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Powering long haul freight: hydrogen refueling station siting using pipeline infrastructure

Jialu Yang, Danesh Hosseinpanahi, Bo Zou, Jane Lin *

Department of Civil, Materials, and Environmental Engineering, University of Illinois Chicago, Chicago, IL 60607, USA

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ABSTRACT

Hydrogen fuel cell trucks (HFCTs) are a promising alternative to diesel trucks (DTs) for decarbonizing long-haul freight while retaining comparable operational performance. This study investigates a large scale HRS siting problem with the aim of minimizing the capital investment in HRS construction and hydrogen delivery cost. A hybrid delivery method is considered: hydrogen is delivered from production hubs by the existing natural gas pipeline network to storage reservoirs, then by truck to HRSs. Assuming 10% of the 2050 Freight Analysis Framework Version 5 (FAF5) truck flow as HFCTs on the U.S. continental interstate highway network, results show that pipeline-based delivery offers major economic advantages over truck-based delivery. Findings highlight the strategic value of leveraging existing pipeline infrastructure and suggest that targeted policy support for hydrogen delivery and refueling infrastructure is essential for facilitating the cost-effective adoption of HFCTs in long-haul freight.

1. Introduction

The increasing urgency to address climate change has prompted governments and international organizations to establish ambitious greenhouse gas (GHG) reduction targets. Due to the transportation sector's substantial share of the U.S. national GHG emissions, it has emerged as a fuel consumption accounted for approximately 39% of total U.S. energy-related CO2 emissions, and the transportation sector contributed 28% of the nation's GHG emission (U.S. Energy Information Administration, 2025). Within the transportation sector, while medium and heavy-duty trucks, which are mainly used for long-haul freight, constitute only 5% of the total traffic volume, they contribute quite disproportionately to the overall GHG emissions in the sector—about 23% in the total (U.S. Environmental Protection Agency, 2024), which underscores the importance of decarbonizing the long-haul freight transportation, that are currently reliant on high-carbon fuels.

Among the various decarbonization strategies in the long-haul freight, replacing the conventional diesel trucks (DTs) with hydrogen fuel cell trucks (HFCTs) is a plausible strategy. Around the globe, there is considerable momentum to use hydrogen in place of conventional energy sources, with over 228 hydrogen projects announced across the hydrogen value chain involving hydrogen production and relevant infrastructure investment (Hydrogen Council, 2021). More than $300 billion investments are projected through 2030, highlighting strong drive for hydrogen technology development and deployment (Hydrogen Council, 2021). In parallel, Hydrogen Council (2021) projects a global objective of 10,500 HRSs by 2030 to fuel hydrogen powered vehicles. To support the deployment of hydrogen powered transportation and the supporting infrastructure, the U.S. has funded a range of modeling tools and

* Corresponding author.
E-mail address: janelin@uic.edu (J. Lin).

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strategic initiatives. For example, the Argonne National Laboratory develops a Hydrogen Delivery Scenario Analysis Model (HDSAM) to estimate levelized hydrogen delivery costs from central production to the forecourt (Mintz et al., 2006). The National Renewable Energy Laboratory (NREL) introduces Scenario Evaluation and Regionalization Analysis (SERA) model to estimate the hydrogen demand at state or national level, and simulate the system-wide evolution of HRSs infrastructure needed to support the adoption of fuel cell electric vehicles (FCEVs) at urban scale (Bush et al., 2019). Further, the U.S. Department of Energy (DOE) presented a national strategy and roadmap in 2023 (U.S. Department of Energy, 2023). The roadmap emphasized on hydrogen fuel storage and delivery strategies to make hydrogen broadly available as an alternative transportation fuel. NREL has also explored the feasibility of blending hydrogen into the U.S. natural gas pipeline network to reduce hydrogen delivery costs (Topolski et al., 2022). Case studies suggest that pipelines can be a viable technology for hydrogen delivery under low blending ratios (Topolski et al., 2022). NREL has also developed modeling approaches to assess hydrogen's impact on pipeline materials and perform techno-economic analysis to determine the safe blending percentage (Melaina et al., 2013).

HFCTs have several important advantages over battery electric trucks (BETs), which are considered as another alternative to conventional DTs. First, current BETs with a range of 250–300 miles require a battery capacity of 600 to 1,000 kWh. In addition, Considering a commonly available charging rate of 350 kW, full charging may take over 1.5 h (Zhao et al., 2024; Zhao et al., 2024). Moreover, battery efficiency is sensitive to ambient temperature, with performance degradation observed under both hot and cold conditions (Lindgren and Lund, 2016; Mareev et al., 2017; Cheng and Lin, 2024). In contrast, HFCTs can readily travel up to 500 miles on a single refuel. The refueling time of HFCTs is comparable to that of DTs, taking as little as 20 min for a full refuel from empty (Nikola Corporation, 2025). Prior research also shows that hydrogen fuel cell vehicles are less sensitive to extreme temperatures than battery electric vehicles (Henning et al., 2019). These advantages position HFCTs as a more compelling solution than BETs for decarbonizing long-haul freight.

Despite the increasing public and private investment in hydrogen delivery technologies, limited research has examined the system wide optimal deployment of a hydrogen delivery and refueling network, particularly at a national scale in the continental U.S. highway system. A cost-effective large scale hydrogen delivery and refueling network requires a combination of technological solutions to reduce hydrogen delivery cost and strategic siting of HRSs to reduce the capital investment in HRSs. In this study, hydrogen delivery takes advantage of the existing natural gas pipeline infrastructure by blending hydrogen with natural gas, and couples it with truck delivery between hydrogen storage facilities and HRSs. Furthermore, optimal siting of HRSs depends on hydrogen delivery cost, HRS capital cost, and hydrogen demand by long-haul HFCTs. Next, relevant literature review on hydrogen production, delivery, storage, and refueling is presented in Section 2. Based on the research gaps identified in the literature review the research contributions are presented at the end of Section 2.

2. Literature review

This section provides a structured review of prior work in three key areas relevant to hydrogen-powered freight transportation including: hydrogen production pathways and associated emissions, technological feasibility of blending hydrogen into existing natural gas pipeline infrastructure for hydrogen delivery from its production hubs to storage facilities, and optimization models for HRSs deployment along road networks. Based on the literature review, the main contributions of the paper are presented.

