, which is an important characteristic of our study. For each scenario, we determined the number of hydrogen stations required in Yokohama City, based on the number of existing hydrogen stations, and the number of fuel cell vehicles predicted by the demand model. Furthermore, to find potential candidate station locations, we used spatial information for existing gas stations to identify those with a surplus surface area sufficiently large to ensure safety. In this study, we assumed a scenario in which new hydrogen stations were installed within existing gas stations, to reduce costs significantly [17].

To determine hydrogen station locations, we first created a Geographic Information System (GIS) overlay that superimposed hydrogen station candidates from the supply model over the spatial distribution of fuel cell vehicle ownership, from the demand model. We subsequently applied supply–demand matching, to determine the potential demand for hydrogen station candidates, and selected candidate locations until we reached the maximum number of hydrogen stations from the supply model.

2.2 Demand model

The numbers of fuel cell vehicles in Yokohama City, under optimistic, intermediate, and pessimistic scenarios, were obtained by multiplying the number of passenger cars in Yokohama City by the fuel cell vehicle replacement rate, under the abovementioned scenarios (see Equation (1)). We considered the decrease in vehicle ownership owing to future population decline, by predicting the number of passenger cars owned separately (see Equation (2)). For the fuel cell car replacement rate model in the optimistic scenario, we applied a time lag to the replacement rate for hybrid vehicles, which are already widely adopted, based on the literature [5] (see Equation (3)). For the fuel cell car replacement rate model in the pessimistic scenario, we applied a time lag to the replacement rate for electric vehicles, which are still in the process of being adopted (see Equation (4)). For the replacement rate in the intermediate scenario, we applied the average of the optimistic and pessimistic replacement rates (see Equation (5)). Equations (1) to (5) are shown below.

$$FCV_{it} = pr_{it} \cdot PC_t \tag{1}$$

$$PC_t = (a_0 + b_0 \cdot t) \cdot P_t \tag{2}$$

$$pr_{i=1,t} = \frac{C_{i=1}}{1+exp[a_{i=1}+b_{i=1}\cdot(t-T_{i=1})]} \tag{3}$$

$$pr_{i=3,t} = a_{i=3} + b_{i=3} \cdot (t - T_{i=3})^2 + C_{i=3} \cdot (t - T_{i=3}) \tag{4}$$

$$pr_{i=2,t} = \frac{pr_{i=1,t}+pr_{i=3,t}}{2} \tag{5}$$

In Equations (1)–(5), i is the scenario (1 = optimistic, 2 = intermediate, 3 = pessimistic), t is the year, FCV is the number of fuel cell vehicles, PC is the number of passenger cars, P is the population, and pr is the replacement rate. Symbols a_0 and b_0 are the parameters of the passenger car ownership model, while a_i and b_i are the replacement rate model parameters for hybrid and electric vehicles. T is the number of years that have elapsed since the start of adoption of hybrid or electric vehicles, up to year t.

Parameters for the passenger car ownership model were estimated using the number of passenger cars owned, and the population in Yokohama City from 2004 to 2017. The replacement rate model parameters for hybrid and electric vehicles were estimated using the number of hybrid and electric vehicles owned in Yokohama, from 1998 to 2017. The estimates used as model parameters are shown in Table 1.

Table 1. Estimates used as model parameters

	Passenger vehicle ownership model	Hybrid vehicle replacement rate model	Electric vehicle replacement rate model
a	6.4	790	170
b	-0.0031	-0.39	0.000043
c		0.25	-0.17
R^2	0.96	0.98	0.99
n	14	20	20

The spatial distribution of fuel cell vehicle ownership in Yokohama City was estimated as follows. The neighborhood-level spatial distribution of fuel cell vehicle ownership was estimated by allocating the fuel cell vehicles owned in Yokohama City among 787 neighborhoods. Assuming that the adoption rate of fuel cell vehicles in each neighborhood correlated with the adoption rate of hybrid vehicles, the number of fuel cell vehicles per neighborhood was estimated as shown in Equations (6) and (7). The adoption rate of fuel cell vehicles in each neighborhood was estimated from the number of hybrid vehicles owned in each neighborhood, in 2009, and in 2016 [22] (see Equation 7).

