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RESEARCH ARTICLE

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Optimal siting and sizing of hydrogen refueling stations considering distributed hydrogen production and cost reduction for regional consumers

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Summary

Hydrogen fuel cell vehicles are currently facing two difficulties in achieving their general use: the lack of hydrogen refueling stations and high hydrogen prices. Hydrogen refueling stations are the middle stage for delivering hydrogen from its sources to consumers, and their location could be affected by the distributed locations of hydrogen sources and consumers. The reasonable siting and sizing of hydrogen refueling stations could both improve the hydrogen infrastructure and reduce regional consumers' cost of using hydrogen. By considering the hydrogen life cycle cost and using a commercial volume forecasting model, this paper creates a relatively thorough and comprehensive model for hydrogen station siting and sizing with the objective of achieving the optimal costs for consumers using hydrogen. The cost-based model includes the selection of the hydrogen sources, transportation methods, and storage methods, and thus, the hydrogen supply chain can also be optimized. A numerical example is established in Section 4 with the solution algorithm and results.

KEYWORDS

cost-based model, hydrogen life cycle cost, hydrogen refueling station, hydrogen supply chain, siting and sizing

1 | INTRODUCTION

Fossil fuels, mainly petroleum and natural gas, have been dominant in transportation for a long time. Due to factors such as the unrenewable nature of fossil fuels and the pollution from their emissions, researchers began to seek clean renewable energy as an alternative fuel for vehicles.

Due its prominent characteristics, such as no pollution, high efficiency, and recyclability, hydrogen is believed to be the ideal energy for the 21st century. Hydrogen fuel cell vehicles (HFCVs), with hydrogen as the energy source, have received extensive attention from researchers over recent years. A look through the entire operational process of a hydrogen fuel cell reveals that there is no consumption of other types of energy, such as oil for refueling or electricity for battery charging; only oxygen and air are used in the process, which undoubtedly saves energy. Meanwhile, water is the only byproduct from the process of electrical energy production in a hydrogen fuel cell; therefore, the goal of zero

Nomenclature: CNY, Chinese yuan; DFRLM, deviation-flow refueling location model; FCLM, flow-capturing location model; FRLM, flow-refueling location model; GH_2, gas hydrogen; GIS, geographic information system; HFCV, hydrogen fuel cell vehicle; LH_2, liquid hydrogen; PSO, particle swarm optimization emissions can be truly achieved. Recently, many companies have been conducting studies on HFCVs and have obtained remarkable results.

With the technical validation largely finished, Mirai, Toyota's HFCV, formally appeared on the Japanese market in December 2014. According to the official introduction, Mirai can be fully refueled in approximately 5 minutes with 5 kg of hydrogen, which provides a cruising range of up to 500 km.[1] At the Tokyo Motorcycle Show, in 2017, Toyota released Sora, which is a hydrogen fuel cell bus. Toyota planned to put more than 100 fuel cell busses into the public transport system in Tokyo during the 2020 Tokyo Olympic Games and Paralympics. In 2018, Hyundai launched its HFCV product, called NEXO, which can add up to 600 km of cruising mileage in just 5 minutes. From 2017 to 2018, China's Yutong Bus, Dongfang Electric, and Yangtze River Automobile launched their respective hydrogen fueled busses with completely proprietary intellectual property, and Dongfeng Motor also launched a hydrogen fuel light truck.

Consumers have not responded favorably to the marketing of HFCVs, although HFCVs have quite a few advantages and have already met performance demands in terms of their refueling time and driving range. The main reason for this is not the HFCVs themselves. The price of hydrogen is much higher than that of gasoline for an equal amount of energy, and high hydrogen costs make HFCVs less competitive in the market. On the other hand, the lack of hydrogen refueling infrastructure has become a major barrier to hydrogen transportation.

By the end of 2017, there were 139 hydrogen refueling stations in operation in Europe, 118 in Asia, 68 in North America, 1 in South America, and 1 in Australia. The United Arab Emirates is a new member of the hydrogen community and has a private hydrogen refueling station in Dubai. In the next 5 years, many countries will accelerate their construction of hydrogen refueling stations. In China, there are currently 31 hydrogen refueling stations that are built or under construction, and 100 hydrogen refueling stations are planned to be built by 2020.

The location and size of hydrogen stations are two problems that are inevitably encountered in their construction. Hydrogen station siting entails considering multiple factors, such as the number of stations to be built, the selection of their locations and the excluded areas, and their multiple economic influences and convenience. The hydrogen station size determines its rated capacity or refueling capacity. Hydrogen station sizing must firstly consider the different flows of vehicles served by the hydrogen refueling stations, and then the stations are designed to meet the different demands for hydrogen refueling. In hydrogen station planning, adequate siting and sizing can allocate resources reasonably, avoid unnecessary waste, and effectively control hydrogen costs while facilitating hydrogen refueling for consumers.

2 | LITERATURE REVIEW

2.1 | Prior research on hydrogen life cycle cost analysis

Researchers have conducted adequate and detailed analyses on the different phases of the hydrogen supply chain, such as hydrogen production,[2-5] delivery,[6-8] and storage,[9-12] thereby providing a basis for the life cycle cost analysis of hydrogen energy.

Due to the various ways of producing, storing, and transporting hydrogen, there is a large difference in the hydrogen life cycle cost.[13-16] Ahmadi and Kjeang[13] divided the life cycle of a passenger vehicle into a fuel cycle and a vehicle cycle. The fuel cycle is more prominent in our work, and in this cycle, the feedstock is produced and transported for producing fuel, which is then distributed to refueling stations and used by vehicles. Yao et al[14] defined the hydrogen life cycle as the whole process of hydrogen generation, storage and transportation, and usage. Moreover, they analyzed the hydrogen life cycle cost in seven scenarios, shown in Table 1. Viktorsson et al[15] analyzed the life cycle costs of a

TABLE 1 The seven proposals of the hydrogen life cycle for HFCVs[14]

Production of Hydrogen	Storage and Transportation of Hydrogen
Coal gasification	Transport hydrogen to the filling station by high-pressure bottles
Coal gasification	Transport hydrogen to the filling station by tankers
Coal gasification	Transport hydrogen to the filling station by pipelines
Steam methane reforming	Transport hydrogen to the filling station by high-pressure bottles
Steam methane reforming	Transport hydrogen to the filling station by tankers
Steam methane reforming	Transport hydrogen to the filling station by pipelines
Water electrolysis	Storage in the filling station

Abbreviation. HFCVs, hydrogen fuel cell vehicle.

hydrogen refueling station and evaluated the levelized costs of hydrogen for a decentralized hydrogen refueling station in Belgium. Li et al[16] divided the life cycle process of a hydrogen system into the hydrogen production phase, storage phase, and utilization/application phase and conducted a life cycle cost analysis of hydrogen systems using low-priced electricity.

2.2 | Prior research on infrastructure siting

The location problem has a relatively long history, and much research has been conducted on locating the refueling infrastructure. Hakimi[17] originally defined the p-median problem for the siting of p facilities in a network in such a manner that the total weighted distance for serving all demands is minimized. It has been widely studied in the literature. Revelle and Swain[18] proposed an integer linear programming formulation, which has been regarded as the basic p-median model and has remained almost unchanged for the last 30 years.

The formulation of the basic p-median model is

$$\text{Minimize } Z = \sum_{i \in U} \sum_{j \in V} h_i d_{ij} y_{ij}, \tag{1}$$

subject to

$$\sum_{j \in V} y_{ij} = 1, \tag{2}$$

$$\sum_{j \in V} x_j = p, \tag{3}$$

$$y_{ij} - x_j \leq 0, \tag{4}$$

$$x_j = \begin{cases} 0 \\ 1 \end{cases}, \tag{5}$$

$$y_{ij} = \begin{cases} 0 \\ 1 \end{cases}, \tag{6}$$

where U is the set of demand points; V is the set of candidate points in the network; h_i is the demand volume of point i; d_{ij} is the distance between the demand point, i, and the facility, j; p is the number of facilities to be built; x_j is a decision variable where if candidate point j is selected, $x_j = 1$, and otherwise $x_j = 0$; and y_{ij} is a decision variable where if the demand of point i can be met by facility j, $y_{ij} = 1$, and otherwise $y_{ij} = 0$.

