Article

Multi-Period Planning of Hydrogen Supply Network for Refuelling Hydrogen Fuel Cell Vehicles in Urban Areas

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Abstract: The hydrogen economy refers to an economic and industrial structure that uses hydrogen as its main energy source, replacing traditional fossil-fuel-based energy systems. In particular, the widespread adoption of hydrogen fuel cell vehicles (HFCVs) is one of the key factors enabling a hydrogen economy, and aggressive investment in hydrogen refuelling infrastructure is essential to make large-scale adoption of HFCVs possible. In this study, we address the problem of effectively designing a hydrogen supply network for refuelling HFCVs in urban areas relatively far from a large hydrogen production site, such as a petrochemical complex. In these urban areas where mass supply of hydrogen is not possible, hydrogen can be supplied by reforming city gas. In this case, building distributed hydrogen production bases that extract large amounts of hydrogen from liquefied petroleum gas (LPG) or compressed natural gas (CNG) and then supply hydrogen to nearby hydrogen stations may be a cost-effective option for establishing a hydrogen refuelling infrastructure in the early stage of the hydrogen economy. Therefore, an optimization model is proposed for effectively deciding when and where to build hydrogen production bases and hydrogen refuelling stations in an urban area. Then, a case study of the southeastern area of Seoul, known as a commercial and residential center, is discussed. A variety of scenarios for the design parameters of the hydrogen supply network are analyzed based on the target of the adoption of HFCVs in Seoul by 2030. The proposed optimization model can be effectively used for determining the time and sites for building hydrogen production bases and hydrogen refuelling stations.

Keywords: hydrogen supply network; hydrogen refuelling station; hydrogen fuel cell vehicle; station location; infrastructure; optimization

1. Introduction

The hydrogen economy is an economic and industrial structure that uses hydrogen as its main energy source. As the hydrogen economy develops, the production will increase of automobiles, ships, trains, and machinery, as well as electricity generation, heat generation, etc., that use hydrogen as an energy source. This will inevitably create new industries and markets for all sectors needed to reliably produce, store, and transport hydrogen [1]. In particular, worldwide efforts are being made to replace gasoline or diesel-based vehicles with hydrogen fuel cell vehicles (HFCVs). They emit almost no greenhouse gases and fine dust, and the adoption rate has increased significantly in several countries because the refuelling time is very short (less than five minutes) and the driving range is much longer (more than 500 km) compared with plug-in or battery electric vehicles. HFCVs were first commercialized in 2014 and, since then, South Korean and Japanese automakers, such as Hyundai,
Toyota, and Honda, have led the global market. Automakers such as GM, Audi, and BMW have also announced plans to launch HFCVs by 2021.

In most countries, however, the hydrogen refuelling infrastructure remains insufficient, making HFCVs less popular than electric vehicles. Therefore, to respond effectively to an increase in the adoption of HFCVs in the near future, a sufficient hydrogen refuelling infrastructure must be built using spending from the national budget. To efficiently build a hydrogen refuelling environment with a limited budget, the decision-making of policy makers should be based on a systematic plan for building a hydrogen supply network that includes hydrogen production facilities, hydrogen refuelling stations, and hydrogen transport facilities, such as pipelines or tube trailers. This plan should include when and where to build such facilities needed to supply hydrogen to HFCVs.

To promote the transition to hydrogen-based energy systems, leading companies in energy and transport gathered to create a global initiative called the “Hydrogen Council”. Their roadmap, released in November 2017, aims to supply 10 to 15 million hydrogen vehicles globally by 2030 [2]. In particular, one in 12 cars in Germany, Japan, Korea, and California are expected to be powered by hydrogen. Governments have also implemented tangible policies to promote the hydrogen economy. To date, 18 governments, which account for over 70% of the global GDP, have developed concrete roadmaps to prepare for the hydrogen economy. This includes plans to build 10,000 hydrogen refuelling stations by 2030 across China, Japan, the U.S., and South Korea [3]. Note that at the end of 2018, 376 hydrogen stations were in operation worldwide. Japan took the lead with 100 stations, followed by Germany (43) and the United States (38).

South Korea has been making preemptive efforts to lead the hydrogen economy market in the future. The South Korean government announced a hydrogen economy roadmap in January 2019 to prepare for the hydrogen economy [4]. Then, in January 2020, for the effective development of the hydrogen economy, the government enacted the world’s first hydrogen-economy-related law, called the Act on the Promotion of Hydrogen Economy and Hydrogen Safety Management [5]. According to the roadmap, the popularization of HFCVs is included as a key factor for the implementation of the hydrogen economy and, to this end, the South Korean government plans to increase the production of HFCVs to 6.2 million units by 2040 and to increase the number of hydrogen refuelling stations, currently at 14, to 1200. South Korea’s aggressive plan is based on the world’s leading technology in the production of hydrogen vehicles and fuel cells. South Korea has much experience and infrastructure in the petrochemical industry, and these are the core foundations of hydrogen supply. Another advantage is that the existing natural gas supply network facilitates the national supply of hydrogen. In this study, the focus was the effective design of a hydrogen supply network for refuelling HFCVs based on the case of South Korea.

The hydrogen supply network in the transportation sector typically consists of four stages: energy source, production, transportation, and refuelling station, as shown in Figure 1. Each stage can have multiple options. First, hydrogen can be produced using a variety of energy sources, such as natural gas, coal, biomass, and wind power. Several industrial processes, such as the production of chlorine, can also produce hydrogen as a byproduct. Next, in the production stage, production techniques such as steam methane reforming (SMR), coal gasification, biomass gasification, and electrolysis can be used. Thereafter, the produced hydrogen is transported to refuelling stations using pipelines, tube trailers, and railways. There are two types of refuelling station. Off-site refuelling stations supply HFCVs with transported hydrogen, whereas on-site refuelling stations supply HFCVs with hydrogen produced in the refuelling station using SMR or electrolysis.
Figure 1. Hydrogen supply network in the transportation sector.