2.1. Hydrogen production

Production of hydrogen can be broadly classified into three main categories based on the source of energy and corresponding environmental impact: green hydrogen, blue hydrogen, and gray hydrogen (Incer-Valverde et al., 2023). Gray hydrogen is the most prevalent form of hydrogen production, accounting for approximately 95% of the hydrogen produced in the U.S. (U.S. Department of Energy, 2020). While gray hydrogen serves as a cost-effective production technique, this process releases substantial amounts of carbon dioxide (International Energy Agency, 2019). Blue hydrogen is produced by reforming natural gas into hydrogen and carbon dioxide, with the carbon dioxide captured and stored to mitigate environmental impact. The primary method for blue hydrogen production is steam methane reforming (SMR), where methane reacts with steam to produce hydrogen and carbon dioxide. Over 90% of carbon dioxide is stored using carbon capture and storage (CCS) technologies (Howarth and Jacobson, 2021). While blue hydrogen reduces carbon dioxide emissions compared to traditional methods, GHG emissions still exist and methane leakage problem in the production process will also cause negative impact on the climate (Howarth and Jacobson, 2021). Compared to gray and blue hydrogen, green hydrogen represents the most sustainable hydrogen production method, utilizing renewable energy sources (wind, solar, etc.) to power the electrolysis of water. This process splits water molecules into hydrogen and oxygen using an electric current, with the only byproduct being oxygen.

However, the large-scale deployment of the green hydrogen requires technology promotion to improve the production efficiency and lower the cost (Schmidt et al., 2017). Production costs for hydrogen vary significantly depending on the method used. Gray hydrogen production typically costs around 0.7 to 1.2 $/kg. Blue hydrogen has higher costs due to CCS implementation, ranging from 1 to 1.3 $/kg. In contrast, green hydrogen currently costs approximately 8 to 13 $/kg (Ayub et al., 2024). Although currently green hydrogen is significantly more expensive than the other options, it is anticipated to achieve cost parity due to declining renewable energy prices and advancements in electrolyzer technology (International Renewable Energy Agency, 2020).

As hydrogen becomes increasingly viable from both economic and environmental perspectives, its application in long-haul freight via HFCTs has attracted growing research and practical interest. Lee et al. (2018) demonstrate that gaseous hydrogen significantly outperforms both liquid hydrogen and diesel in terms of reducing greenhouse gas emissions. de las Nieves Camacho et al. (2022)

present a review of 95 papers on HFCTs and conclude that while HFCTs are in an early commercial phase, there is a clear trend towards their adoption as a key strategy for decarbonizing the heavy-duty transport sector; however, successful implementation will require coordinated efforts between academia, industry, and policymakers to address the identified gaps and accelerate the transition to a hydrogen-based economy. Basma et al. (2022) further highlights the need for substantial government subsidy in both HFCTs and hydrogen fuel to reach total cost of ownership parity with DTs, to make HFCTs viable until 2035.

2.2. Hydrogen delivery and storage using natural gas infrastructure

The possibility of blending hydrogen into natural gas pipeline has been proposed and studied in different parts of the world. Chae et al. (2022) find that blending hydrogen concentrations below 20% typically do not pose significant risks to pipeline integrity or safety. Mahajan et al. (2022) review the state-of-art blending technologies and the several hydrogen-methane delivery projects such as HyDeploy in UK, GRHYD in France, HyBlend in US, etc. The paper points out the current challenges lie in the design modifications to certain end-use appliances, increased risk of leakage, lower mass flow and energy due to low density of hydrogen, and potential corrosion to pipelines. Morgan et al. (2024) develop a NG-H2 P COM (Natural Gas Hydrogen Pipeline Cost Model) model to evaluate the costs associate with blending hydrogen and natural gas based on pipeline capacity and flow rate, Compressor station sizing, and capital can operation cost.

Hydrogen storage in geological formations, particularly depleted natural gas reservoirs, salt caverns, and oil reservoirs, is also promising. Among these, natural gas reservoirs are particularly well-suited for accommodating the substantial storage volumes required for seasonal energy balancing, thereby supporting the integration of variable renewable energy sources into the future hydrogen delivery (Osman et al., 2022). Their scalability, low operational costs, and the ability to leverage existing infrastructure make natural gas reservoirs a cost-effective option (International Energy Agency, 2019). International projects in countries such as the UK, Austria, Canada, Poland, and Argentina show the practical feasibility and economic viability of hydrogen storage and co-storage with natural gas in these reservoirs (Muhammed et al., 2023; Tarkowski and Uliasz-Misiak, 2022). These further underscores the potential of delivering hydrogen via pipeline networks and utilizing existing underground natural gas storage infrastructure for hydrogen storage and extraction.

2.3. Refueling infrastructure deployment

The refueling infrastructure location problem has been widely studied over the years. Hodgson (1990) develops flow-capture location allocation model (FCLM) to maximize the flow captured by candidate facilities along paths between multiple origin–destination (O-D) pairs under the total facility number constraint. Kuby and Lim (2005) later introduce the flow refueling location model (FRLM), a mixed-integer program approach to optimally locate alternative-fuel refueling stations along the shortest paths. This foundational work has been applied broadly to planning alternative fuel stations (AFS). Furthermore, Kim and Kuby (2012) formulate a deviation flow refueling model (DFRLM) to integrate route deviations into location optimization problem. MirHassani and Ebrazi (2013) propose a reformulated FRLM to improve computational efficiency and scalability by introducing an expanded network and relaxing constraints. As such, the model handles larger datasets and adapts to varying coverage objectives. Yıldız et al. (2016) introduce the refueling station location problem with routing (RSLP-R), which generalizes DFRLM to handle driver tolerance for detours, to maximize refueled traffic flow.

Aside from FRLM and its variants, Capar et al. (2013) propose an arc-cover path-cover model (AC-PC) formulation that covers arcs instead of nodes along round-trip paths, reducing computational complexity for generating all feasible node combinations along paths. Wang and Lin (2009) develop a hybrid model with the dual objectives of minimum locating cost and maximum population coverage. Compared with FRLM and AC-PC model, this framework does not require any pre-computation of feasible station combinations before implementing the model. Huang et al. (2015) presents a model which minimizes the cost of locating stations on the network considering deviation from shortest path.

Recently, with the advancement of hydrogen fuel cell electric vehicles (HFCVs) technology, research attention has shifted toward deploying HRSs under realistic infrastructure constraints. Rose et al. (2020) extend the FRLM by incorporating HRS storage capacity restrictions (NCFRLM) along shortest path, recognizing that storage capacity impact HRSs deployment. Their case study on Germany's highway network reveals that stricter node capacity limits significantly increase the number of required HRSs and elevate average HRSs utilization. Building on this, De Padova et al. (2024) present a spatial MILP framework integrating geospatial data and operational constraints to site HRSs for heavy-duty freight transportation. Kim et al. (2020) develop a nationwide HRSs deployment framework to satisfy the bus refuel demand for the Republic of Korea. The proposed framework achieves over 90% coverage under budget constraints, offering a scalable methodology for national-level HRSs planning.