Equation 1 minimizes the summation of the products of the distances between the demand points and p facilities and the volumes demanded at the points. Constraint (2) ensures that each demand point must be assigned to one facility. Constraint (3) limits the number of facilities to be built. Constraint (4) means that only when candidate point j is selected to be built can the demanded volume of point i be assigned to facility j. Constraints (5) and (6) are integer constraints. Nicholas and Ogden[19] and Nicholas et al[20] developed various variants of the p-median model and applied them to minimizing the total travel time to the nearest refueling stations for a set of trips originating from each traffic analysis zone in California metropolitan areas.

Berman et al[21,22] and Hodgson[23] presented another widely utilized model, the flow-capturing location model (FCLM), which located p facilities to maximize the necessary trips.

The formulation of a basic FCLM is

$$\text{Maximize } Z = \sum_{q \in Q} f_q x_q, \tag{7}$$

subject to

$$\sum_{i \in N} x_i = n, \tag{8}$$

$$\sum_{i \in N_q} x_i \geq x_q, \tag{9}$$

$$x_i = \begin{cases} 0 \\ 1 \end{cases}, \tag{10}$$

$$x_q = \begin{cases} 0 \\ 1 \end{cases}, \tag{11}$$

where N is the set of candidate points in the network; N_q is the set of candidate points along path q; Q is the set of paths whose traffic volumes are not 0; n is the number of facilities to be built; f_q is the traffic volume of path q in the unit period, $q \in Q$; x_i is a decision variable where if candidate point i is selected, $x_i = 1$, and otherwise $x_i = 0$; and x_q is a decision variable where if there is at least one facility located on path q, $x_q = 1$, and otherwise $x_q = 0$.

Equation 7 maximizes the summation of the traffic volumes that are captured by all facilities on the paths. Constraint (8) limits the number of facilities to be built. Constraint (9) means that if path q is selected, at least one candidate along path q is selected. Constraints (10) and (11) are integer constraints.

Kuby and Lim[24,25] introduced a driving range parameter into the FCLM to deal with the fuel limitations, thereby making the model suitable for locating refueling stations. The resulting location model, the FRLM, maximized the flow volume that can be refueled with respect to the range limitations of the vehicles, which were measured either in the number of trips or the vehicle's miles traveled. Kim and Kuby[26] developed a DFRLM that considered the limited driving range of vehicles and the necessary deviations that drivers were likely to make from their shortest paths to refuel their vehicles. Kim and Kuby[27] developed heuristic algorithms for the DFRLM that overcame this difficulty through a network transformation. Yıldız et al[28] proposed a branch and price approach that implicitly took into account deviation tolerances without requiring the pregeneration of the routes, and thus significantly decreasing the solution times.

In addition, a kind of siting model based on the life cycle cost has been presented. He et al[29] proposed a cost-based model for siting hydrogen refueling stations along expressways. The model optimized the hydrogen life cycle cost arising in the hydrogen source-station stage. By taking the multisource hydrogen supply into consideration, Sun et al[30] improved this cost-based model and applied it to an expressway.

2.3 | Contributions

Previous studies only considered the relationship between the hydrogen stations and consumers or between the hydrogen stations and hydrogen sources, which was not a comprehensive approach. In addition, these siting models did not involve the sizing of the hydrogen stations. For instance, the work of He et al[29] and Sun et al[30] only considered the hydrogen costs that arise when hydrogen is transported from the hydrogen sources to hydrogen stations. Their work mainly optimized the hydrogen life cycle cost. For consumers, this provides a lower hydrogen price and thus reduces the consumers' hydrogen purchase costs. However, this may lead to locating hydrogen stations far away from consumers, so that the consumers have to spend a large amount in refueling costs to drive to the hydrogen stations. Therefore, from the perspective of optimizing costs, it is more comprehensive to optimize the total costs of the hydrogen purchase costs and the hydrogen refueling costs. In this way, the distribution and hydrogen demand volumes of consumers and the probability of each hydrogen station being selected by consumers need to be taken into account. This also provides a basis for estimating the capacities of the hydrogen refueling stations.

In this paper, the refueling costs are defined as the costs of the hydrogen consumed in driving to a hydrogen refueling station, arising when hydrogen goes from the hydrogen station to the consumer. Since mankind depends on group living, consumer positions for hydrogen refueling can be allocated to several demand points where people and vehicles are concentrated. Hydrogen refueling costs are subject to the joint effects of hydrogen's unit price, the volume of hydrogen consumed per unit distance, and the distances between the stations and demand points for hydrogen refueling. The former two are related to the hydrogen station's location and reasonable hydrogen station locations are especially important to lower the consumers' hydrogen refueling costs. The consumers' costs of using hydrogen are defined in this study as the sum of the purchase costs and refueling costs.

We consider both the stage from the hydrogen source to the hydrogen station and that from the hydrogen station to the consumer and propose a model for the consumers' costs of using hydrogen with respect to the economic factors arising in hydrogen's entire process from the source to the consumer. In addition, this paper introduces the classic Huff model[31,32] into the location model to estimate the probabilities of users' selections of a hydrogen refueling station, and based on the probabilities, the model concurrently optimizes the sizes and locations of the hydrogen refueling stations. In the location model, the objective function calculates the consumers' optimal costs for driving to the hydrogen stations and refueling, provided that the demand for hydrogen refueling is met.

Consequently, the main purpose of this paper is to provide a new cost-based model for hydrogen refueling station siting and sizing, and some important contributions can be listed as follows:

- Optimizing the sum of hydrogen purchase costs and refueling costs for regional consumers.
- Coordinating the hydrogen life cycle cost and hydrogen refueling distance so that the cost of hydrogen is reduced while convenience is taken into consideration.
- Combining hydrogen refueling station sizing with siting to yield more reasonable solutions.

3 | THE MODEL

The model established in this research is intended to optimize the total costs of using hydrogen by all the HFCV users in an area. This is defined as the sum of the annual hydrogen purchase costs and the annual refueling costs of consumers in the area.

The variables used in this chapter are described below:

$i/j/k$	index of stations/sources/excluded areas,
h	index of demand points for hydrogen refueling,
c	index of the types of HFCVs,

$N/M/K$	set of stations/sources/excluded areas,
H	set of all demand points for hydrogen refueling,
T	set of types of HFCVs,
SC/SO	annual construction investments/ operation and maintenance costs of stations,
$HP/HT/HS$	hydrogen production/hydrogen transport/hydrogen storage costs,
C_i/E_i	construction investment/annual operation and maintenance cost of station i,
r_0	discount rate,
t	depreciable life of stations,
p_j	cost per kilogram of hydrogen produced from source j,
w_i	capacity of station i,
w_{ij}	weight of hydrogen bought from source j by station i,
t_{ij}	cost per kilometer for transporting hydrogen from source j to station i,
s_{ij}	cost for storing a unit weight of hydrogen,
λ	hydrogen station's annual profit margin,
v_{hc}	annual refueling times of c-type HFCVs at demand point h,
P_{hi}	probability of a vehicle going from demand point h to station i for hydrogen refueling,
A_i	attractiveness of station i,
φ_c/q_c	c-type HFCV's hydrogen cost/ consumption per kilometer,
a	price per kilogram of hydrogen,
$d_{ij}/d_{i,i+1}/d_{ik}/d_{hi}$	distance from station i to source j/adjacent station $i+1$/excluded area k/ demand point h,
D	upper bound of the distance between two adjacent stations,
D_k	covering radius of excluded area k,
y_c	volume of hydrogen that c-type HFCVs are refueled with per time,
η	an index determined in the experiment, where 2 is its value herein,
L_j	upper bound on the productivity of source j, and
ρ	penalty factor for a penalty term which is used to discard excluded areas.

3.1 | Hydrogen station capacity design

According to Huff,[31,32] the probability of consumers going to a store for consumption is in direct proportion to the store's attractiveness and in inverse proportion to his distance to the store. The Huff model is extensively applied to forecast commercial volumes in urban areas. In the Huff model, a store's attractiveness is largely reflected by aspects such as its popularity, promotional events, and the store's area (representing the range of commodities). The model is also applicable to the consumers' selection of hydrogen refueling stations.