Depending on the characteristics of each country and region, one or more alternatives for each stage of the hydrogen supply network should be selected to build the entire infrastructure for supplying hydrogen to HFVCs. This requires a comprehensive assessment of the different types of supply network regarding not only costs but also environmental impacts such as greenhouse gas emissions. Some studies have been published related to the environmental impact and sustainability assessment for each stage of the hydrogen supply network, such as energy source [6,7], production [8], transportation [9], and refuelling stations [10,11]. The hydrogen supply network based on hydrogen produced from renewable energy such as wind and solar power has little environmental impact, but its cost is relatively high. The hydrogen supply network based on hydrogen produced from fossil fuels such as SMR and coal gasification has the most environmental impact, but are currently the most widely used due to its low cost. Note that no single hydrogen supply network is the most promising in terms of both costs and environmental impacts.

Table 1 summarizes the papers that address the optimization of hydrogen supply network design in the transportation sector published since 2010. To effectively compare the characteristics of each paper, the papers were classified according to the scope of hydrogen supply network and the spatial scale of the model. Several review papers on hydrogen supply network design in the transportation sector were published. Li et al. [12] recently reviewed the research published until 2018 that pertained to hydrogen supply network design models. In particular, they presented an overview of the research regarding the use of optimization methods for hydrogen supply network design. Kurtz et al. [13] reviewed the development of modern hydrogen infrastructure, including the costs, benefits, and operational considerations, such as safety, reliability, and availability, as well as challenges to scaling up the hydrogen infrastructure. Before that, Dagdougui [14] reviewed optimization methods, geographical information systems, and assessment plans that can be used for the transition to a hydrogen infrastructure.

Since the recent commercialization of hydrogen-fuelled vehicles, research results on the optimal location of hydrogen refuelling stations have been published along with several review papers [15–17]. The optimization models for the facility location problems of most alternative fuel stations, including hydrogen stations, can be divided into node-based and path-based models. Most node-based models are variants of the traditional p-median model [18]. In the p-median model, the refuelling demands are represented as points in space, and it is assumed that drivers prefer refuelling at the site nearest to their residence [19]. Therefore, to minimize the total weighted distance between demand nodes and refuelling stations, the p-median model selects p candidate sites for refuelling stations and assigns one refuelling station to each demand node. In a previous work [20], a p-median-based optimization model for locating hydrogen refuelling stations in Sacramento County, California, was proposed. A geographic information system was used to synthesize different information to assess possible station sites. In another study [21], a node-based model that minimizes the total fuel-travel-back time was proposed. The model was applied to obtain an optimal station roll-out plan for Southern California. In other research [22], a hydrogen station location model based...
on the \( p \)-median model was proposed, and genetic and greedy algorithms were applied to solve the problem.

**Table 1.** Summary of characteristics of papers on optimization models for hydrogen supply network design in the transportation sector published since 2010 (TR, transportation; RS, refuelling station; Multi, Multiple dimension; NAT, national; REG, regional; and URB, urban.)

| Scope | Spatial Scale |
|-------|--------------|
| TR    | RS | Multi | NAT | REG | URB |
| Agnolucci et al. [23] | × | × | | | |
| Almansoori and Betancourt-Torcat [24] | × | × | | | |
| Almansoori and Shah [25] | × | × | | | |
| Almaraz et al. [26] | × | × | | | |
| Almaraz et al. [27] | × | × | × | | |
| Almaraz et al. [28] | × | × | | | |
| Andre et al. [29] | × | × | | | |
| Andre et al. [30] | × | × | | | |
| Bique and Zondervan [31] | × | × | | | |
| Brey et al. [32] | × | × | | | |
| Cho et al. [33] | × | × | | | |
| Dagdougui et al. [34] | × | × | | | |
| Dayhim et al. [35] | × | × | | | |
| Gim et al. [36] | × | × | | | |
| Han et al. [37] | × | × | | | |
| Han et al. [38] | × | × | | | |
| He et al. [39] | × | × | | | |
| Honma and Kuby [40] | × | × | | | |
| Hwangbo et al. [41] | × | × | | | |
| Johnson and Ogden [42] | × | × | | | |
| Konda et al. [43] | × | × | | | |
| Krishnan et al. [44] | × | × | | | |
| Lahnaoui et al. [45] | × | × | | | |
| Lin et al. [42] | × | × | | | |
| Kim and Kim [46] | × | × | | | |
| Kim and Kim [47] | × | × | | | |
| Moreno-Benito et al. [48] | × | × | | | |
| Nunes et al. [49] | × | × | | | |
| Ogumerem et al. [50] | × | × | | | |
| Parker [51] | × | × | | | |
| Rosenberg et al. [52] | × | × | | | |
| Sabio et al. [53] | × | × | | | |
| Sabio et al. [54] | × | × | | | |
| Samsati et al. [55] | × | × | | | |
| Stephens-Romero et al. [56] | × | × | | | |
| Sun et al. [57] | × | × | | | |
| Sun et al. [58] | × | × | | | |
| Won et al. [59] | × | × | | | |

In the path-based model, demand is defined as the amount of traffic that passes through the path between the origin and the destination nodes. The path-based model assumes that the driver stops at a refuelling station located on the path while driving. The flow-capturing location model (FCLM) proposed by Hodgson [60] was the first path-based model. The FCLM locates \( p \) refuelling stations over the network to maximize the flow volume passing through them. Kuby and Lim [61] proposed a flow refuelling location model (FRLM) that extends the FCLM to consider the driving range of alternative-fuel vehicles. Many extensions of the FRLM have been proposed for various types of alternative fuel station [62–65]. Kuby et al. [66] used the FRLM to investigate strategies for rolling out an initial hydrogen refuelling infrastructure in Florida. Upchurch and Kuby [67] compared the \( p \)-median and flow-refuelling models for locating alternative-fuel stations. A similar comparison
between node-based and path-based location models for urban hydrogen refuelling stations was also conducted [40].