2.4. Study contributions

Table 1 summarizes the existing studies of the refueling infrastructure location problem with respect to the objective function, routing flexibility, driving range, station capacity, hydrogen delivery, and network type. The cost considerations refer to budget constraint or cost minimization in the model formulation. Route flexibility indicates whether the model restricts vehicles to the shortest path or allows deviations from it.

As shown in Table 1, our work has the following contributions:

Table 1
Summary of relevant literature on AFS location problem.

Study	Obje***ctive	Modeling approach	Budget consideration	Route flexibility	Driving range	Station capacity	Hydrogen delivery	Network	Solution method
Hodgson (1990)	Max flow	MILP	–	–	–	–	–	Hypothetical 25 nodes	Greedy
Kuby and Lim (2005)	Max flow	MILP	–	–	Homogeneous	–	–	Hypothetical 25 nodes	Greedy
Kim and Kuby (2012)	Max flow	MILP	–	✓	Homogeneous	–	–	Hypothetical 25 nodes	Xpress solver
MirHassani and Ebrazi (2013)	Min stations	MILP	–	✓	Homogeneous	–	–	Hypothetical 25 nodes	CPLEX
Yıldız et al. (2016)	Max flow	MILP	–	✓	Heterogeneous	–	–	California 339 nodes	Branch and price
Capar et al. (2013)	Max flow	MILP	–	–	Homogeneous	–	–	Florida 750 nodes	Xpress solver
Wang and Lin (2009)	Min stations	MILP	–	–	Homogeneous	–	–	Taiwan 51 nodes	ILOG solver
Huang et al. (2015)	Min cost	MILP	✓	✓	Homogeneous	–	–	Hypothetical 25 nodes	CPLEX
Rose et al. (2020)	Min stations	MILP	–	–	Homogeneous	✓	–	Germany 2,397 nodes	Gurobi
De Padova et al. (2024)	Min stations	MILP	–	–	Homogeneous	✓	–	Italy 972 nodes	CPLEX
Kim et al. (2020)	Max flow	MILP	✓	–	Homogeneous	✓	–	Korea	Deployment optimization algorithm
Hosseini and MirHassani (2017)	Max flow	MILP	✓	–	Homogeneous	✓	–	Hypothetical 1,000 nodes	Lagrangian relaxation
Our study	Min system cost	MILP	✓	✓	Homogeneous	✓	✓	USA 278 nodes	Gurobi

- This study aims for optimal siting of HRSs to reduce the sum of hydrogen delivery cost and HRSs capital cost. While previous studies have explored pipeline-based hydrogen delivery to HRSs, their application to large-scale, long-haul freight transportation remains limited. This work contributes by explicitly modeling the cost interplay between HRS location and hydrogen delivery within a national context.
- Our model simultaneously considers HFCTs path deviation, HFCTs driving range, and HRS capacity in determining the optimal siting of HRSs. Unlike most existing studies that treat routing, range, and capacity in isolation or under simplified assumptions, our integrated modeling framework explicitly captures the interdependence among these operational factors. This enables a more realistic representation of HFCTs refueling behavior on long-haul routes.
- We implement the model to long-haul trucking in the U.S. We find that pipeline-based hydrogen delivery is more cost effective than truck-based delivery. Sensitivity analysis further illustrates how the optimal siting of HRSs is affected by key model parameters such as HFCTs driving range and HRS capacity. The findings provide quantitative policy implications for the investment in pipeline utilization, HFCTs driving range improvement, and HRS capacity expansion.

This rest of the paper proceeds as follows: Section 3 describes the problem definition and model formulation. Section 4 presents the case study, input data preprocessing steps, and the model results. Section 5 contains sensitivity analysis. Discussion of the results are in Section 6. Finally, conclusions and future research recommendations are drawn in Section 7.

3. Methodology

3.1. Problem statement

This study aims to identify the optimal siting of HRSs on a given interstate highway network, such that the total HRS capital cost and hydrogen delivery cost is minimized while satisfying the hydrogen refueling demand for long-haul freight transportation. Specifically, we consider HFCTs driving range, HRS capacity, and a hybrid hydrogen delivery framework that combines pipeline-based and truck-based hydrogen delivery as shown in the gray area of Fig. 1. The framework involves delivering hydrogen from the production hubs to hydrogen storage facilities (co-located with the natural gas reservoirs) by the natural gas pipeline network and delivering hydrogen from reservoirs to HRSs by truck. This study builds on the current hydrogen production hubs and the existing natural gas pipelines and reservoirs. The problem becomes one that determines the location of HRSs such that sum of the HRS capital cost and the hydrogen delivery cost are minimized.

Mathematically, consider a graph $G = \{V,E\}$, where V is the set of highway nodes, also candidate HRS nodes. Node cost consists of capital cost, if an HRS is built at the node, and the hydrogen delivery cost to the HRS. An HRS has a fixed station capacity C, which limits the total volume of hydrogen available at the HRSs. The HRS capital cost is assumed to increase linearly with its capacity C. The unit hydrogen delivery cost from a production hub to a candidate HRS i is denoted as p_i and is predetermined. Specifically, the production hubs and hydrogen storage reservoirs in our study are considered given—their locations are predetermined based on the Regional Clean Hydrogen Hubs initiative and the existing natural gas reservoir system (see Section 4.1.2 and Fig. 5–Fig. 6). Therefore, the pipeline distance between a given hub–reservoir pair is predetermined, so is the truck delivery distance from a reservoir to a candidate HRS node. We can then predetermine which hub and reservoir supply hydrogen to a candidate HRS by precomputing the minimum-cost path of hub-reservoir-HRS (production hub → pipeline delivery → reservoir → truck delivery → HRS) for each candidate HRS. By doing so, the model implicitly assumes that each candidate HRS receives hydrogen from a single source – a single hub and a single reservoir. This is reasonable since each paired hub-reservoir for a given HRS offers the minimum delivery cost among all possible combinations for that HRS. The problem becomes one that determines the location of HRSs such that the sum of HRS capital cost and hydrogen delivery cost is minimized. E is the set of highway links connecting the highway nodes. Link cost represents the link distance, which is also an input parameter into our model. HFCTs with a limited fuel capacity F must travel from their respective origin nodes $r \in V$ to destination nodes $s \in V$, under a given origin–destination (O-D) demand denoted as q_{rs}. For each O-D pair (r,s), a set of feasible paths Krs is precomputed using the k shortest path algorithm (Yen, 1971). HRSs must be strategically placed on selected nodes $i \in V$ such that O-D demand q_{rs} can be met within the HFCTs driving range constraint. The objective is to determine the optimal siting of HRSs such that the total cost—comprising HRS capital cost and hydrogen delivery cost—is minimized, while satisfying the routing and refueling requirements of all HFCTs to meet the O-D demand.