$$FCV_{ijt} = \frac{HV_{jt}}{\sum_j HV_{jt}} \cdot FCV_{it} \tag{6}$$

$$HV_{jt} = HV_{j,t=2016} + \frac{HV_{j,t=2016} - HV_{j,t=2009}}{8} \cdot (t - 2016) \tag{7}$$

In (6) and (7), i, j, and t are the scenario, neighborhood, and year, respectively, while FCV and HV are the numbers of fuel cell vehicles and hybrid vehicles, respectively.

2.3 Supply model

We determined the number of hydrogen stations required in Yokohama City from the predicted number of fuel cell vehicles obtained by the demand model under each scenario. We set 900 fuel cell vehicles per hydrogen station, based on data from the Fuel Cell Commercialization Conference of Japan [23]. Currently, in Yokohama City, four off-site stationary hydrogen stations, with a hydrogen supply capacity of 300 Nm^3, exist, along with two mobile hydrogen stations, each with a hydrogen supply capacity of 100 Nm^3. Table 2 shows the forecast trend in the construction costs of hydrogen stations [24]. The estimated construction costs for 100-Nm^3 and 300-Nm^3, off-site, stationary hydrogen stations, in 2030, are 180 million yen and 217 million yen, respectively. Because this cost difference is not significant, we have anticipated that 300-Nm^3 off-site stationary hydrogen stations will primarily be constructed. We have also anticipated that no mobile hydrogen stations will be adopted after 2025, as reductions in construction costs for stationary hydrogen stations would erode the cost advantage of the mobile stations. Based on the estimates above, the number of hydrogen stations required in Yokohama City, from 2020–2030, under each scenario, could be obtained by dividing the predicted number of fuel cell vehicles under each scenario by 900. We assumed that the existing stationary hydrogen stations would continue to be used, and that the mobile hydrogen stations would be used until 2025.

Table 2 Trends in hydrogen station construction costs (in millions of yen per hydrogen station)

	2016 actual	2020 forecast	2025 forecast	2030 forecast
Off-site-type stationary 300 Nm^3	350.6	301.3	269.4	217.5
Off-site-type stationary 100 Nm^3		250.8	210.4	180.2
Mobile 100 Nm^3	209.7	189.7		

We selected candidate hydrogen stations from the existing gas stations in the following manner. Regulations by the Ministry of Economy, Trade, and Industry specify the surface area of model hydrogen stations to include a 700 m^2 safety buffer [25]. Using residential map information [26], we calculated the surplus surface areas of 327 gas stations in Yokohama City. Each gas station with a surplus surface area of 700 m^2, or more, was considered as a candidate hydrogen station, on the assumption that it could host an adjoining hydrogen station safely. The surplus area of each gas station was obtained by subtracting the building area and roof (canopy) area from the gas station's lot size. The distribution of Yokohama City gas station surplus areas is shown in Fig. 3. As shown, 95 gas stations were calculated to have surplus areas of 700 m^2, or more, and are therefore candidates for accepting installation of hydrogen refueling stations.