Recent studies on the optimal siting of hydrogen refuelling stations include Sun et al. [57], in which optimal hydrogen refuelling station locations were determined for a multi-source hydrogen supply. A particle swarm optimization algorithm was applied for the station location problem for the Shanghai–Nanjing Expressway in China. He et al. [39] proposed a hydrogen refuelling station siting model for a hydrogen energy expressway system based on the optimization of hydrogen life cycle cost. In another work [58], an optimal siting and sizing model was proposed for hydrogen refuelling stations, which considers distributed hydrogen production and cost reduction for regional consumers.

In this study, the focus was on designing a hydrogen supply network for refuelling HFCVs in urban areas, where a large volume of hydrogen supply from external hydrogen sources is not suitable. Therefore, a scenario was envisioned wherein all refuelling stations operate in the on-site form, i.e., hydrogen is generated in the refuelling stations. In addition, to cope with uncertainties in hydrogen refuelling demand, building distributed small-sized hydrogen production facilities that supply hydrogen smoothly to on-site refuelling stations across urban areas was considered. The scenario using on-site hydrogen refuelling stations and distributed hydrogen production bases described so far is in the planning stage to meet the refuelling demand of hydrogen vehicles in Seoul, South Korea. Therefore, in this study, for the systematic implementation of this scenario, we attempted to determine the optimal time and place to build hydrogen production facilities as well as hydrogen refuelling stations. In particular, most of the existing studies on hydrogen supply network design only dealt with the decision on where to locate the facilities, but this study contributes to the existing literature by presenting a multi-period optimization model that considers the time of construction as well as the location of facilities.

In this work, a case study in the southeastern area of Seoul was conducted to validate an optimization model for building a hydrogen supply network in an urban area. As shown in Table 1, few studies have been conducted on the design of hydrogen supply networks in urban areas. Therefore, our findings will contribute to the existing literature with a systematic case study in the southeastern area of Seoul. Several studies have been conducted regarding the design of a hydrogen supply network in South Korea [36,41,59,68]. However, most of the research addressed the problem of designing a nationwide hydrogen supply chain to effectively transport a large amount of hydrogen produced in chemical complexes by pipeline. Recently, an optimization model was developed for designing a hydrogen supply network for South Korea using a centralized storage model [69]. On-site and off-site refuelling stations were both considered for satisfying the hydrogen demand in cities, but the focus was on a nationwide design of a hydrogen supply network. In the present work, the focus was especially on the design of an urban hydrogen supply network for refuelling HFCVs in a multi-period setting.

This paper is organized as follows. In Section 2, the problem of designing a multi-period urban hydrogen supply network for refuelling HFCVs is described in detail. An optimization model for the problem is proposed in Section 3. The data and scenarios used in a case study in the southeastern area of Seoul are described in Section 4. The results of the case study are provided in Section 5, and conclusions are outlined in Section 6.

2. Problem Description

Hydrogen can be produced from a variety of sources, such as natural gas, coal, biomass, and wind or solar power, as well as through a variety of production technologies, such as electrochemical, thermochemical, and biological methods [6,9]. Therefore, hydrogen refuelling stations can take many forms depending on the hydrogen source and production technology. The hydrogen refuelling stations already built or planned to be built in South Korea can be classified into two categories, off-site and on-site stations, depending on the hydrogen supply method. In general, an off-site station is supplied with a large amount of hydrogen produced in nearby petrochemical complexes through a pipeline or tube trailers. It uses hydrogen generated in industrial processes occurring in the petrochemical and
steel industries, and this method can produce a large amount of hydrogen at a low cost. However, a disadvantage is that transporting hydrogen is expensive. Therefore, off-site stations are appropriate for areas close to hydrogen supply sources. The construction of off-site stations is not desirable in urban areas, which have a high demand for hydrogen refuelling but are far from hydrogen supply sources.

On-site stations are those that produce their own hydrogen through reforming of LPG or CNG. With this method, hydrogen can be produced according to the refuelling demand of each refuelling station because hydrogen is produced and supplied at the same place, and can also be introduced without hydrogen transport infrastructure, such as a pipeline. However, on-site stations require hydrogen reforming and refining facilities, resulting in a higher construction cost than for off-site stations. A typical on-site station has a hydrogen supply capacity of 100–300 Nm\(^3\)/h. This corresponds to a capacity for refuelling five HFCVs or fewer per hour. In South Korea, petrochemical complexes, which are the main hydrogen supply sources, are located in the southeastern and southwestern parts of the country, so long-distance transportation of 400–500 km is necessary to Seoul, which has the largest hydrogen refuelling demand. Therefore, for Seoul, construction of on-site stations is more appropriate than off-site stations.