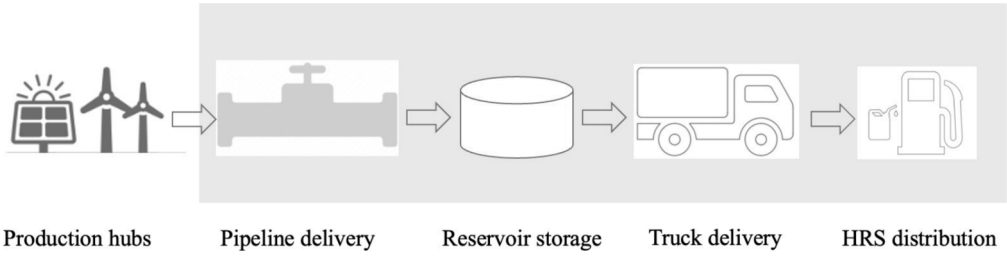

Fig. 1. Hydrogen delivery framework considered in this study.

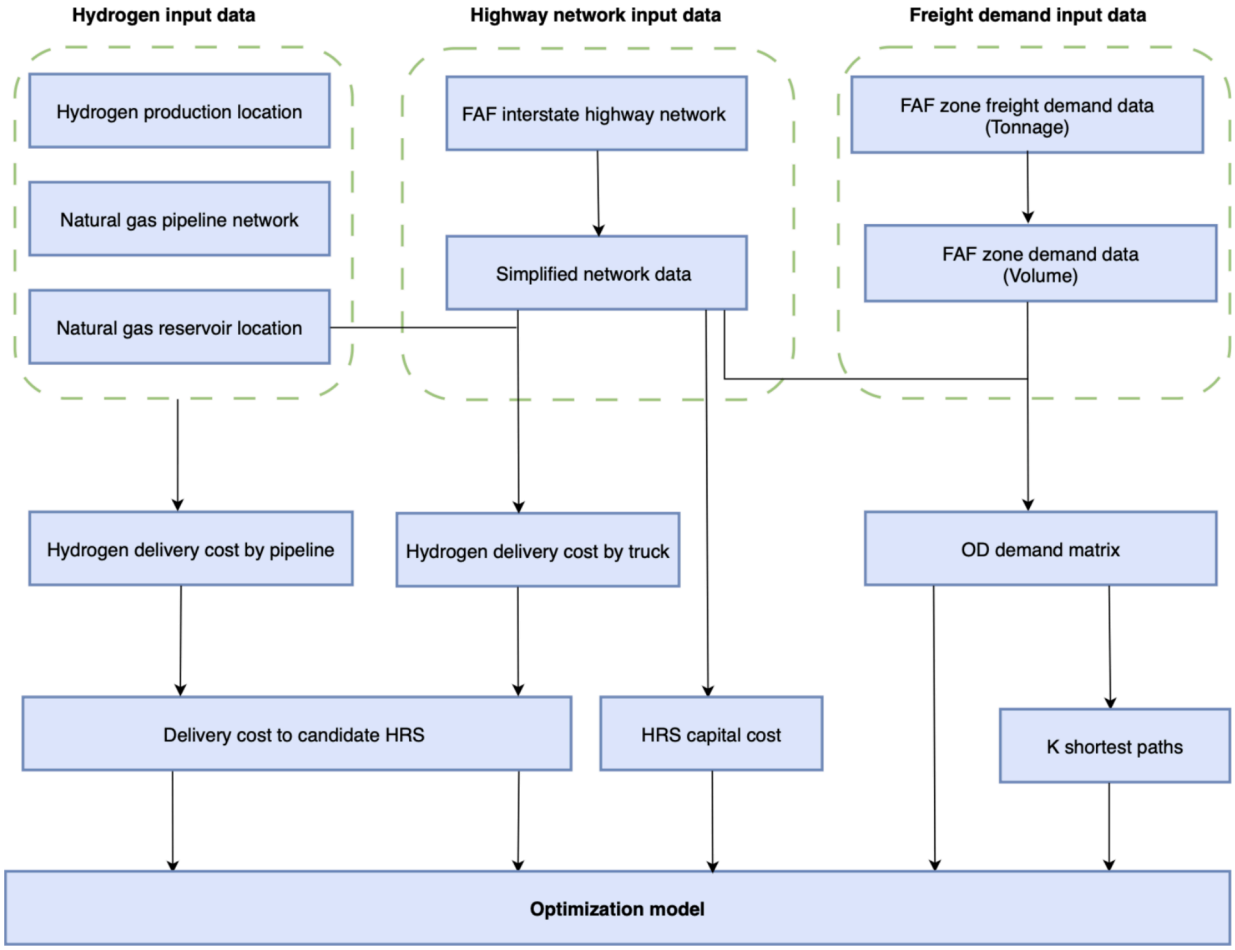

Fig. 2. Data pre-processing flowchart.

Fig. 3. Actual U.S. continental interstate highway system.

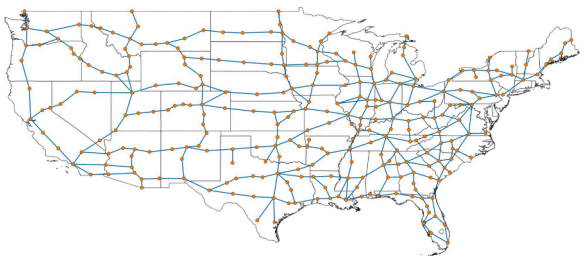

Fig. 4. The Federal Highway Administration (FHWA) national highway system.

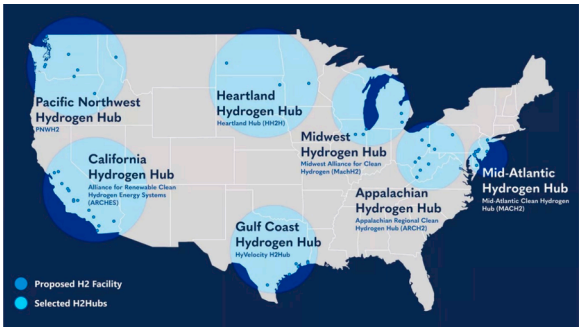

Fig. 5. Hydrogen production hubs.