According to the Huff model, the probability of consumers' selection of hydrogen refueling stations can be estimated by Equation 12.

$$P_{hi} = \frac{A_i d_{hi}^{-\eta}}{\sum_{i \in N} A_i d_{hi}^{-\eta}} \tag{12}$$

Based on the users' selection probability, the hydrogen refueling volumes at the demand points are allocated to the refueling stations, and the capacities of the stations are determined accordingly. Considering that different types of vehicles (e.g., cars and busses) obviously vary in the volumes of hydrogen they demand, this paper establishes Equation 13 to estimate the capacities of the stations.

$$w_i = \sum_{h \in H} \sum_{c \in T} v_{hc} y_c P_{hi} = \frac{\sum_{h \in H} \sum_{c \in T} v_{hc} y_c A_i d_{hi}^{-\eta}}{\sum_{i \in N} A_i d_{hi}^{-\eta}}. \tag{13}$$

3.2 | Measurement of consumers' annual hydrogen purchase costs in an area

It is relatively tedious to measure the consumers' annual hydrogen purchase costs in an area. Based on the assumption that all the hydrogen sold at the hydrogen stations in the area is used for refueling HFCVs, the annual sales of hydrogen stations in the area can be used in place of the consumers' annual hydrogen purchase costs in the area since the two are numerically identical, which simplifies the calculations. The annual sales of hydrogen stations in the area are composed of the stations' annual costs and profits.

The annual costs of the hydrogen stations are derived from the work of Sun et al,[30] which is shown in Equation 14.

$$F = \sum_{i \in N} C_i \frac{r_0 (1+r_0)^t}{(1+r_0)^t - 1} + \sum_{i \in N} E_i + \sum_{i \in N} \sum_{j \in M} p_j w_{ij} + \sum_{i \in N} \sum_{j \in M} t_{ij} d_{ij} + \sum_{i \in N} \sum_{j \in M} s_{ij} w_{ij}. \tag{14}$$

The discount rate, r_0, and depreciable life, t, are introduced into Equation 14 to change it from a present value to an annual value to express the investments in hydrogen station construction. An $i \times j$-dimensional matrix formed by w_{ij} is established to represent the allocation scheme for the hydrogen, which is denoted as a multi-source hydrogen supply scheme.

Since the annual profit margin of hydrogen stations is introduced as the coefficient λ, the annual sales of hydrogen stations in the area, or the equivalent annual hydrogen purchase costs by consumers in the area, can be estimated according to Equation 15.

$$G_1 = (1+\lambda)\times F = (1+\lambda) \times \left(\sum_{i \in N} C_i \frac{r_0(1+r_0)^t}{(1+r_0)^t - 1} + \sum_{i \in N} E_i + \sum_{i \in N}\sum_{j \in M} p_j w_{ij} + \sum_{i \in N}\sum_{j \in M} t_{ij} d_{ij} + \sum_{i \in N}\sum_{j \in M} s_{ij} w_{ij} \right). \tag{15}$$

3.3 | Estimation of the annual hydrogen refueling costs of consumers in the area

Equation 16 is established to calculate the total costs of driving from the demand points for hydrogen refueling to the corresponding refueling stations. The probability, P_{hi}, of consumers going to the refueling stations, as described in Section 3.1, and is added here as well.

$$G_2 = \sum_{h \in H}\sum_{i \in N}\sum_{c \in T} v_{hc} d_{hi} P_{hi} \varphi_c. \tag{16}$$

The c-type HFCV's unit costs per kilometer, φ_c, in Equation 16 are affected by the hydrogen price, which can be found using the annual sales and sales volume of hydrogen stations in the area, as shown in Equation 17.

$$\varphi_c = a q_c = \frac{G_1 q_c}{\sum_{i\in N}\sum_{j\in M} w_{ij}} = \frac{(1+\lambda) q_c}{\sum_{i\in N}\sum_{j\in M} w_{ij}} \times \left(\sum_{i \in N} C_i \frac{r_0(1+r_0)^t}{(1+r_0)^t - 1} + \sum_{i \in N} E_i + \sum_{i \in N}\sum_{j \in M} p_j w_{ij} + \sum_{i \in N}\sum_{j \in M} t_{ij} d_{ij} + \sum_{i \in N}\sum_{j \in M} s_{ij} w_{ij} \right). \tag{17}$$

Therefore, the annual hydrogen refueling costs of consumers in the area can be estimated from Equation 18.

$$G_2 = \sum_{h \in H}\sum_{i \in N}\sum_{c \in T} \frac{(1+\lambda) v_{hc} A_i d_{hi}^{1-\eta} q_c}{\sum_{i\in N} A_i d_{hi}^{-\eta} \sum_{j\in M} w_{ij}} \times \left(\sum_{i \in N} C_i \frac{r_0(1+r_0)^t}{(1+r_0)^t - 1} + \sum_{i \in N} E_i + \sum_{i \in N}\sum_{j \in M} p_j w_{ij} + \sum_{i \in N}\sum_{j \in M} t_{ij} d_{ij} + \sum_{i \in N}\sum_{j \in M} s_{ij} w_{ij} \right). \tag{18}$$

3.4 | Geographic information factors in hydrogen station construction

A penalty function is added to the model herein to discard the locations where no station can be built (such as some large office buildings, schools, libraries, and museums), as shown in Equation 19. When a location where no station can be built is chosen, the model will obtain a very bad value to avoid the selection of that location.

$$P(d_{ik}) = \begin{cases} \rho \times (D_k - d_{ik})^2, & d_{ik} \le D_k \\ 0, & d_{ik} > D_k \end{cases} \tag{19}$$

3.5 | The hydrogen station siting and sizing model

A hydrogen station siting and sizing model can be obtained by synthesizing the contents in Sections 3.1 to 3.4, as shown in Equation 20.

$$\text{Minimize } G = G_1 + G_2 + P(d_{ik}) = (1+\lambda) \times \left(1 + \sum_{h \in H}\sum_{i \in N}\sum_{c \in T} \frac{v_{hc} A_i d_{hi}^{1-\eta} q_c}{\sum_{i \in N}\sum_{j \in M} w_{ij} \sum_{i \in N} A_i d_{hi}^{-\eta}} \right) \times \left(\sum_{i \in N} C_i \frac{r_0(1+r_0)^t}{(1+r_0)^t - 1} + \sum_{i \in N} E_i + \sum_{i \in N}\sum_{j \in M} p_j w_{ij} + \sum_{i \in N}\sum_{j \in M} t_{ij} d_{ij} + \sum_{i \in N}\sum_{j \in M} s_{ij} w_{ij} \right) + \sum_{k \in K} P(d_{ik}), \tag{20}$$

subject to

$$d_{i,i+1} < D,\ \forall i \in N,\ i+1 \in N, \tag{21}$$

$$w_i = \frac{\sum_{h\in H}\sum_{c\in T} v_{hc} y_c A_i d_{hi}^{-\eta}}{\sum_{i\in N} A_i d_{hi}^{-\eta}}, \tag{22}$$

$$\sum_{i \in N} w_i = \sum_{i \in N}\sum_{j \in M} w_{ij} = \sum_{h \in H}\sum_{c \in T} v_{hc} y_c, \tag{23}$$

$$\sum_{i \in N} w_{ij} \le L_j,\ \forall j \in M, \tag{24}$$

$$\sum_{j \in M} w_{ij} = w_i,\ \forall i \in N. \tag{25}$$

The objective function (20) evaluates the overall effectiveness of the hydrogen station construction in terms of the consumers' optimal costs of using hydrogen. It consists of three parts: the annual hydrogen purchase costs in the area (annual costs of the hydrogen stations), the overall annual hydrogen refueling costs of consumers in the area, and the exclusion of landforms where no station can be built. The former two parts include the economic factors arising in hydrogen's entire process from the source to the consumer and constitute the consumers' costs of using hydrogen. Constraint (19) prevents hydrogen stations from being located in areas not appropriate for establishing stations. Constraint (21) sets an upper bound on the distance between adjacent stations due to the limited coverage of every station. Constraint (22) determines the capacities of the stations by allocating the demanded volume for hydrogen refueling at the demand points to the stations, according to the probability, through distances from the demand points to the stations. Constraint (23) is the assumption that the hydrogen sold by hydrogen stations in the area is all purchased by HFCV users, which is a precondition for the annual sales of hydrogen stations in the area to replace by consumers' hydrogen purchase costs in the area. Constraint (24) ensures that the hydrogen provided for all stations by every source should not exceed their productivity. Constraint (25) ensures that every station can be supplied sufficiently by all the sources.