In the early development stages of the hydrogen economy, the key foundation for the smooth supply of hydrogen is the production of hydrogen through the reformation of natural gas [70]. The establishment of a hydrogen production base that produces reformed hydrogen by constructing hydrogen extractors with a capacity of 300 Nm\(^3\)/h or more in LPG or CNG refuelling stations or CNG bus garages near the hydrogen refuelling demand can be a valid alternative, especially in urban areas far from petrochemical complexes that can supply byproduct hydrogen. Due to the high cost, it is not possible to build on-site stations in every location where a demand for hydrogen refuelling exists. Therefore, South Korea plans to build on-site hydrogen production bases in urban areas in the early stage of HFCV introduction. This distributed hydrogen production base can be operated as a mother station that produces hydrogen using a city gas supply network and that supplies hydrogen to nearby refuelling stations. For large-scale hydrogen production bases of 1000 Nm\(^3\)/h or more, securing sufficient construction space in urban areas is difficult. In addition, due to the opposition of residents, quickly establishing these locations is challenging. However, the decentralized small-sized hydrogen production base uses LPG and CNG refuelling stations that are already in operation, so it is relatively easy to introduce in the early stages of the hydrogen economy. The decentralized hydrogen production base will initially be built at the CNG bus garage to supply hydrogen for public transport, such as hydrogen buses and hydrogen taxis, and to supply hydrogen to nearby small hydrogen stations using tube trailers. Figure 2 illustrates the structure of the hydrogen supply network addressed in this study. Note that to build such a hydrogen supply network in urban areas, hydrogen stations, production facilities, and transportation vehicles must meet strict safety standards. In Korea, a law on the safe management of the hydrogen industry is applied to ensure that people can enjoy a level of safety similar to that of natural gas in use. For example, strict safety standards are applied to hydrogen-related facilities, such as the use of parts that have passed safety inspection in accordance with ISO standards, installation of explosion-proof structures, and employment of safety managers.
In the urban areas of large cities such as Seoul, on-site refuelling stations must be built that extract hydrogen from city gas using reforming equipment to meet the refuelling demand. However, the construction of an on-site station costs approximately USD 5 million, which is twice the cost of constructing an off-site station. Therefore, in the early stages of the hydrogen economy, many of the stations will operate without hydrogen reforming equipment; instead, they will be supplied with hydrogen from distributed hydrogen production bases. In addition, it is advantageous to be able to receive hydrogen from the hydrogen production base to cope with the uncertainty of the refuelling demand, even in an on-site station with hydrogen reforming equipment. When the demand is low, operating the reforming equipment is inefficient and when the demand is high, additional hydrogen can be supplied from the hydrogen production base for demand beyond the capacity of the on-site station. In addition, because the production efficiency of small hydrogen reforming equipment is not high enough yet, it is economically more advantageous to use medium and large hydrogen reforming equipment in the hydrogen production base. Therefore, as the hydrogen economy develops, it is important to decide to establish a decentralized hydrogen production base and hydrogen refuelling stations in the correct place and at the correct time under a limited budget. Therefore, we focused on the multi-period optimization problem for designing a hydrogen supply network, including a distributed hydrogen production base and hydrogen refuelling station in urban areas.

3. Optimization Model

In this study, the multi-period hydrogen supply network design problem for refuelling HFCVs was addressed using the $p$-median model. The $p$-median model is one of the most widely used models for facility location. It divides the entire area into a set of demand nodes and assigns each node to one of $p$ facilities selected from possible facility candidates. In this case, the sum of the total distances from the node to the facility should be minimized. The $p$-median model attempts to select the location of the refuelling station so that drivers can refuel near where they live, and in actual urban areas, many studies demonstrated that drivers tend to recharge near where they live [19]. In this model, unlike in most previous studies, the focus was constructing a multi-period plan for hydrogen supply infrastructure that determines the optimal location for different numbers of hydrogen stations and production bases as well as the time of their construction. Prior to presenting the optimization model, the notation used throughout the paper is defined.

Sets and Indices

- $i \in I$: The set of demand nodes;
- $j \in J$: The set of candidate sites for hydrogen refuelling station;
- $J(i)$: The set of candidate sites for hydrogen refuelling station that can cover demand node $i$;
- $k \in K$: The set of candidate sites for hydrogen production base;
- $K(j)$: The set of candidate sites for hydrogen production base that can cover hydrogen refuelling
station site \( j \);  
\( T = \{1, \ldots, \tau\} \): The set of planning periods (year).

**Parameters**
- \( \text{DIST}_{ij} \): Travel distance between demand node \( i \) and hydrogen refuelling station site \( j \);
- \( \text{DIST}_{jk} \): Travel distance between hydrogen refuelling station site \( j \) and hydrogen production base site \( k \);
- \( H_i \): The number of HFCVs at demand node \( i \) in time period \( t \);
- \( P_i \): The number of hydrogen refuelling stations to be built in time period \( t \);
- \( Q_k \): The number of hydrogen production bases to be built in time period \( t \);
- \( \text{CAP}_{kt} \): The number of hydrogen refuelling stations that can be covered by hydrogen production base \( k \) in time period \( t \);
- \( p \): Weight used to control the importance of two types of distance terms in the objective function.

**Decision Variables**
- \( x_{jt} \): 1 if hydrogen refuelling station \( j \) is in operation in time period \( t \), 0 otherwise;
- \( y_{ijt} \): 1 if demand node \( i \) is covered by hydrogen refuelling station \( j \) in time period \( t \), 0 otherwise;
- \( z_{jt} \): 1 if hydrogen refuelling station \( j \) is built in time period \( t \);
- \( u_{kt} \): 1 if hydrogen production base \( k \) is in operation in time period \( t \);
- \( v_{kt} \): 1 if hydrogen production base \( k \) is constructed in time period \( t \);
- \( w_{jkt} \): 1 if hydrogen refuelling station \( j \) is covered by hydrogen production base \( k \) in time period \( t \).

With the notation defined, the optimization model for the multi-period hydrogen supply network design problem for refuelling HFCVs can be developed as:

\[
\min \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \text{DIST}_{ij} H_i y_{ijt} + p \sum_{j \in J} \sum_{k \in K} \sum_{t \in T} \text{DIST}_{jk} w_{jkt} \\
\text{s.t.} \sum_{j \in J(i)} y_{ijt} = 1 \quad \forall i \in I, \forall t \in T, 
\]
(1)

\[
y_{ijt} \leq x_{jt} \quad \forall i \in I, j \in J, t \in T, 
\]
(2)

\[
x_{jt} \leq x_{j(t+1)} \quad \forall j \in J, t \in T \setminus \{\tau\}, 
\]
(3)

\[
z_{jt} = x_{jt} - x_{j(t-1)} \quad \forall j \in J, t \in T, 
\]
(4)

\[
\sum_{j \in J} z_{jt} = P_t \quad \forall t \in T, 
\]
(5)

\[
\sum_{k \in K(i)} w_{jkt} = x_{jt} \quad \forall j \in J, t \in T, 
\]
(6)

\[
\sum_{j \in J} w_{jkt} \leq \text{CAP}_{kt} u_{kt} \quad \forall k \in K, t \in T, 
\]
(7)

\[
u_{kt} \leq u_{k(t+1)} \quad \forall k \in K, t \in T \setminus \{\tau\}, 
\]
(8)

\[
v_{kt} = u_{kt} - u_{k(t-1)} \quad \forall j \in J, t \in T, 
\]
(9)

\[
\sum_{k \in K} v_{kt} = Q_t \quad \forall t \in T, 
\]
(10)

\[
x_{jt}, y_{ijt}, z_{jt}, u_{kt}, v_{kt}, w_{jkt} \in \{0, 1\} \quad \forall i \in I, j \in J, k \in K, t \in T. 
\]
(11)