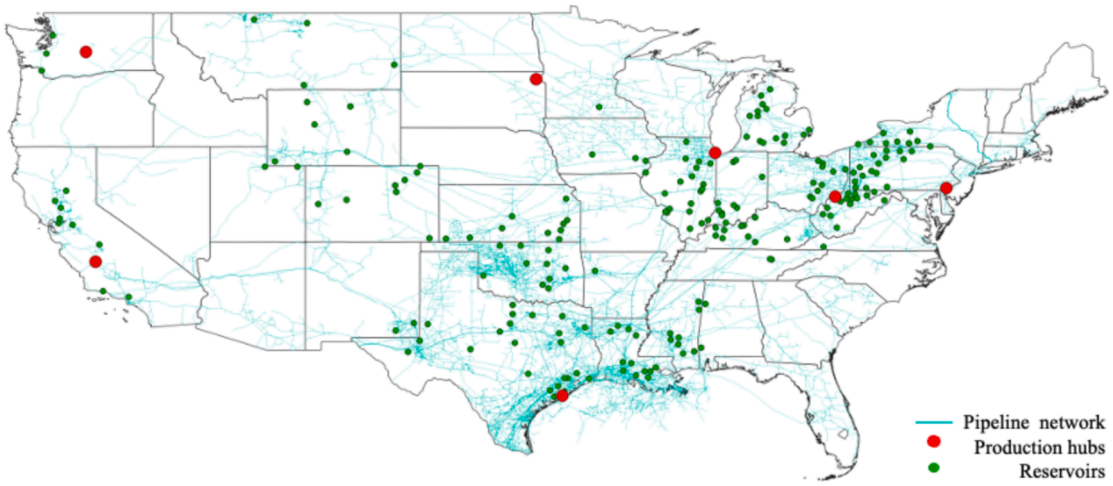

Fig. 6. Production hubs, reservoirs, pipeline network.

Our modeling framework has the following key assumptions:

1. Production facilities are directly connected with the pipeline network.
2. Hydrogen reservoirs are co-located with natural gas reservoirs.
3. Hydrogen can be blended into the existing natural gas pipeline network for delivery of hydrogen from the production hubs to hydrogen storage facilities (reservoirs). And the blended gas can be separated and stored in respective reservoirs.
4. For modeling simplicity, each HFCT is assumed to begin its journey with a half-full tank and refuel at HRSs as needed. This assumption takes into consideration that HFCTs may begin at the origins with varying fuel levels, so on average assume each truck starts with a half-full tank. This is consistent with prior studies (Kuby and Lim, 2005; MirHassani and Ebrazi, 2013; Kim and Kuby, 2012).
5. Hydrogen production hubs have sufficient supply capacity for the HFCT demand. The proposed Regional Clean Hydrogen Hubs (H2Hubs) in the United States, although no specification about the production capacities at this point, are designed to supply hydrogen to a wide range of industrial sectors in the service regions, heavy-duty freight vehicles being one of them. Furthermore, our case study assumes only a 10% market penetration rate of hydrogen fuel cell trucks (HFCTs) by 2050. Under this relatively low adoption scenario, we believe it is reasonable to assume that production hubs can meet the required HFCT refueling demand without being a binding constraint. (Figueroa et al., 2023).
6. Fuel consumption is proportional to travel distance.
7. Drivers have full knowledge about the location of HRSs and can refuel as needed to complete the trip.
8. All HRSs have the same pre-determined station capacity.
9. Hydrogen delivery trucks are regular diesel trucks.

3.2. Model formulation

In this section, a MILP model is presented. Before that, Table 2 summarizes the notations used in the model.

$$\text{minimize } Y\left(\sum_{(r,s)\in(R,S)}\sum_{k\in K_{rs}}\sum_{i\in P_k^{rs}}\sum_{t\in T} q_{rs}^t h_{k,i}^{rs,t} p_i\right) + \frac{Q(1+Q)^N}{(1+Q)^N-1} C p_1 \sum_{i\in V} x_i$$

$$\sum_{k\in K_{rs}} y_k^{rs,t} = 1 \forall r \in R, s \in S, t \in T \tag{1}$$

$$b_{k,i}^{rs,t} + h_{k,i}^{rs,t} \le F^t \forall r \in R, s \in S, k \in K_{rs}, i \in P_k^{rs}, t \in T \tag{2}$$

$$-\left(b_{k,i}^{rs,t} + h_{k,i}^{rs,t} - \frac{d_{i,i+1}^k}{e} - b_{k,i+1}^{rs,t}\right) \le M\left(1 - y_k^{rs,t}\right) \forall r \in R, s \in S, k \in K_{rs}, i \in P_k^{rs}, t \in T \tag{3}$$

$$b_{k,i}^{rs,t} + h_{k,i}^{rs,t} - \frac{d_{i,i+1}^k}{e} - b_{k,i+1}^{rs,t} \le M\left(1 - y_k^{rs,t}\right) \forall r \in R, s \in S, k \in K_{rs}, i \in P_k^{rs}, t \in T \tag{4}$$

$$\sum_{(r,s)\in(R,S)}\sum_{k\in K_{rs}}\sum_{t\in T} q_{rs}^t h_{k,i}^{rs,t} \le C \cdot x_i \forall i \in P_k^{rs} \tag{5}$$

$$h_{k,i}^{rs,t} \le M y_k^{rs,t} \forall r \in R, s \in S, k \in K_{rs}, i \in P_k^{rs}, t \in T \tag{6}$$

$$b_{k,r}^{rs,t} = 0.5 F^t \forall r \in R, s \in S, k \in K_{rs}, t \in T \tag{7}$$

$$x_i \in \{0,1\} \forall i \in V \tag{8}$$

$$y_k^{rs,t} \in \{0,1\} \forall r \in R, s \in S, k \in K_{rs}, t \in T \tag{9}$$

$$b_{k,i}^{rs,t} \ge 0, h_{k,i}^{rs,t} \ge 0 \forall r \in R, s \in S, k \in K_{rs}, i \in P_k^{rs}, t \in T \tag{10}$$

The objective is to minimize the total annual cost, which includes hydrogen delivery cost from hydrogen production hubs to HRSs, and HRS capital cost. The term $\frac{Q(1+Q)^N}{(1+Q)^N-1}$ is the capital recovery factor (CRF). CRF converts a one-time capital investment into an equivalent annual cost, enabling consistent comparison with annual operating expenses. Constraint (1) states that exactly one path (either a shortest route or a deviated route) is selected for each O–D pair and for each specific truck type *t*. Constraint (2) restricts the sum of the remaining onboard fuel and the refueled amount to not exceed the truck's maximum fuel capacity F^t at any location on the selected path. Constraints (3) and (4) together enforce fuel conservation between consecutive nodes *i* and $i+1$ when path *k* is selected ($y_k^{rs,t} = 1$) via big-*M* constraints. Constraint (5) imposes a capacity limit on each HRS, ensuring that the total hydrogen dispensed to all

Table 2
Sets, parameters, and decision variables.