4 | NUMERICAL EXAMPLE

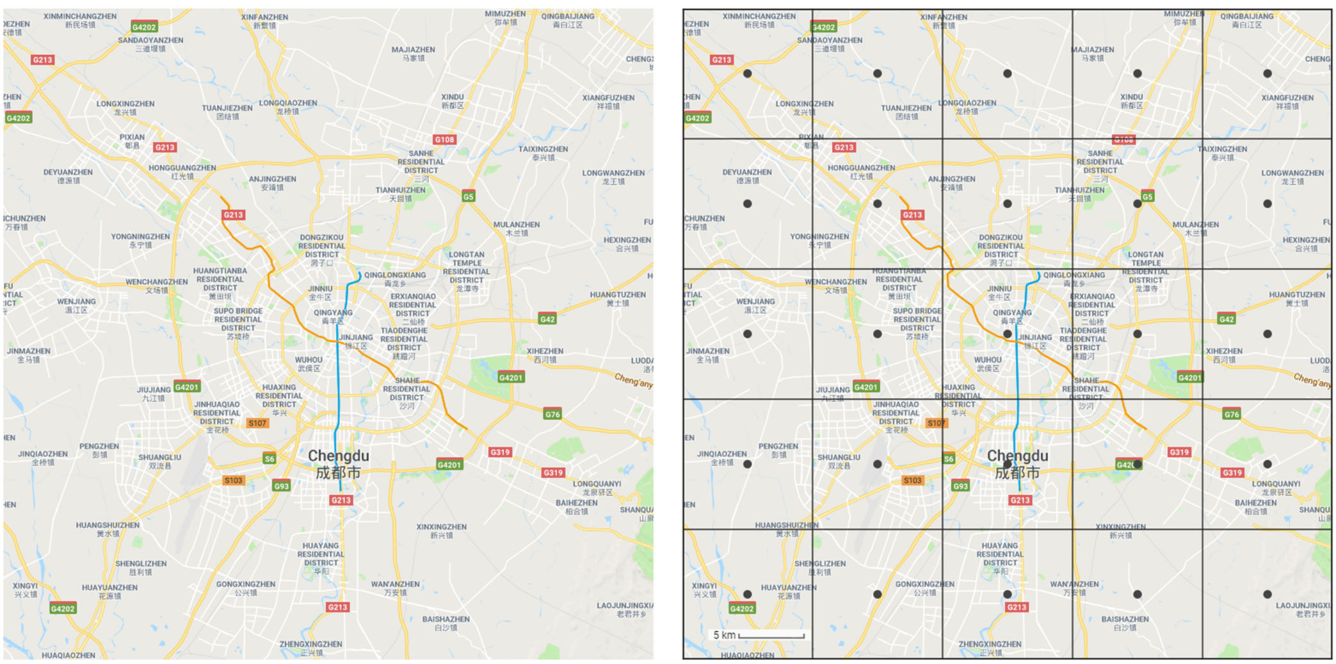
4.1 | Area and data

Chengdu is the provincial capital of Sichuan, China, and a megalopolis in the inland southwest. There are plans to turn it into a national central city in southwest China by 2020. In 2017, Chengdu had a population of approximately 16 million permanent residents and achieved a regional gross domestic product of 1389 billion CNY. There were 30 national-level scientific research establishments, 67 national-level research and development platforms, 56 colleges and universities, and up to 281 of the world's top 500 enterprises located in Chengdu as of January 2018. Sichuan has shown a strong interest in the HFCV field over recent years, and a hydrogen fuel cell bus, independently developed by Sichuan, was delivered

TABLE 2 Data on the types of HFCVs

	One-Time Hydrogen Refueling Volume, kg	Hydrogen Consumption per Kilometer, kg/km
Hydrogen fuel cell car	5.00	0.01
Hydrogen fuel cell bus	19.00	0.04

Abbreviation. HFCVs, hydrogen fuel cell vehicle.



(A) (B)

FIGURE 1 The area to be planned: A, Raw map. B, Discretized demand points for hydrogen refueling [Colour figure can be viewed at wileyonlinelibrary.com] for use in Chengdu in February 2018, and a hydrogen refueling station was built in support of this. Chengdu has abundant economic power, strong scientific research abilities, an extensive population base, and active policy support. Therefore, a square area that is 50 km long and 50 km wide that includes Chengdu's central urban districts is chosen as an example, as shown in Figure 1A.

To briefly demonstrate the application of the model in this article, the area to be planned is divided into 25 grids at average intervals of 10 km and the HFCV users in the area are discretized into 25 demand points for hydrogen refueling, with the centers of the grids where they are located used as the respective locations of the points, as shown in Figure 1B. However, if high accuracy is

TABLE 3 Data for the demand points for hydrogen refueling in the area

	Location, km	Annual Total Times Cars Are Refueled With Hydrogen	Annual Total Times Busses Are Refueled With Hydrogen	Annual Total Volume That Hydrogen Cars Are Refueled With, kg	Annual Total Volume That Hydrogen Busses Are Refueled With, kg	Annual Total Volume of Hydrogen Demanded at the Points, kg
Point 1	(5.00,5.00)	120	80	600.00	1520.00	2120.00
Point 2	(5.00,15.00)	320	150	1600.00	2850.00	4450.00
Point 3	(5.00,25.00)	2760	2040	13 800.00	38 760.00	52 560.00
Point 4	(5.00,35.00)	1320	1860	6600.00	35 340.00	41 940.00
Point 5	(5.00,45.00)	360	550	1800.00	10 450.00	12 250.00
Point 6	(15.00,5.00)	1280	1640	6400.00	31 160.00	37 560.00
Point 7	(15.00,15.00)	3800	2200	19 000.00	41 800.00	60 800.00
Point 8	(15.00,25.00)	3200	3640	16 000.00	69 160.00	85 160.00
Point 9	(15.00,35.00)	3300	2900	16 500.00	55 100.00	71 600.00
Point 10	(15.00,45.00)	1000	400	5000.00	7600.00	12 600.00
Point 11	(25.00,5.00)	2360	2040	11 800.00	38 760.00	50 560.00
Point 12	(25.00,15.00)	3120	3100	15 600.00	58 900.00	74 500.00
Point 13	(25.00,25.00)	4360	4320	21 800.00	82 080.00	103 880.00
Point 14	(25.00,35.00)	2700	2560	13 500.00	48 640.00	62 140.00
Point 15	(25.00,45.00)	1700	1060	8500.00	20 140.00	28 640.00
Point 16	(35.00,5.00)	300	100	1500.00	1900.00	3400.00
Point 17	(35.00,15.00)	1360	1500	6800.00	28 500.00	35 300.00
Point 18	(35.00,25.00)	2720	3400	13 600.00	64 600.00	78 200.00
Point 19	(35.00,35.00)	2420	2400	12 100.00	45 600.00	57 700.00
Point 20	(35.00,45.00)	2720	2400	13 600.00	45 600.00	59 200.00
Point 21	(45.00,5.00)	80	20	400.00	380.00	780.00
Point 22	(45.00,15.00)	1360	1200	6800.00	22 800.00	29 600.00
Point 23	(45.00,25.00)	920	400	4600.00	7600.00	12 200.00
Point 24	(45.00,35.00)	420	300	2100.00	5700.00	7800.00
Point 25	(45.00,45.00)	1120	1400	5600.00	26 600.00	32 200.00

TABLE 4 Data on the hydrogen sources

	Location, km	Hydrogen Productivity, kg/day	Hydrogen Price, CNY/kg	CO_2 Disposal, CNY/kg	Carbon Tax, CNY/kg
Source 1	(6.00,2.00)	800.00	35.22	0.14	0.12
Source 2	(20.00,48.00)	1100.00	34.51	0.21	0.13
Source 3	(36.00,43.00)	1000.00	34.89	0.11	0.13

Abbreviation: CNY, Chinese yuan.

required regardless of the computational time, the grid should be divided more finely. Furthermore, in actual planning, a geographic information system (GIS) should be introduced to acquire the actual paths and distances between the demand points and hydrogen refueling stations.