Constraint (2) enables each demand node to be assigned exactly one hydrogen station at all time periods. Constraint (3) means that all demand nodes must be assigned to the hydrogen station that is currently in operation. Constraint (4) ensures that once a refuelling station is built and starts to operate, it cannot be stopped afterward. Constraints (5) link together the binary variables \( z_{jt} \) and \( x_{jt} \) and mean that the refuelling station starts operating from the year in which it was built. Constraint (6)
states that a fixed number of refuelling stations must be constructed each year. Constraint (7) links together the binary variables $w_{jk}$ and $x_{jt}$. They indicate that if the refuelling station is in operation, it should be covered by one of the hydrogen production bases. Constraint (8) ensures that the number of refuelling stations covered by a hydrogen production base does not exceed the maximum capacity of that production base. Constraint (9) ensures that once a hydrogen production base is built and has started to operate, it cannot be stopped afterward. Constraint (10) links together the binary variables $v_{kt}$ and $u_{kt}$ and means that the hydrogen production base starts operating from the year in which it was built. Constraint (11) states that a fixed number of hydrogen production bases must be constructed each year. The binary restrictions on all of the variables are given in Constraint (12). Finally, the objective function (1) minimizes the weighted sum of the travel distances between demand nodes and refuelling stations and those between refuelling stations and hydrogen production bases. The weight used for the distance between demand node $i$ and the hydrogen station assigned to demand node $i$ in time period $t$ is given as the number of HFCVs at demand node $i$ in time period $t$, $H_{it}$. The parameter $p$ controls the importance of the distance between hydrogen stations and hydrogen production bases relative to the distance between demand nodes and hydrogen stations.

4. Case Study: Area and Data

A case study was conducted for the southeastern area of Seoul to design a hydrogen supply network for refuelling HFCVs based on the target of HFCV introduction from 2021 to 2030. Seoul is divided into five zones. Among them, the southeastern area is a commercial and residential center including the well-known Gangnam district, where the quality of life, such as living environment, income, and education level, is higher than in other parts of Seoul. It also has the largest population and highest number of vehicle registrations among the five zones in Seoul. Therefore, the southeastern area of Seoul is expected to have sufficient adoption of HFCVs in the early stage of the hydrogen economy. There were two hydrogen refuelling stations in Seoul as of January 2020, one of which is located in the southeastern area. Figure 3a shows a map of the southeastern area of Seoul, which is divided into 46 small administrative divisions called “dongs”. The opacity of the region represents the relative magnitude of the number of HFCVs in the region. In the case study, a node for hydrogen refuelling demand was created for each of the 46 dongs. In addition, the community offices located in the residential center of each dong were set as the central coordinate of the demand node.

![Figure 3.](image-url)
The amount of HFCV adoption \((H_{it})\) of demand node \(i\) in time period (year) \(t\) was calculated as follows: First, the yearly target of HFCV adoption for the whole of Seoul from 2021 to 2030 was obtained from [71]. Then, the demand of node \(i\) at year \(t\) was calculated by multiplying the target of HFCV adoption of Seoul at year \(t\) by the ratio of the number of registered vehicles of node \(i\) to the number of all registered vehicles in Seoul. This assumes that the regional distribution of the vehicle does not vary significantly depending on the type of fuel. Figure 4a shows how the total target amount of HFCV introduction in the southeastern area of Seoul changes by year, and the distribution of the target amount of HFCV introduction by demand node is depicted in Figure 4b, where the y-axis represents the percentage of the HFCV introduction target of each node relative to the total introduction target. The figure shows the percentage values for 46 demand nodes in ascending order.

![Figure 4](image_url)

**Figure 4.** (a) Annual total target of HFCV introduction in the southeastern area of Seoul. (b) Distribution of HFCV introduction target percentage of each demand node relative to the total HFCV introduction target.

Next, candidate sites for hydrogen refuelling stations were assumed to be 17 LPG stations currently in operation in the southeastern area of Seoul and 13 public facilities, such as parks, district offices, and public parking lots. According to the hydrogen economy roadmap of South Korea, in the early stages of the hydrogen economy, priority is given to converting LPG stations, which are easily supplied with LPG, into complex refuelling stations capable of supplying both LPG and hydrogen. In addition, public facilities that can easily secure space for building hydrogen refuelling stations in the city were considered potential candidate sites. In 2019, due to the deregulation related to the construction of hydrogen stations, the requirements for establishing hydrogen stations in the city center were considerably eased. Since then, the construction of hydrogen stations in parks and public facilities in urban areas that can satisfy the safety management regulations has been actively promoted [4].

For hydrogen production bases, seven CNG refuelling stations located in city bus garages in the southeastern area of Seoul were selected as candidate sites. The hydrogen economy roadmap first aims to popularize hydrogen buses in the early stages of the hydrogen economy. To this end, building hydrogen production bases at the CNG refuelling station could be an effective option to produce hydrogen by reforming CNG and smoothly supplying hydrogen to the hydrogen buses [4]. In this case, the hydrogen produced at the production base is first supplied to the hydrogen buses, and the remaining hydrogen can be supplied to the nearby hydrogen refuelling station using tube trailers. Figure 3b shows the locations of candidate sites for the hydrogen refuelling stations and the hydrogen production bases described so far. Four hydrogen refuelling stations shown in the map are already planned for construction by 2020, so a plan from 2021 to 2030 was formulated. Most of the candidate
sites for hydrogen production bases are located outside the city center because most of the city bus garages are located in areas outside the city center, and it is almost impossible to find a site to build a new hydrogen production base in the city due to the expensive land prices and opposition from residents.