Sets	
V	Set of all nodes in the highway network
R	Set of all origins of HFCTs,$\forall R \in V$
S	Set of all destinations of HFCTs,$\forall S \in V$
K_{rs}	Set of paths from origin *r* to destination *s*
P_k^{rs}	Sequence of nodes in path *k* of O-D pair (*r, s*),$\forall k \in K_{rs}$
T	Set of all truck types
Parameters	
q_{rs}^t	Total HFCTs of type *t* from origin *r* to destination *s*, *vehicles/day*
C	Station capacity at each candidate HRS, *tons*
p_i	Unit delivery cost of hydrogen from a production hub to candidate HRSs $i \in V$, $/*ton*
d_{ij}^k	Distance between node *i* and *j* on path *k*, *miles*
p_1	Unit HRS capital cost, $/*ton*
F^t	Maximum tank capacity of HFCT type *t*, *ton*
e	HFCTs fuel economy, *miles/ton*
N	Service lifespan of an HRS
Q	Discount rate
Y	1 *year*, 365 *days*
M	A sufficiently large number, 1e6
Decision variables	
x_i	Binary variable, 1 if an HRS is installed at node *i*
$y_k^{rs,t}$	Binary variable, 1 if path *k* of O-D pair (*r, s*) is selected for HFCT type *t*
$b_{k,i}^{rs,t}$	Amount of hydrogen remained in a type *t* HFCT when arriving at node *i* along path *k* of O-D pair *rs*, *tons/vehicle*
$h_{k,i}^{rs,t}$	Amount of hydrogen refueled at node *i* along path *k* of O-D pair *rs* for each type *t* HFCT, *tons/vehicle*

truck types does not exceed the HRS maximum capacity C. Constraint (6) states that hydrogen refueling occurs only along paths that are actually selected ($y_k^{rs,t} = 1$). Constraint (7) implements the assumption that each truck starts its journey with half a tank of hydrogen. Constraints (8) and (9) define the binary decision variables. Constraint (10) ensures that fuel level $b_{k,i}^{rs,t}$ and refueling amount $h_{k,i}^{rs,t}$ remain non-negative throughout the path.

4. Applications to US national highway network

This section presents a numerical experiment to evaluate the performance of the proposed optimization model and to provide empirical insights into HRSs deployment under projected freight demand and hydrogen supply. The experiment builds on the national highway network of the continental US and the FAF Version 5 data (FAF5) (U.S. Federal Highway Administration, 2017). For the purpose of the study, we simplify the national highway network to include only highway nodes that are also candidate HRSs while preserving the network topology properties. In addition, the hydrogen production hubs, the natural gas pipeline networks, and the natural gas reservoirs are integrated into the FAF5 highway network to calculate the hydrogen delivery cost from the production hubs to candidate HRSs prior to solving the optimization model. Moreover, although the mathematical formulation proposed in Section 3.2 can optimize for a heterogeneous fleet with varying ranges and tank capacities, this case study assumes a homogeneous fleet of HFCTs. This simplification is necessitated by the resolution of the FAF5 dataset, which provides aggregate freight tonnage demand but lacks the granularity to distinguish between vehicle configurations or the specific market mix of truck driving ranges. Consequently, we adopt a single, representative heavy-duty truck specification to establish a baseline for national infrastructure requirements. Therefore, significant data preprocessing steps are carried out to preprocess the input for hydrogen delivery by pipeline. The following subsections detail the experimental setup, including the data sources, the preprocessing techniques, and the parameter assumptions used.

4.1. Data preprocessing

The data preprocessing procedure is illustrated in Fig. 2. The input data consists of three main categories: (1) highway network data (Section 4.1.1); (2) hydrogen-related data, including hydrogen production sites, natural gas pipelines, and natural gas reservoirs (Section 4.1.2); (3) freight demand data, which includes zonal freight demand (Section 4.1.3) and HRS station capacity (Section 4.1.4).

4.1.1. Highway network

Fig. 3 shows the continental U.S. national highway network. To reduce the computational burden while maintaining the key topological properties such as the shortest paths, connectedness of the network, and node criticality, several key steps using QGIS are made to reduce the highway nodes and links (QGIS Development Team, 2025). First, the “Simplify” function is utilized, which utilize the Ramer–Douglas–Peucker algorithm (Ramer, 1972; Douglas and Peucker, 1973). The Ramer algorithm simplifies a curve by iteratively creating a polyline that approximates the original curve within a specified tolerance (Ramer, 1972). The Douglas-Peucker algorithm begins with a baseline drawn directly between the start and end points of a curve. The algorithm then finds the point on the original curve that is farthest from this baseline (Douglas and Peucker, 1973), thereby reducing the number of nodes based on a tolerance value. The output of this function will be simplified links of the highway network. By doing so with an appropriate tolerance level, the resulting simplified network preserves the distances between major points on the network within the specified tolerance. Second, the “Extract vertices” function is applied to retrieve the vertices of simplified network links. Third, the “Snap geometries to layer” function is used to merge nearby nodes under a tolerance of one. The resulting network has 278 nodes and 354 links as illustrated in Fig. 4.

4.1.2. Production hubs, reservoirs, and pipeline network

The pipeline network data utilized in this study comes from U.S. Energy Information Administration (2020). The hydrogen production hubs are adopted from the national initiative of the Regional Clean Hydrogen Hubs (H2Hubs) across the U.S. (The White House, 2023) as shown in Fig. 5. Because the precise production locations of the hubs have not been determined, the geographic centroid of the region that each hub covers is chosen as the hub location. The locations of natural gas reservoirs are found in the Natural Gas Annual Respondent Query System (U.S. Energy Information Administration, 2024). After aggregated by county, 215 valid have resulted. Fig. 6 displays the spatial distribution of the existing natural gas pipelines, the proposed hydrogen production hubs, and the current natural gas reservoirs throughout the country. Unit hydrogen delivery cost, p_i, ($/*ton*), is calculated as follows. For each candidate HRS, hydrogen delivery consists of two parts: pipeline delivery between a production hub and a reservoir and truck delivery between a reservoir and an HRS. For the former, the shortest distance of each hub–reservoir pair is known. According to Great Plains Institute (2024), the unit pipeline delivery cost ranges from $0.19 to $0.35/(*ton* • *mile*), including costs for compressor stations,

Table 3
Delivery cost breakdown.