Referring to Toyota's hydrogen fuel car, Mirai, and its hydrogen fuel bus, Sora, this paper adopts their one-time refueling volumes and hydrogen consumption per kilometer as representative of those types of vehicles, as shown in Table 2. For demonstration purposes, this paper assumes that the annual total times for refueling HFCVs

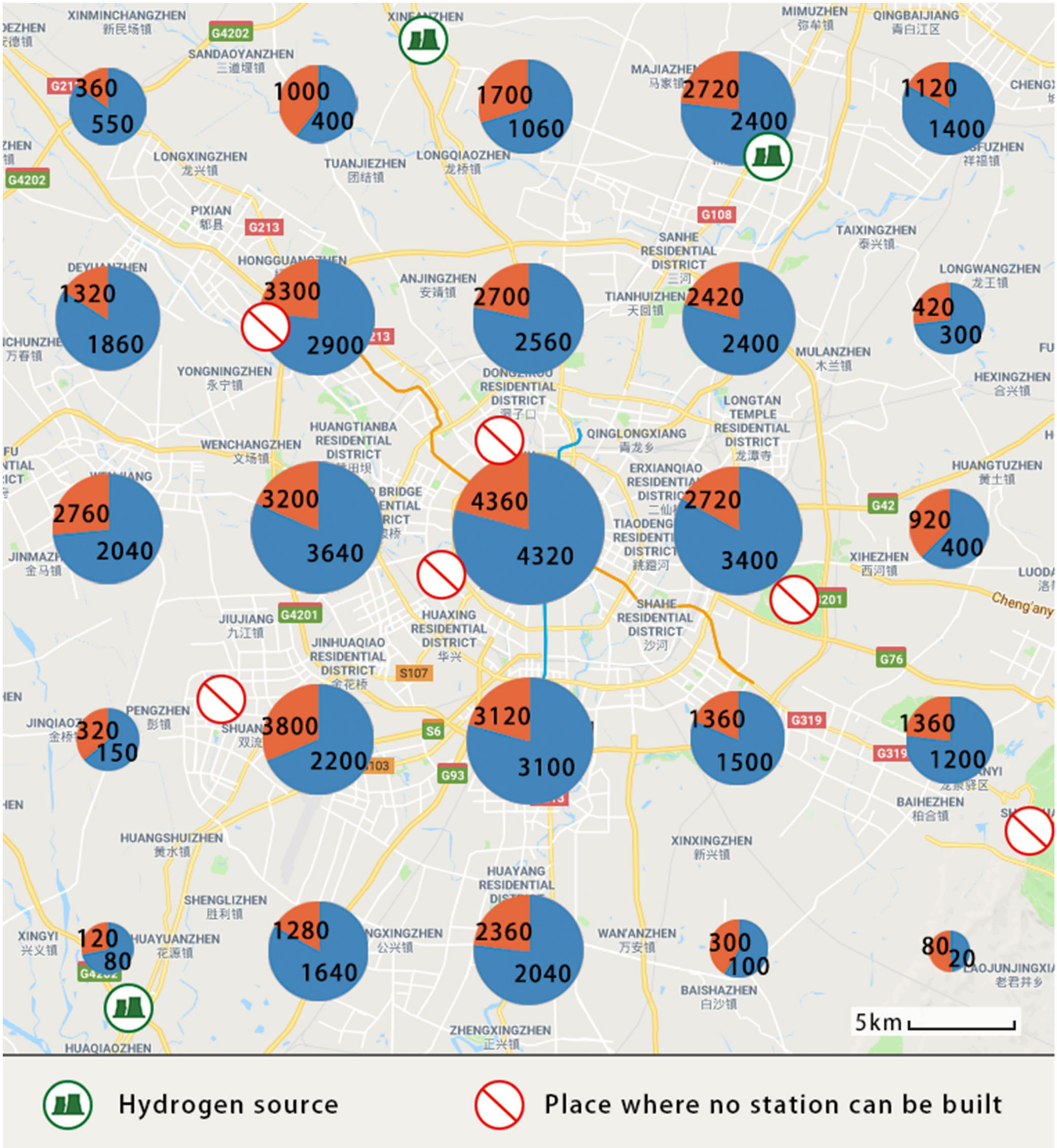


FIGURE 2 Data on the demand points for hydrogen refueling, hydrogen sources, and excluded areas [Colour figure can be viewed at wileyonlinelibrary.com]

of these types at the demand points for hydrogen refueling and that the annual total volume of hydrogen demanded in the future are based on the density of the road networks within the grids, as shown in Table 3.

Hydrogen made from the byproducts of chlor-alkali is of high purity, has a lower cost, and its production process is eco-friendly. Thus, it fully meets the requirements of HFCVs, and hydrogen stations in the area can use chlor-alkali plants near Chengdu as their source of hydrogen. Table 4 shows data on the hydrogen sources in the area.

TABLE 5 Excluded areas

	Location, km	D_k, km
School 1	(10.50, 17.00)	0.60
Airport	(12.50, 34.50)	1.50
Park 1	(21.00, 22.50)	0.60
School 2	(24.00, 29.00)	1.40
Park 2	(37.60, 21.80)	3.60
Mountain	(48.00, 11.20)	5.00

TABLE 6 Hydrogen station information

Variable	Value
C_i	15.00 million CNY
E_i	1.00 million CNY
r_0	8%
t	10 y
D	80.00 km

Abbreviation: CNY, Chinese yuan.

TABLE 7 Alternative ways of storage

	Energy Consumption, kWh/kg	Electricity Cost, CNY/kg
Compression (P = 3 MPa)	0.10	0.06
Compression (P = 20 MPa)	1.00	0.56
Liquefaction (T = 21 K)	11.00	6.13

Abbreviation: CNY, Chinese yuan.

TABLE 9 The components of the optimal consumers' annual total costs

Component	Cost, CNY/y
Station construction investments	8 941 769.32
Station operation and maintenance costs	4 000 000.00
Hydrogen production costs (including the environment costs)	35 707 432.25
Hydrogen transport costs	610 018.65
Hydrogen storage costs	474 003.43
Consumers' hydrogen purchase costs	57 193 207.20
Consumers' hydrogen refueling costs	1 610 179.27
Consumers' optimal costs of using hydrogen	58 803 386.47

Many schools, scientific research establishments, parks, and other places where no station can be built have exist in Chengdu's urban areas. Only some of the points are chosen as representative in this example to make the data clear and concise. In the actual planning process, all places where no station can be built should be excluded.

Figure 2 aggregates the information from Tables 3–5. The central positions of the circles in Figure 2 are the locations of the demand points for hydrogen refueling. The areas of the circles reflect the size of the demand for hydrogen refueling at those points. The different colors indicate the percentages of the different types of hydrogen fuel vehicles at the points of their demand for hydrogen, and the numbers denote the total times for refueling vehicles of the corresponding types. The locations of hydrogen sources and excluded areas are also reflected in Figure 2.

A brief description was given earlier in this paper with respect to hydrogen sources, the demand points, and the excluded areas. This paper illustrates an example of hydrogen station location and sizing with consideration given to the costs to consumers for using hydrogen and the geological information factors. In this example, there are three new hydrogen stations that are to be established by the government or a certain company, and the hydrogen prices are identical at each station. The stations therefore have an equal attractiveness, which is to say that the A_i of the stations is identical. The conditions that the example is based on are shown in Tables 6–8.