The travel distances $DIST_{ij}$ between the demand node $i$ and the hydrogen station $j$ and $DIST_{jk}$ between the hydrogen station $j$ and the hydrogen production base $k$ were calculated using Google Maps [72]. In addition, we assumed that each hydrogen station can cover a demand node located within 15 km (i.e., $DIST_{ij} < 15$), and each production base can supply hydrogen only to a hydrogen station located within 20 km (i.e., $DIST_{jk} < 20$).

Next, the number of hydrogen refuelling stations ($P_t$) to be built at time period $t$ was calculated as follows: First, we assumed that one hydrogen station can refuel 70 vehicles per day, which is the average hydrogen supply capacity of the hydrogen stations currently operating in Seoul. In addition, it is possible to drive about 300 km with a single refuel of hydrogen at a hydrogen station currently operated in Seoul. As the average daily driving distance of Korean drivers is about 40 km [73], we assumed that the hydrogen is refuelled approximately once per week on average. Therefore, the capacity of one hydrogen station can be considered as approximately 490 HFCVs. Then, by dividing the amount of HFCV introduction in 2030 by the capacity of one hydrogen station, 17 hydrogen stations should be constructed in 2030. Because four hydrogen stations are already scheduled to be built in the southeastern area of Seoul by 2020, plans should be constructed to build 13 additional hydrogen stations from 2021 to 2030. In the case study, the following three scenarios were analyzed: (1) $P_1$: building less initially and building more over time according to the amount of HFCV adoption, (2) $P_2$: the number of hydrogen stations increases at the same rate, and (3) $P_3$: building a large number of hydrogen stations in the early stage. Figure 5 shows how $P_t$ values evolve over time for these three scenarios.

The hydrogen economy roadmap aims to build 18 hydrogen production bases nationwide by 2022, gradually increasing the number of production bases as the adoption rate of hydrogen vehicles increases. Therefore, considering the ratio of HFCV adoption in the southeastern area of Seoul, the basic scenario is assumed to involve building three hydrogen production bases by 2030 in the southeastern area of Seoul. As with the hydrogen stations, we analyzed three scenarios of when to construct production bases: (1) $Q_1$: building less initially and building more over time ($Q_1 = Q_7 = Q_9 = 1$), (2) $Q_2$: building with the same time interval ($Q_1 = Q_5 = Q_9 = 1$), and (3) $Q_3$: building more in the
early stage \((Q_1 = Q_3 = Q_6 = 1)\). In addition to the default case, we analyzed cases where the total number of hydrogen stations and the number of hydrogen production bases have different values.

Finally, the maximum number of hydrogen stations that can be covered by one hydrogen production base \((CAP_{kt})\) was set as \(\lceil \frac{\sum_{t'=1}^{t} p_{t'}}{\sum_{t'=1}^{t} Q_{t'}} \rceil\), the rounded-up value of the number of hydrogen stations built up to time period \(t\) divided by the number of hydrogen production bases built up to time period \(t\). Because this was performed, all hydrogen stations in operation could be allocated to one of the hydrogen production bases in operation. This also allowed the hydrogen stations to be allocated as evenly as possible to the production bases.

5. Results and Discussion

In this section, the results of the case study on the southeastern area of Seoul are presented. All the computational tests were performed on a 2.2-GHz Intel Core i5 processor with 8 GB of random-access memory. The resolution of the optimization model was achieved using the Xpress 8.5 solver [74] with the default parameter settings. The model consisted of approximately 17,000 binary variables and 18,000 linear constraints. All tested models could be solved within seconds.

5.1. Comparison of Different Scenarios

First, different scenarios of construction of hydrogen refuelling infrastructure were simulated, i.e., nine scenarios for different values of \(P_t\) and \(Q_t\) over the planning horizon. Each scenario is denoted by \(P_xQ_y\), which means that the scenario \(P_x\) for the hydrogen refuelling station and the scenario \(Q_y\) for the hydrogen production base were used. The default value of parameter \(p\) was set to 200. The results change for different values of \(p\) in the next subsection. Because the objective function used in the case study was the weighted sum of the two types of travel distance, the simulation results of the tested scenarios were assessed using these distances, i.e., the average travel distance between each demand node and the hydrogen station assigned to the demand node, and the average travel distance between each hydrogen station and the hydrogen production base assigned to the hydrogen station.

Figure 6 shows how the average travel distance between demand nodes and hydrogen stations changes over time for all scenarios. The average travel distance tends to decrease as the number of hydrogen stations built increases over the planning horizon. Although we observed small differences depending on the scenario, the average travel distance, which was approximately 4 km for 2021, decreased to approximately half by 2030 with the help of the additional construction of 13 hydrogen stations. Figure 7 depicts how the average travel distance between the hydrogen stations and hydrogen production bases changes over time for all scenarios. As with the trend observed in Figure 6, the average travel distance between the hydrogen stations and the production bases also tended to decrease. Although the average travel distance between demand nodes and hydrogen stations decreased relatively slowly over the planning horizon, the average travel distance between hydrogen stations and production bases decreased sharply at the time the production base was constructed. However, it sometimes increased when the number of hydrogen production bases did not increase. In addition, the travel distance between hydrogen stations and production bases was approximately two to three times larger than the travel distance between demand nodes and refuelling stations.
Figure 6. Change in average travel distance between demand nodes and hydrogen refuelling stations over time.

Figure 7. Change in average travel distance between hydrogen refuelling stations and hydrogen production bases over time.