Delivery type	Cost	Distance (mile)	Source
Pipeline	$0.2/(*ton·mile*)	–	(Great Plains Institute, 2024)
Truck	$500/*ton*	0–62	(Hydrogen Council, 2021)
Truck	$1,500/*ton*	62–311	(Hydrogen Council, 2021)
Truck	$2,000/*ton*	> 311	(Hydrogen Council, 2021)

pipeline upgrades, and operational expenses. In this study, we use \$0.2/(*ton* • *mile*) as the unit pipeline delivery cost. For the latter, the shortest path distance between each reservoir and candidate HRS is also known. According to the Hydrogen Council (2021), truck-based delivery cost is distance–dependent: \$100–\$1,000/*ton* for delivery distances under 62 miles, \$1,000–\$2,000/*ton* for 62–311 miles, and over \$2,000/*ton* beyond 311 miles. In this study, we choose \$500, \$1,500, \$2,000/*ton* respectively, as shown in Table 3.

Utilizing the QGIS shortest path function, we obtain the shortest paths from all production hubs to all reservoirs, and from all reservoirs to all candidate HRSs. Multiplying the shortest path distance by the unit costs, we obtain the per-ton delivery cost from all production hubs to all candidate HRSs.

Assuming a rational decision of choosing the lowest per–ton delivery cost path to deliver hydrogen, we set the unit delivery cost p_i equal to the minimum per-ton cost to HRS *i*. It is worth mentioning that this approach must be supported by Assumption 5, which posits sufficient supply at production hubs, ensuring that the lowest-cost delivery route is always available. Consider a simple example in Fig. 7. Hydrogen to the HRS can be delivered from hub A or B via reservoir 1 or hub C via reservoir 2. For path A–1–HRS, the pipeline delivery cost is \$20/*ton*, and the 50-mile truck delivery costs \$500/*ton*, resulting in a total unit cost of \$520/*ton*. Similarly, for the path B–1–HRS, the pipeline cost is \$40/*ton*, which combined with the same truck delivery cost, yields a total of \$540/*ton*. For path C-2–HRS, the total unit cost is \$1,560/*ton*. So the final unit delivery cost *pi* for this HRS *i* is determined to be \$520/*ton*.

4.1.3. Freight demand

To model the flow of HFCTs across the U.S. highway network, this study employs the real-world commodity O-D demand data derived from the FAF5 estimation for 2050. FAF5 provides zone-level commodity demand estimates in tonnage. We convert the O-D commodity demand into truck flows using a truck payload factor 22 tons, which is used in U.S. Federal Highway Administration (2020). Each FAF zone is assigned to its nearest highway node using spatial proximity. To capture potential deviations from the shortest paths, we implement Yen's *k*-shortest path algorithm with a routing tolerance of 1.2 (Yen, 1971), where the path lengths are evaluated in terms of travel distance rather than travel time. The resulting truck flow network under a 10% HFCTs adoption scenario serves as a key input to our optimization model.

4.1.4. HRS capacity

HRS station capacity plays a critical role in infrastructure planning, directly affecting the HRS capital cost and HFCTs refueling and routing decisions. In general, the HRS capital cost depends on the station capacity, the hydrogen delivery mode (gaseous or liquid), the compression system, and the number of dispensers. In our study, we adopt a unit HRS capital cost of \$1,800/*kg* for gaseous hydrogen delivery (U.S. Department of Energy, 2021).

The station capacity of HRSs can be categorized as follows (H2 MOBILITY, 2021): Small: 500 kg, Medium: 1000 kg, Large: 2000 kg, and Extra-large: 4000 kg. To ensure reliable bi-directional service coverage at highway nodes, we assume that each HRS serves traffic in both directions. While various capacities are examined later, an initial capacity of 16 tons is chosen as the baseline. Lower capacities are found to be infeasible for the given demand and network size.

The parameter values are summarized in Table 4. The model is implemented in Gurobi 12.0.0 with a convergence gap of 0.03 (Gurobi Optimization, 2024). It is run on an Apple M3 Pro Chip with 32 GB memory.

4.2. Results

4.2.1. HRS distribution

The resulting spatial distribution of 140 HRSs is shown in Fig. 8. The result shows the dominance of high-demand HRSs across the highway network. Out of the total 140 HRSs, 127 have refueling demand between 12 and 16 tons, comprising 90.7% of the network. For the remaining 13 HRSs, eight have refueling demand between 8 and 12 tons. Three have refueling demand between 4 and 8 tons.

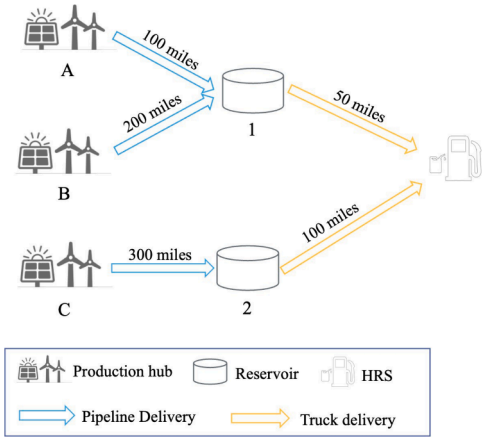

Fig. 7. Unit delivery cost process illustration.

Table 4
Parameter values.

Parameters	Value	Source
$p1$	$1,800,000/*ton*	U.S. Department of Energy (2021)
C	16 *tons*	H2 MOBILITY, 2021
F	0.07 *ton*	Nikola Corporation (2025)
D	500 *miles*	Nikola Corporation (2025)
e	7140 *miles/ton*	Nikola Corporation (2025)
N	20 *years*	Pratt et al. (2015)
R	15%	Pratt et al. (2015)

Two have refueling demand between 0 and 8 tons.