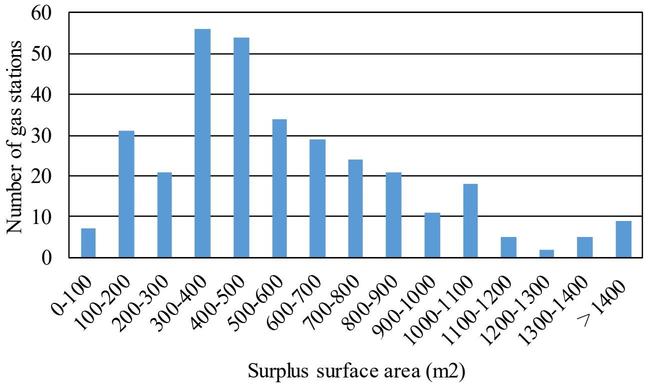
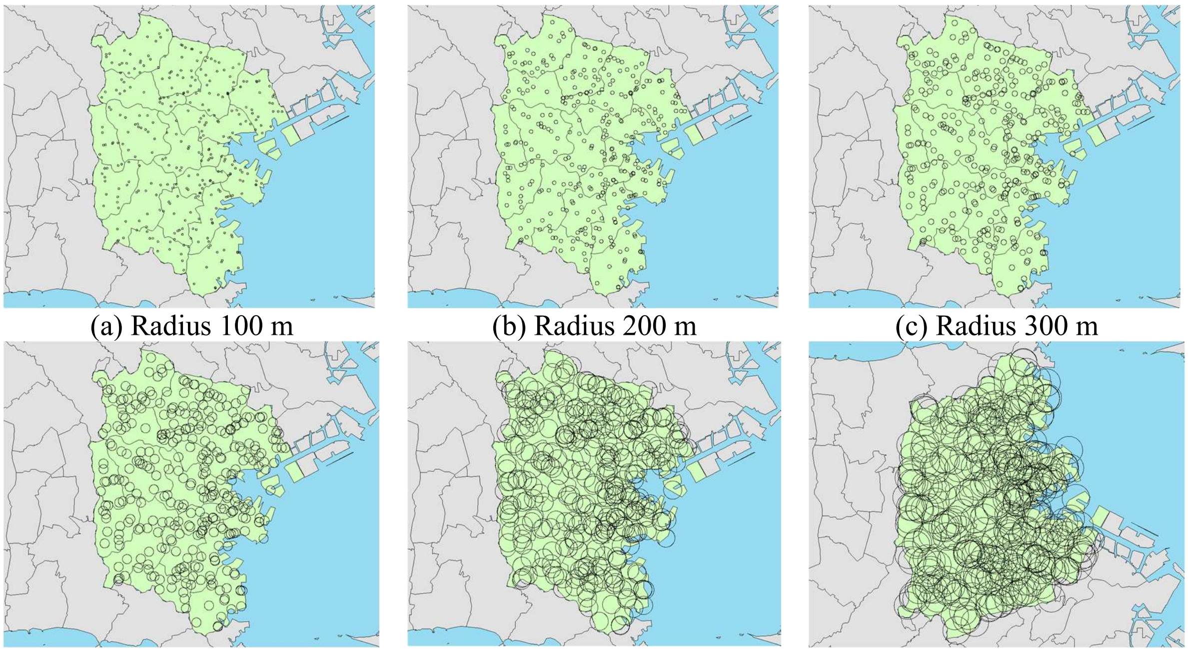


Figure 3. Distribution of surplus areas of gas stations in Yokohama City

2.4 Supply and demand matching

A GIS was used to store the location information for the number of fuel cell vehicles per neighborhood (from the demand model), and the hydrogen station candidates (from the supply model). After superimposing the number of fuel cell vehicles per neighborhood over the hydrogen station candidates on the GIS, we extracted the number of fuel cell vehicles in a 500 m radius around each hydrogen station candidate, and set this number as the potential demand for that hydrogen station. We subsequently matched the supply and demand by selecting hydrogen stations in descending order of potential demand (highest first), until reaching the maximum number of hydrogen stations set in the supply model for each scenario. However, to avoid spatial overlap of the stations, we first selected hydrogen stations in each of the 18 wards that constitute Yokohama City.When determining potential demand, we initially tested radii of 100, 200, 300, 500, 1,000, and 1,500 m. As shown in Fig. 4, when the radii were set to 100 and 300 m, the circles around the gas stations did not cover the map sufficiently; conversely, when the radii were set to 1,000 and 1,500 m, the circles overlapped each other. We therefore adopted a radius of 500 m in this study. The background maps shown in Fig.4 can be obtained by the national land numerical-information data-download service provided by the MLIT [20].