TABLE 8 Alternative ways of transport

	Load Capacity	a, CNY · kg^{-1} · km^{-1}	b, CNY · km^{-1}
Liquid truck (LH_2)	About 4000 kg/truck	0.01	8.00
Tube trailer (GH_2)	About 500 kg/trailer	0.04	4.00
Pipeline (LH_2)	Huge	0.00	2.00 million

Abbreviation: CNY, Chinese yuan.

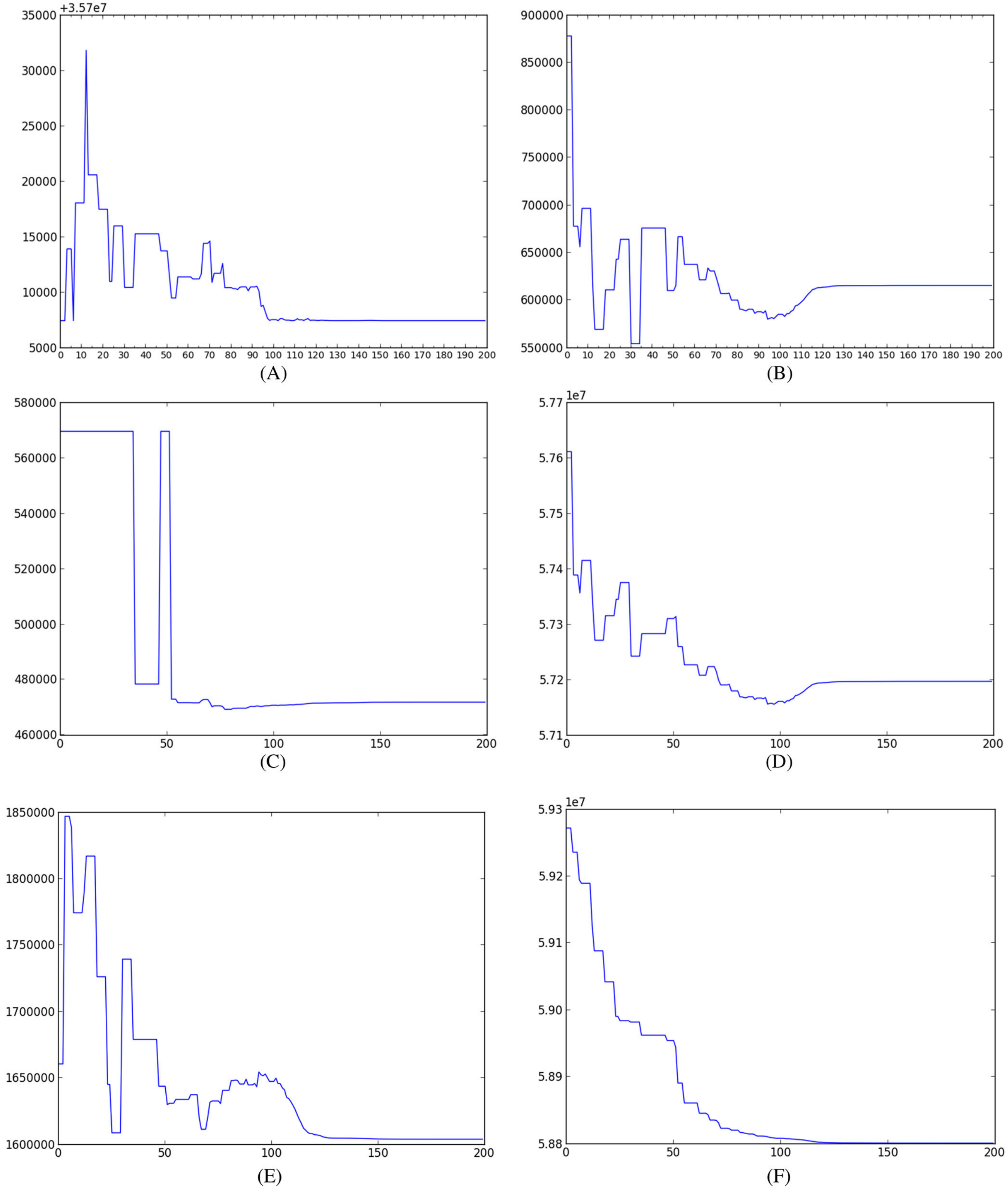


FIGURE 3 Results of program convergence: A, Hydrogen production costs. B, Hydrogen transport costs. C, Hydrogen storage costs. D, Consumers' hydrogen purchase costs. E, Consumers' hydrogen refueling costs. F, Consumers' costs of using hydrogen [Colour figure can be viewed at wileyonlinelibrary.com]

This example chooses two currently common methods of hydrogen storage, as shown in Table 7. The data on energy use in Table 7 are assumed according to Chang et al,[33] and the power cost is calculated according to the Chengdu industrial electricity price.[34]

The transport cost per kilometer varies with the volume of hydrogen transported, and it can be approximated by Equation 26:

$$t_{ij} = a \times w_{ij} + b \times v, \tag{26}$$

where t_{ij} is transport cost per kilometer per kilogram of hydrogen; a is the increased cost per kilometer of a vehicle resulting from loading one more kilogram of hydrogen, including the fuel consumption and vehicle wear due to increased weight; b is the cost per kilometer for an unloaded vehicle, in which the drivers' salary, road tolls, fuel consumption, and vehicle wear of the unloaded vehicle are taken into consideration; and v is the number of vehicles to be used when a liquid truck or a tube trailer is selected, or $v = 1$ when a pipeline is selected.

See Table 8 for the transport capacities and price parameters for the transport methods assumed in this example.

4.2 | Algorithm and results

Particle swarm optimization (PSO) is a kind of swarm-based algorithm. Each possible solution is regarded as an individual that has its own position, velocity, and fitness value.[35] The particles are expected to find the optimal solution in a search space.

The optimization of locations and sizes is based on the model presented in combination with the PSO algorithm. Through a number of iterations, the locations of the hydrogen stations are determined by optimizing the consumers' total costs of using hydrogen and the multisource hydrogen supply scheme for station construction. In this process, the capacities of the stations are determined, and the hydrogen transport and storage methods for those objectives are obtained.

This chapter creates two kinds of matrix particles to solve this example: the position particle and the weight particle. The position particle is a kind of $N \times 2$-dimensional matrix particle, which represents the locations of the N stations. The structure of the position particle is shown in Equation 27. The first column of the position particle denotes the x coordinates of the stations' locations, and the second column denotes the y coordinates. Both of them meet the length limitations in the x and y directions, respectively, on the area to be planned. The weight particle is a kind of $N \times$ M-dimensional matrix particle that expresses the multisource hydrogen supply scheme, and its structure is shown in Equation 28. In Equations 27 and 28, i represents the index of the particles and k is the index of the iterations.

$$\text{position}_i^k = \begin{bmatrix} x_1^{k,i} & y_1^{k,i} \\ x_2^{k,i} & y_2^{k,i} \\ \vdots & \vdots \\ x_N^{k,i} & y_N^{k,i} \end{bmatrix}, \tag{27}$$

$$\text{weight}_i^k = \begin{bmatrix} w_{11}^{k,i} & \cdots & w_{1M}^{k,i} \\ \vdots & \ddots & \vdots \\ w_{N1}^{k,idx} & \cdots & w_{NM}^{k,i} \end{bmatrix}. \tag{28}$$

The algorithm box shows the core procedures of the PSO to solve the siting and sizing example in pseudocode. The optimization of the weight particle is similar to that of the position particle, except for the step of estimating the stations' capacities. Therefore, we provide no more details on the description.