Figure 8a compares the overall average travel distances between demand nodes and hydrogen stations for all scenarios. As expected, the travel distance tended to increase in the order of P1, P2, and P3. This occurred because the more hydrogen stations built at the beginning of the planning horizon, the shorter the travel distance between hydrogen stations and demand nodes. However, the difference in the time of construction of a hydrogen production base (Q1, Q2, or Q3) did not have a significant effect on the travel distance between hydrogen stations and demand nodes. Figure 8b compares overall average travel distances between hydrogen stations and production bases for all scenarios. The travel distance decreased in the order of Q1, Q2, and Q3. In addition, the travel distance tended to decrease in the order of P1, P2, and P3. In other words, the travel distance between hydrogen
stations and production bases decreases as more hydrogen stations are built in the early stages of the planning horizon.

Figure 8. (a) Overall average travel distance between demand nodes and hydrogen refuelling stations over the planning horizon. (b) Overall average travel distance between hydrogen refuelling stations and hydrogen production bases over the planning horizon.

Figure 9 graphically illustrates the locations of the hydrogen refuelling stations and hydrogen production bases to be built for three scenarios, P1Q1, P2Q2, and P3Q3. In this map, the facilities have different colors depending on the year in which each facility was built. The locations of hydrogen production bases are the same regardless of the scenario, and the distributions of hydrogen station locations are also similar, regardless of the scenario. In particular, in the P1Q1 and P2Q2 scenarios, the locations of the hydrogen stations as well as hydrogen production bases are the same. If a single-period planning problem is considered, the location of each facility will not differ significantly from those in Figure 9. Therefore, when the multi-period planning problem is considered, the problem is reduced to determining the construction time of each facility rather than the location of each facility.

Figure 9. Geographical illustration of the locations of the hydrogen refuelling stations (circles) and hydrogen production bases (squares) to be built for different scenarios: (a) P1Q1, (b) P2Q2, and (c) P3Q3.

5.2. Sensitivity Analysis

The sensitivity of the results was further analyzed with respect to various parameters, including the parameter \( p \) in the objective, the total number of hydrogen stations to be built, and the total number of hydrogen production bases to be built. Note that \( p \) controls the relative importance of
two types of distances. As $p$ increases, the importance of the distance between the hydrogen station and the production base becomes greater than that of the distance between the hydrogen station and the demand node. It is still unclear how often hydrogen will be supplied from the production base to the hydrogen station, so we needed to simulate the results for various $p$ values. Figure 10 shows how the average travel distances changes over time for different $p$ values. The results are only reported for $p = 100, 200, 500,$ and $900$. This is because the results for the average travel distance change drastically only for these four $p$ values. In the figure, each line represents the average computed over nine scenarios. As expected, there is a clear trend that, as $p$ increases, the distance between the hydrogen station and the production base decreases, and the distance between the hydrogen station and the demand node increases. This trend can also be observed in Figure 11, in which the overall average travel distances over a 10-year planning period are compared for each $p$ value. When $p = 100,$ the ratio of the average travel distance between the hydrogen station and the production base and the average travel distance between the hydrogen station and the demand node is approximately 2.81, but when $p = 900,$ this ratio decreases to approximately 1.95. Figure 12 shows the locations of all selected facilities over the planning horizon for scenario P3Q3, which enables comparison of the geographical distribution of the selected facilities for different $p$ values. When the $p$ value is small, the hydrogen stations tend to be evenly distributed over the planning area. However, as the $p$ value increases, the candidate stations near the production station tend to be selected. By comparing the simulation results for various $p$ values, policy makers can determine the appropriate $p$ value according to the future introduction of HFCVs and the construction of the hydrogen refuelling infrastructure. For the multi-period planning problem, different $p$ values can be set for each planning year. This creates the situation in which the frequency of hydrogen supply between the hydrogen station and the hydrogen production base changes over time is considered in the optimization model.

![Figure 10](image_url)

**Figure 10.** (a) Change in average travel distance between demand nodes and hydrogen refuelling stations for different $p$ values. (b) Change in average travel distance between hydrogen refuelling stations and hydrogen production bases for different $p$ values.
Figure 11. (a) Overall average travel distance between demand nodes and hydrogen refuelling stations for different $p$ values. (b) Overall average travel distance between hydrogen refuelling stations and hydrogen production bases for different $p$ values.

Figure 12. Geographical allocation of hydrogen refuelling stations and hydrogen production bases to be built in scenario P3Q3 for different $p$ values: (a) $p = 100$, (b) $p = 200$, and (c) $p = 500$.

Next, we conducted a sensitivity analysis of the number of hydrogen stations to be built. Let $P = \sum_{t=1}^{T} P_t$ be the total number hydrogen stations built over the planning horizon. Three cases were considered: $P = 12, 17,$ and $22$. In this sensitivity analysis, only the total number of hydrogen stations was changed while the pattern of increasing the number of hydrogen stations in scenarios P1, P2, and P3 was maintained. Figure 13 shows the change in the overall average travel distances according to the increase in the number of total hydrogen stations for scenarios P1Q1, P2Q2, and P3Q3. Figure 13a shows that as the total number of hydrogen stations increases, the overall average travel distance between hydrogen stations and demand nodes decreases. In particular, the rate of decrease was the greatest in scenario P3Q3. In other words, the average travel distance changes sensitively to the total number of hydrogen stations when not many hydrogen stations have been built at the early stage. However, Figure 13b shows that the average travel distance between hydrogen stations and hydrogen production stations is not very sensitive to changes in the total number of stations. In particular, in scenario P3Q3, when the number of hydrogen stations increases, the average travel distance between the hydrogen stations and the hydrogen production base increases. Figure 14 geographically illustrates the locations of selected hydrogen stations and hydrogen production bases for scenario P3Q3 for different $P$ values. When $P = 17$, the hydrogen stations near the production base seem to be sufficiently selected, but when $P = 22$, five additional stations must be constructed,
so the average travel distance between hydrogen stations and production bases increases by selecting hydrogen stations far from the production bases.