(a) Radius 100 m (b) Radius 200 m (c) Radius 300 m

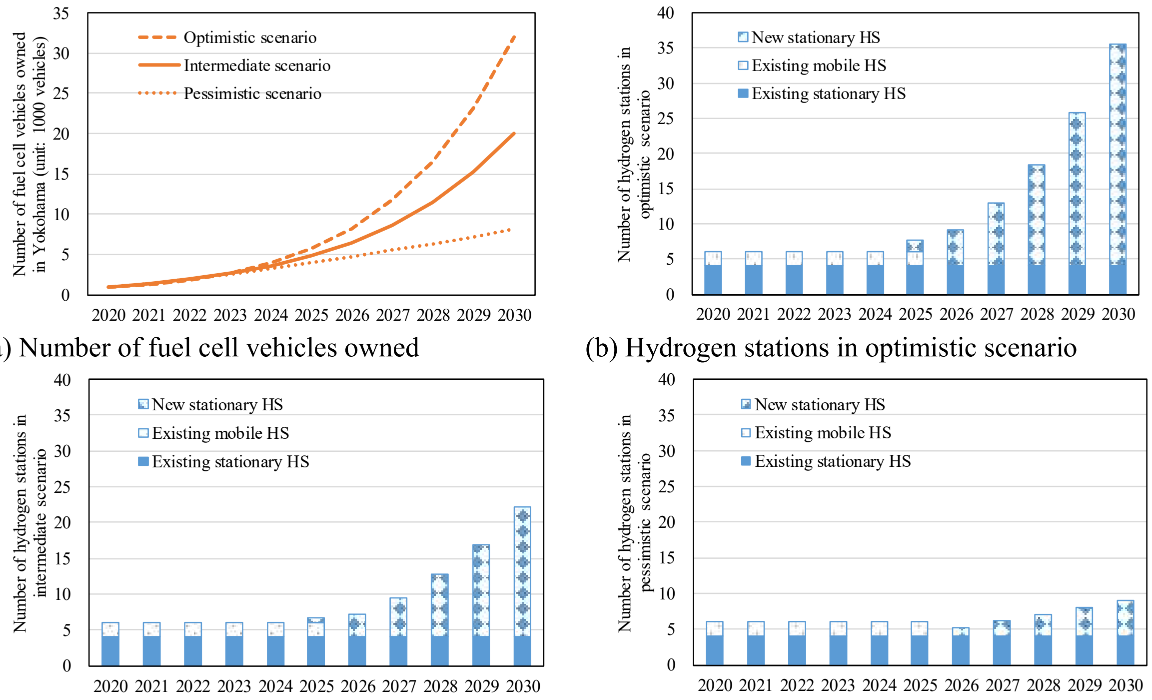
(d) Radius 500 m (e) Radius 1,000 m (f) Radius 1,500 m

Figure 4. Spatial distribution of circles around gas stations

3. RESULTS

3.1 Results of the accident network

Fig. 5 shows the predicted number of fuel cell vehicles and hydrogen stations in Yokohama City from 2020 to 2030. As shown in Fig. 5 (a), by 2020, Yokohama City is predicted to contain 600 fuel cell vehicles under the optimistic scenario, 540 under the intermediate scenario, and 490 under the pessimistic scenario; no significant difference is indicated among the scenarios. Until 2024, no significant difference is indicated in the predicted number of fuel cell vehicles under the three scenarios. Starting in 2025, the forecasts began to differ, and by 2030, we have predicted 32,000 fuel cell vehicles, under the optimistic scenario, 20,000 under the intermediate scenario, and 8,100 under the pessimistic scenario. By this date, significant differences have arisen among the scenarios. As shown in Figs. 5 (b), (c), and (d), the predicted number of hydrogen stations in Yokohama City varies depending on the number of fuel cell vehicles owned. In 2020, we have predicted six hydrogen stations in Yokohama City under all three scenarios (optimistic, intermediate, and pessimistic), as no significant differences were indicated in the predicted number of fuel cell vehicles, under the three scenarios. These six comprise the four existing stationary hydrogen stations, and the two existing mobile hydrogen stations. We have predicted that the hydrogen supply capacity of these six existing hydrogen stations would be adequate to supply the number of fuel cell vehicles owned under all three scenarios, until 2024. Starting in 2025, demand from the forecast number of fuel cell vehicles would exceed the supply capacity of the existing hydrogen stations; simultaneously, mobile hydrogen stations would no longer be used, thus necessitating new hydrogen stations. Consequently, by 2030, the number of hydrogen stations in Yokohama City was predicted to increase, to 36 under the optimistic scenario, 22 under the intermediate scenario, and 9 under the pessimistic scenario. Therefore, new stationary hydrogen stations would be required, at 32 locations under the optimistic scenario, 18 under the intermediate scenario, and 5 under the pessimistic scenario.