Algorithm PSO for siting and sizing

for each particle **do**
  Initialize position p_i and velocity v_i of particle i randomly
  Estimate stations' capacities according to Equation (13)
  Evaluate fitness F_i of particle i Set F_i as personal best fitness F_{pi}
  Set p_i as personal best position $pBest_i$
end for
  Set $\min_i F_{p_i}$ as global best fitness F_g
  Set $pBest_{\operatorname{argmin}_i F_{p_i}}$ as global best position $gBest$
while not stop
  for each particle **do**
    Update position p_i and velocity v_i
    Estimate stations' capacities according to Equation (13)
    Evaluate fitness F_i of particle i
    if $F_i < F_{pi}$ **then**
      Set F_i as personal best fitness F_{pi}
      Set p_i as personal best position $pBest_i$
    end if
    if $\min_i F_{p_i}$ F_g **then**
    Set $\min_i F_{p_i}$ as global best fitness F_g
    Set $pBest_{\operatorname{argmin}_i F_{p_i}}$ as global best position $gBest$
    end if
  end for
end while

TABLE 10 Results of hydrogen station siting and sizing

	Location, km	Capacity, kg/day
Station 1	(15.00, 35.00)	739.86
Station 2	(16.63, 9.00)	686.69
Station 3	(28.87, 30.40)	836.33
Station 4	(36.00, 43.00)	523.81

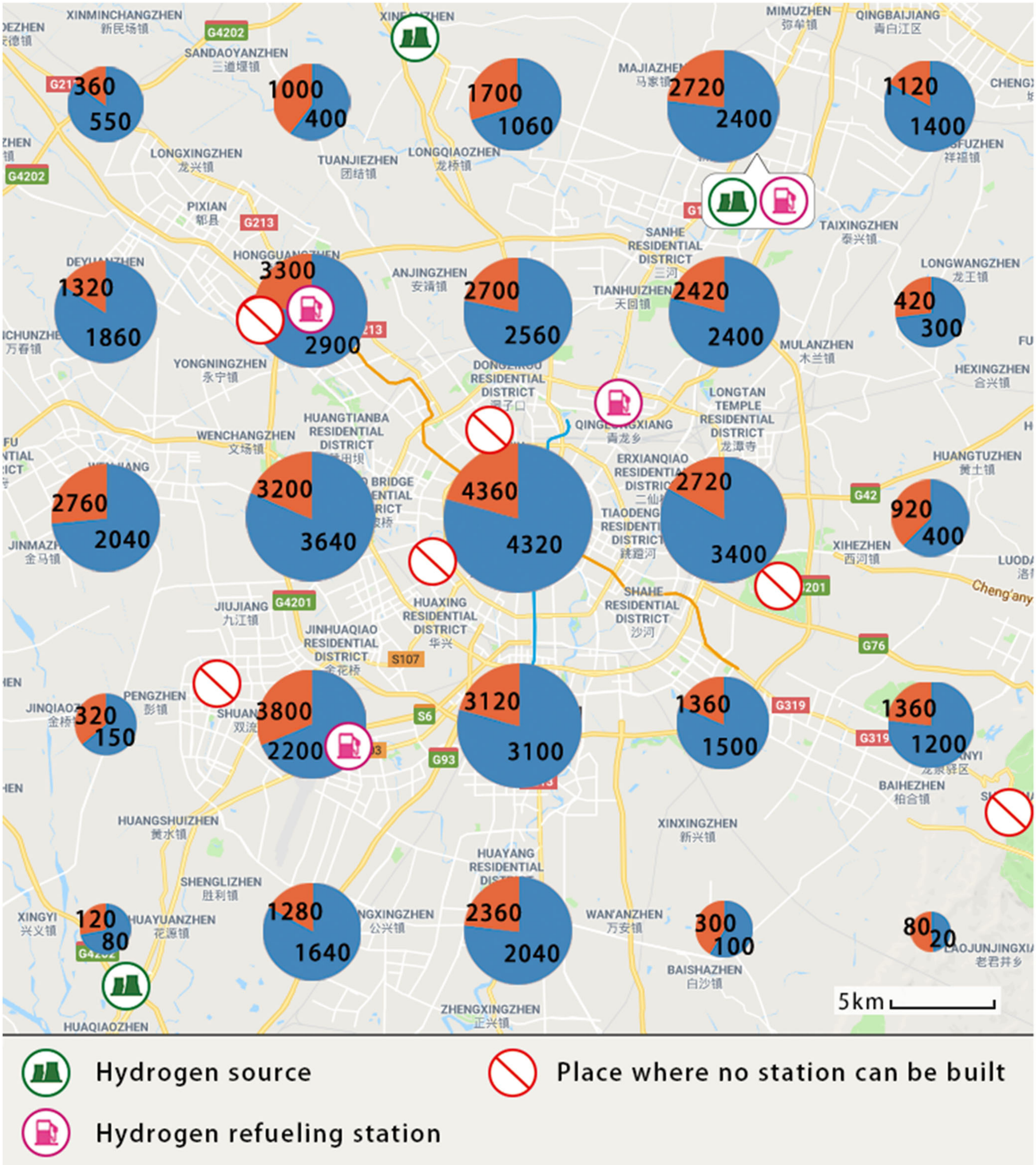


FIGURE 4 Results of hydrogen station siting and sizing: comprehensive distribution of the hydrogen stations and the relevant factors [Colour figure can be viewed at wileyonlinelibrary.com]

By using the above algorithm, programmed in Python, and substituting the data in Tables 2–8, the optimized hydrogen refueling station locations, storage and transport ways, and station capacities are determined. When the population of the particles is set as 30 and the number of iterations reaches 200, the optimal consumers' annual total costs of using hydrogen of approximately 58.80 million CNY/year is obtained. Table 9 shows the components of the optimal consumers' annual total costs.

Figure 3 shows the changes in various aspects of the costs during the program iteration process. The variations

TABLE 11 The probabilities of the stations being selected by the demand points

	Station 1	Station 2	Station 3	Station 4
Point 1	0.113	0.747	0.093	0.047
Point 2	0.207	0.605	0.128	0.059
Point 3	0.500	0.255	0.167	0.078
Point 4	0.719	0.089	0.122	0.070
Point 5	0.624	0.087	0.159	0.129
Point 6	0.020	0.950	0.021	0.009
Point 7	0.079	0.821	0.074	0.026
Point 8	0.508	0.196	0.229	0.066
Point 9	1.000	0.000	0.000	0.000
Point 10	0.646	0.050	0.159	0.145
Point 11	0.068	0.787	0.103	0.043
Point 12	0.121	0.571	0.240	0.067
Point 13	0.152	0.093	0.687	0.068
Point 14	0.225	0.030	0.623	0.122
Point 15	0.276	0.040	0.242	0.442
Point 16	0.134	0.492	0.254	0.120
Point 17	0.141	0.303	0.412	0.144
Point 18	0.092	0.078	0.689	0.142
Point 19	0.070	0.027	0.474	0.429
Point 20	0.010	0.003	0.019	0.968
Point 21	0.157	0.345	0.312	0.186
Point 22	0.150	0.232	0.392	0.226
Point 23	0.127	0.120	0.439	0.314
Point 24	0.091	0.055	0.290	0.564
Point 25	0.065	0.031	0.138	0.766

TABLE 14 Results for comparison

	Location, km
Station 1	(0.30, 1.48)
Station 2	(19.90, 50.00)
Station 3	(21.74, 50.00)
Station 4	(36.00, 43.00)

in production costs, transport costs, and storage costs are described in Figure 3A-C. Figure 3D shows the variation in consumers' hydrogen purchase costs, which is directly proportional to the superposition of Figure 3A-C. Figure 3 F is the superposition of Figure 3D,E because the consumers' costs of using hydrogen are composed of the consumers' hydrogen refueling costs and hydrogen purchase costs. During the whole optimization process, the costs shown in Figure 3A-E do not always converge to their respective optimal values but towards the consumers' optimal combined costs of using hydrogen.

Table 10 shows the optimal locations and sizes of the hydrogen stations. The distribution of the hydrogen sources, hydrogen refueling stations, and excluded areas is shown in Figure 4, which is obtained by marking the station locations from Table 10 in Figure 2.

Tables 11–13 show the probabilities of the stations being selected by the demand points for hydrogen refueling, the multisource hydrogen supply scheme, and the hydrogen transportation scheme.

Table 13 shows the hydrogen transport scheme that is a result of the optimization. Most of the stations use tube trailers for transportation, which confirms the conclusion of Chang et al.[33] The tube trailer is the most suitable

TABLE 12 Multisource hydrogen supply scheme

	Station 1	Station 2	Station 3	Station 4	Total Demand	Productivity of Sources
Source 1	0.00	686.69	0.00	0.00	686.69	800.00
Source 2	739.86	0.00	360.14	0.00	1100.00	1100.00
Source 3	0.00	0.00	476.19	523.81	1000.00	1000.00
Capacity of stations	739.86	686.69	836.33	523.81		

Note. kg/day.