![Figure 13](image1.png)

**Figure 13.** Overall average travel distance between (a) demand nodes and hydrogen refuelling stations and (b) hydrogen refuelling stations and hydrogen production bases for different numbers of total hydrogen refuelling stations built.

The impact of the total number of hydrogen production bases built over the planning horizon, $Q = \sum_{t=1}^{T} Q_t$, was analyzed. To analyze the sensitivity of the results for the $Q$ value, the value was varied between one and five for scenario P3Q3. For each $Q$ value, the years when hydrogen production bases are to be built were determined so that they are built more in the early stage, in line with scenario Q3. Figure 15 shows the overall average travel distances computed for different $Q$ values. The number of total hydrogen production bases did not have much impact on the average travel distance between hydrogen stations and demand nodes. However, as expected, the average travel distance between hydrogen stations and production bases decreased significantly with the increase in the number of total hydrogen production bases. Figure 16 geographically illustrates the locations of selected hydrogen stations and hydrogen production bases for $Q = 1$, $Q = 3$, and $Q = 5$. As the number of hydrogen production bases increases, the production bases tend to be distributed as evenly as possible within the planning area to minimize the distance between the hydrogen station and production base.
Figure 15. Overall average travel distance between (a) demand nodes and hydrogen refuelling stations and (b) hydrogen refuelling stations and hydrogen production bases for different numbers of total hydrogen production bases built.

Figure 16. Geographical allocation of hydrogen stations and production bases to be built in scenario P3Q3 for different Q values: (a) Q = 1, (b) Q = 3, and (c) Q = 5.

5.3. Discussion

In the computational experiments, we solved the hydrogen supply network design problem in the southeastern area of Seoul for various scenarios of when the hydrogen stations and production bases are to be built, and performed sensitivity analysis on various parameters. The results obtained from the experiments can be summarized as follows:

- If the hydrogen supply network is established early in the development of the hydrogen economy, the distance between the driver and the hydrogen station and the distance between the hydrogen station and the hydrogen production base are considerably reduced, which can increase convenience. Depending on the scenario, the average travel distance varies by more than 20%.

- If a sufficient hydrogen supply network is established by 2030, the average travel distance for hydrogen refuelling and hydrogen supply will be reduced by about half compared to 2021.

- The average travel distance for hydrogen refuelling and hydrogen supply is very sensitive to the parameter p, the number of hydrogen stations and the number of production bases.

The results of our experiments are expected to help policy makers involved in the construction of the hydrogen supply network in transportation sector to make decisions. Policy makers should reasonably determine the parameter p, the number of hydrogen stations, and the number of hydrogen bases.
production bases based on the simulation results. At this stage, the costs and environmental impacts of the construction and operation of the facilities should be considered simultaneously.

The proposed model differs from those in previous studies mainly because it considers multi-period planning. Therefore, the model can be easily extended to consider a situation that changes over time, such as a change in the number of introduced HFCVs and expansion of the hydrogen refuelling infrastructure. In addition, when the model is applied in real-world practice, it can be solved repeatedly every year by shifting the planning horizon, which reflects the changing environment or data every year and generates a yearly plan that modifies the previous plan. For example, if the construction of a previously planned facility is delayed, a model considering this can be solved again to develop a new plan. The model enables the use of more accurate data over time. Because many of the data used in the model are forecasts, data for a relatively distant future could be highly uncertain. However, by applying the model repeatedly over time, the negative impact of such uncertain data could be minimized.

The specific design of a hydrogen supply network in an urban area, the southeastern area of Seoul, was addressed in this study. The proposed model can be easily extended to a model for areas with different characteristics. Especially for cities not far from petrochemical complexes, a model with off-site refuelling stations that receive hydrogen from such complexes could be considered. A model could also be constructed that considers the transport of hydrogen between cities as a method to address the uncertainty in demand for hydrogen refuelling in the early stages of the hydrogen economy.

6. Conclusions

In this study, we examined a multi-period hydrogen supply network design problem for refuelling HFCVs in urban areas. In particular, we considered an area where supplying large amounts of hydrogen from other areas is difficult. We considered a scenario in the southeastern area of Seoul where on-site refuelling stations supply hydrogen directly to HFCVs, and several small-sized distributed hydrogen production bases are constructed to supply hydrogen to on-site stations to cope with the uncertainty of hydrogen refuelling demand. An optimization model was proposed to develop a multi-period plan to simultaneously build on-site hydrogen refuelling stations and small-sized distributed hydrogen production bases over the planning horizon. A case study of the southeastern area of Seoul was then conducted. Various scenarios were analyzed for the design parameters of a hydrogen supply network based on the target of adopting HFCVs in Seoul from 2021 to 2030. The case study showed that the proposed optimization model can be effectively used for determining the time and place to build hydrogen production bases and hydrogen refuelling stations. The two main contributions of our model to the existing literature are: (1) designing of a hydrogen supply network for urban areas where supplying large amount of hydrogen from the outside is difficult and (2) multi-period planning to determine when and where to build hydrogen supply facilities.

Future studies can extend the model to consider other design elements in the hydrogen supply network. In addition to the existing hydrogen sources, South Korea has recently announced plans to expand eco-friendly hydrogen production using surplus power from renewable energy and to import hydrogen from overseas in the long term [4]. Therefore, future research can include the design of the hydrogen supply network considering these various hydrogen sources. Because South Korea is also considering building a hydrogen transport network using pipelines in urban areas after 2030, the model can be extended to consider this development. The existing on-site hydrogen stations and off-site hydrogen stations that are supplied with hydrogen by pipeline can be considered simultaneously in the model. Our future work can also be extended to solving the proposed model by considering data uncertainty. In particular, the number of HFCVs introduced in the future can be significantly changed by factors such as future market conditions and the amount of government subsidies when purchasing hydrogen vehicles. Robust optimization techniques could be used to effectively reflect this uncertainty in the model.
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