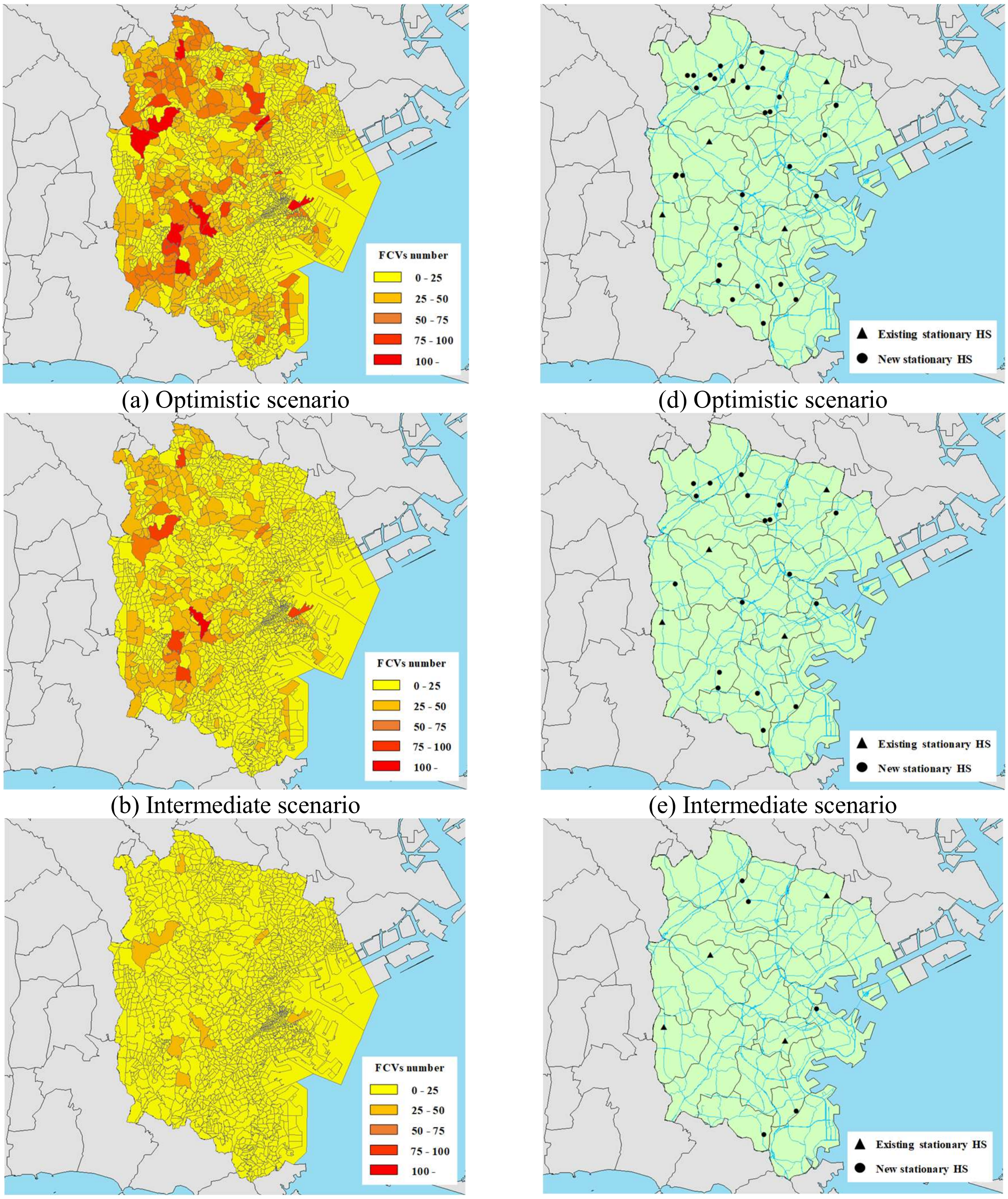
(a) Number of fuel cell vehicles owned (b) Hydrogen stations in optimistic scenario