TABLE 13 Hydrogen storage and transport scheme

	Station 1	Station 2	Station 3	Station 4
Source 1		Tube trailer, compression ($P = 20$ MPa)		
Source 2	Tube trailer, compression ($P = 20$ MPa)		Tube trailer, compression ($P = 20$ MPa)	
Source 3			Tube trailer, compression ($P = 20$ MPa)	Pipeline, compression ($P = 3$ MPa)

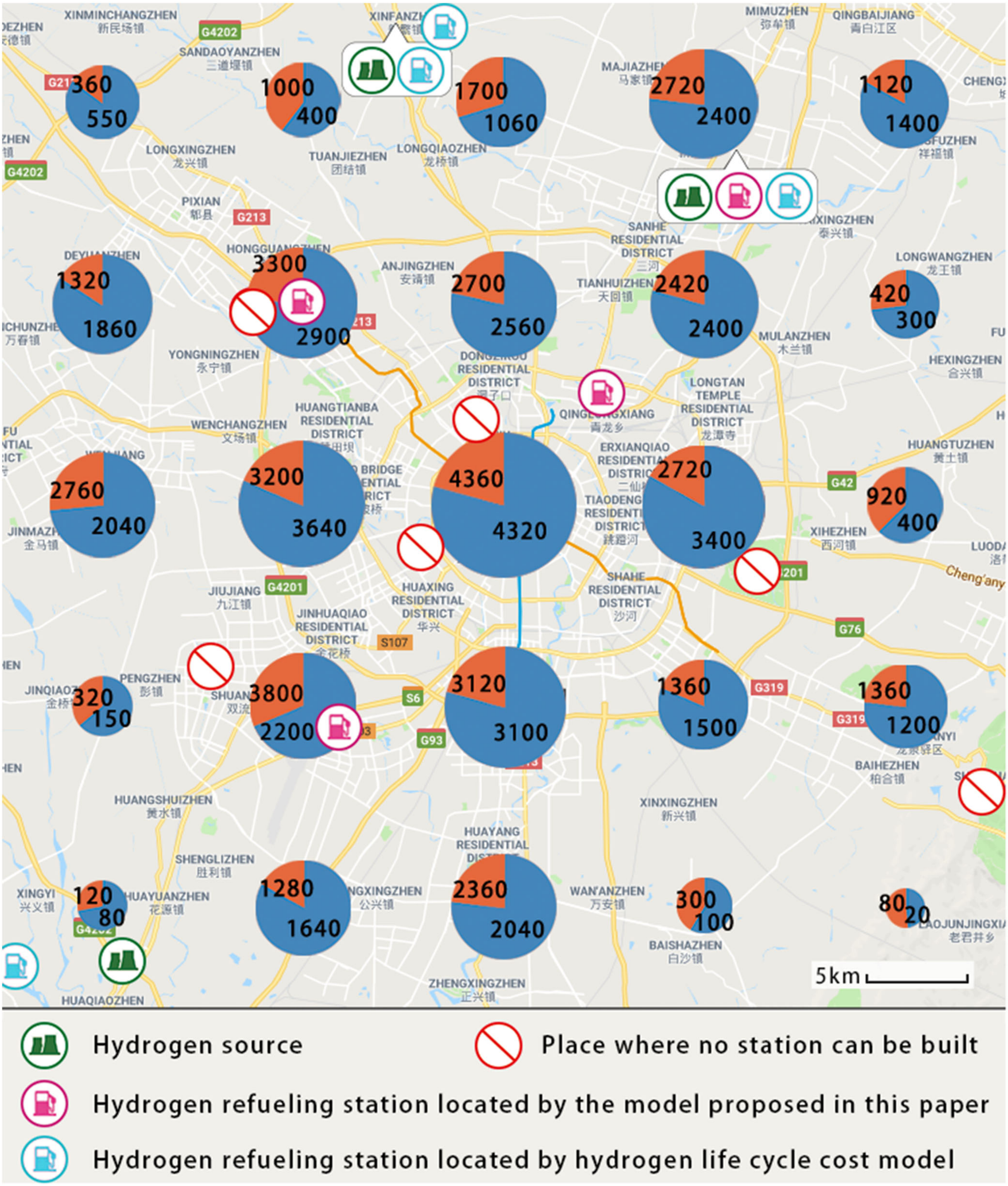


FIGURE 5 Results of the hydrogen station siting obtained from the two models [Colour figure can be viewed at wileyonlinelibrary.com]

vehicle for small-scale and short-distance transport scenarios. Because of the short distance between sources 3 and 4, which is built immediately next to source 3, the construction investment of the pipeline is relatively low. Thus, using the pipeline transport method can achieve the consumers' optimal costs of using hydrogen.

For comparison purposes, the model that only optimizes the hydrogen life cycle cost in Sun et al[30] is modified to apply to this numerical example; ie, Equation 14 is taken as an objective function subject to Constraints (21)–(25). Using the aforementioned PSO algorithm, the locations are obtained and are shown in Table 14. In Figure 5, these locations are marked with blue signs.

By comparing the locations of the hydrogen stations obtained from the two models, it can be seen that when only the hydrogen life cycle cost is considered, the hydrogen stations will be located as close as possible to the hydrogen sources under the given constraints. This can be explained by the fact that regardless of which hydrogen source is chosen for hydrogen supply, the proximity of the hydrogen stations to hydrogen sources can reduce the transportation costs, which in turn reduces the hydrogen life cycle cost. However, the sizes of the hydrogen stations are related to the distances between the stations and the demand points, and they also affect the hydrogen life cycle cost. Therefore, although some hydrogen stations are close to hydrogen sources, they are not in the positions where the hydrogen sources are. In addition, the locations of the hydrogen stations determined by the model that optimizes the total costs will be closer to the large demand points than those locations determined by the former model. However, they are not too far from the hydrogen sources to provide convenience for consumers and reduce the total costs.

5 | CONCLUSIONS

Based on the effectiveness of hydrogen station construction, this paper analyzes the effects of hydrogen sources and demand points on hydrogen station siting and sizing. With the given locations of the demand points and hydrogen sources, the station locations will affect the distance between the stations and sources and the distance between the stations and demand points. The distance between the stations and sources will affect the selection of the sources by the stations, the hydrogen life cycle cost, and the hydrogen costs and prices. The distance between the stations and demand points will also affect the probability of users' selection of the stations and thus the capacity design of the stations. Through the probability of users' selection of the stations, the capacities of the stations can be reasonably designed, thereby avoiding the unnecessary waste of resources and ensuring that the demand for hydrogen refueling is met and the hydrogen life cycle cost is controlled.

This paper defines the consumers' costs of using hydrogen as the sum of the purchase costs and refueling costs. The model proposed in this paper aims to optimize the consumers' costs of using hydrogen and to improve the conditions under which HFCV use is being generalized in terms of hydrogen refueling infrastructure and the costs of using hydrogen. The model also reduces the consumers' costs of using hydrogen while facilitating refueling and sharpening the market competitiveness of HFCVs. Concurrently, to optimize the locations of the hydrogen stations, a Huff model is added to estimate the selection probability of the stations by users at the demand points. Based on these probabilities, the demand volume for hydrogen refueling at the demand points is allocated to the stations, and the capacities of the stations are designed accordingly. The paper also considers the possibility that a single station may need to have hydrogen supplied from several sources and adds a multisource hydrogen supply scheme to optimize the volume of hydrogen bought by the stations from the sources. The paper also details the process of optimizing the locations of the stations and the multisource hydrogen supply scheme using the PSO algorithm. Then, a numerical example of hydrogen station siting and sizing is created, and the siting and sizing of three hydrogen stations around Chengdu is achieved in combination with the multidimensional PSO algorithm, which has exemplary significance. Finally, the location results of this model are compared with those of the previous hydrogen life cycle cost model. This model provides consumers with convenient hydrogen refueling, while the total costs for regional consumers are reduced.

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