(c) Hydrogen stations in intermediate scenario (d) Hydrogen stations in pessimistic scenario

Figure 5. Predicted number of fuel cell vehicles and hydrogen refueling stations in Yokohama City, from 2020 to 2030

Fig. 6 shows the predicted number of fuel cell vehicles owned per neighborhood, in Yokohama City, in 2030, and the selected hydrogen station locations under each scenario. The background maps shown in

Fig.6 can be obtained by the national land numerical-information data-download service provided by the MLIT [20]. Figs. 6 (a), (b), and (c) show that the predicted number of fuel cell vehicles owned per neighborhood varies significantly depending on the scenario. Under the optimistic scenario, the predicted number of fuel cell vehicles differed significantly between regions. Meanwhile, under the intermediate and pessimistic scenarios, the regional differences appeared less significant. Figs. 6 (d), (e), and (f) show the specific locations of the 36 hydrogen stations under the optimistic scenario, the 22 under the intermediate scenario, and the 9 under the pessimistic scenario, respectively. The four existing hydrogen stations in the pessimistic scenario in (f) do not necessarily align with the spatial distribution of fuel cell vehicles under the pessimistic scenario in (c). Therefore, under the pessimistic scenario, users of fuel cell cars may need to drive further to refuel.



(a) Optimistic scenario (d) Optimistic scenario

(b) Intermediate scenario (e) Intermediate scenario

(c) Pessimistic scenario (f) Pessimistic scenario

Figure 6. (a)–(c) predicted numbers of fuel cell vehicles owned, per neighborhood, in Yokohama City, in 2030, and (d)–(f) selected hydrogen station locations under each scenario

4. CONCLUSIONS

We have developed and presented a plan for the near-term deployment of hydrogen refueling stations in Yokohama City, from 2020 to 2030. Our city-level deployment plan emphasized the safety of the hydrogen stations.

With respect to the demand for hydrogen stations, we predicted the number of fuel cell vehicles at the neighborhood level under three scenarios: optimistic, intermediate, and pessimistic. With respect to the supply of hydrogen stations, in consideration of safety, we imposed a constraint that hydrogen stations could only be established inside existing gas stations that were sufficiently large to ensure a safety buffer zone, in accordance with safety regulations. Finally, gas stations that aligned with our supply and demand model were selected as hydrogen station locations.

Our results suggested that the existing stationary and mobile hydrogen stations could supply the predicted number of fuel cell vehicles up to 2024. Starting in 2025, the number of fuel cell vehicles owned, number of hydrogen stations, and station locations will vary significantly, depending on the scenario. In particular, under the pessimistic scenario, the locations of the existing hydrogen stations, which did not reflect demand, would hinder refueling access. This result reaffirms the importance of hydrogen station location planning.

Cities outside Yokohama that have not yet rolled out hydrogen stations, but anticipate the future adoption of fuel cell vehicles, can gain useful information from our research when planning hydrogen station locations. One recommendation is to identify hydrogen stations candidates among gas stations with a surplus surface area, in neighborhoods where demand for fuel cell vehicles is expected to be high. The literature indicates that the number of hydrogen stations in an area influences the adoption of fuel cell vehicles. Therefore, an effective strategy in the first five years, when little demand for fuel cell vehicles is expected, is to provide hydrogen refueling at gas stations in multiple locations using mobile hydrogen stations instead of stationary ones. After the first five years, stationary hydrogen stations would become the primary focus. However, in the long term, the number of gas stations with a large surplus surface area will be limited, and the assumption that gas stations will host adjoining hydrogen stations will become obsolete. To mitigate these constraints on supply, we propose revisiting regulations on safety buffer zones, and designing more compact hydrogen stations.

5. ACKNOWLEDGMENT

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