4.2.2. Truck flow

The HFCTs truck flow results (Fig. 9) are displayed side by side with the FAF5 2050 estimated average daily truck volumes (Fig. 10), for sanity check of truck flow distribution consistency. While Fig. 9 shows only 10% of the FAF flow which is converted to HFCTs, we observe an overall spatial consistency between our model results and FAF5 results. For example: I-5 and I-10 in southern California and Arizona host several large HRSs, reflecting heavy freight traffic along the Pacific corridor. The Texas triangle (Dallas–Houston–San Antonio) is well-covered by HRSs, aligned with Texas' role as a central freight hub. I-80, which spans east–west across the mid-west states, also exhibit dense HRSs presence. On the other hand, lower-traffic regions in the upper mid-west align with the FAF5 truck flow estimation. Overall, the recommended HRS deployment by our model corresponds to regions with high truck traffic and high hydrogen refueling demand.

4.2.3. Regional cost analysis

To further investigate the spatial heterogeneity of the total costs, we aggregate the total annual cost by state. States are grouped into four cost categories as shown in Fig. 11, from the lowest cost range of 0–$17 M (in green) to the highest >$36 M (in maroon). The blue dots are hydrogen reservoirs.

The results reveal pronounced regional variation across the continental United States. High-cost regions are primarily concentrated in the southern, western, and Midwest states, which collectively account for a substantial share of national freight movements. These states host dense long-haul truck flows along major interstate corridors, leading to high refueling demand and hydrogen delivery cost. Two key drivers underline these spatial disparities: (i) large aggregate refueling demand driven by heavy-duty freight flow, and (ii) longer average delivery distances of hydrogen, which increase delivery cost. For example, Texas tops the state list for total cost (Table 5), in which two-thirds comes from the capital investment driven by the high truck volumes and energy demand, and only one-third is attributed to the hydrogen delivery cost. This is because Texas has many hydrogen reservoirs, reducing the delivery distance to the refueling stations. Similar results are found in California, Illinois, and Louisiana. On the other hand, states such as Arizona, Georgia, Tennessee, Indiana, Missouri, and New Mexico have the opposite pattern, i.e., higher hydrogen delivery cost because these states tend to be zero or low reservoir density and lower capital cost due to the relatively small number of refueling stations in those states to California, Texas, and Illinois.

The skewed distribution of total cost toward the south and Midwest suggests that (i) there is a need for strategic investment in pipeline infrastructure and reservoirs in states like Arizona, New Mexico, Georgia, and Tennessee; and (ii) policy to divert hydrogen

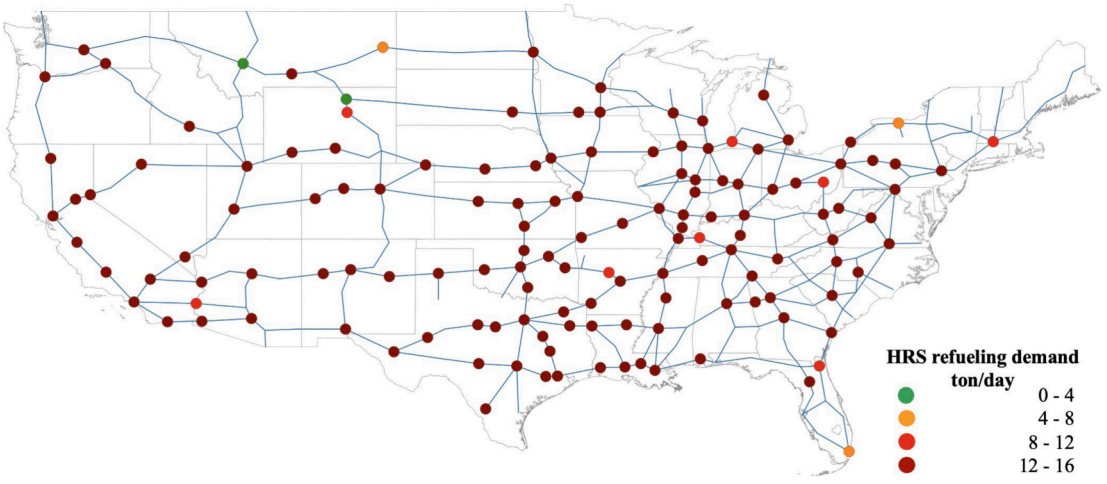

Fig. 8. Baseline HRSs distribution result.

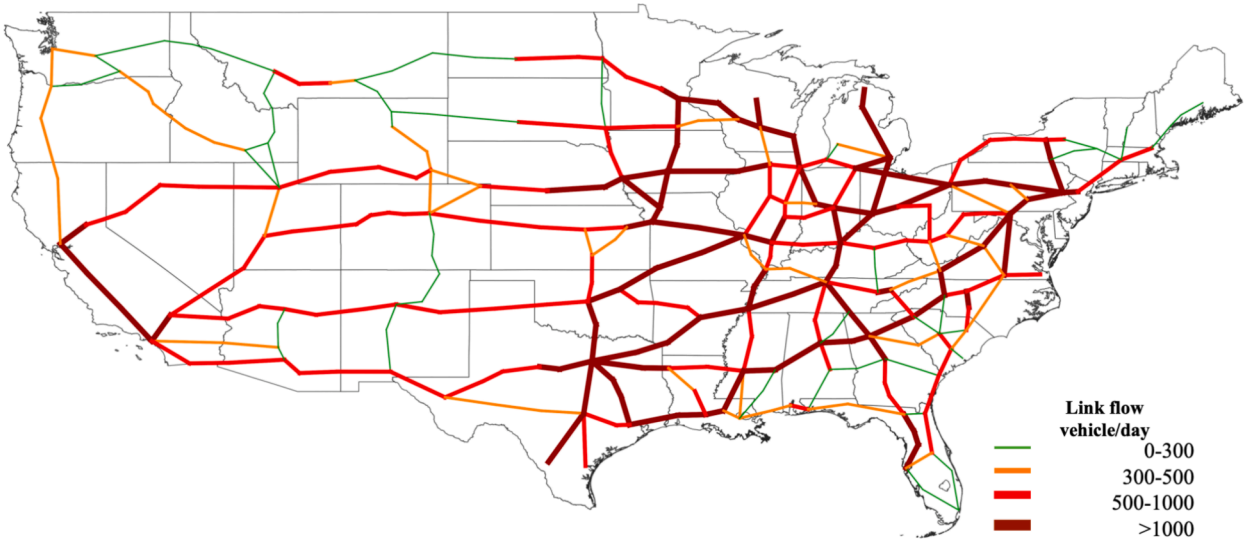

Fig. 9. Baseline HFCTs flow result.

Fig. 10. Estimated 2050 average FAF5 daily volumes for trucks on national highway system.

truck flow to the northern routes is needed to balance out the total cost landscape.

4.2.4. Carbon emission reduction

To quantify the environmental benefit enabled by HRSs employment, we estimate the reduction in tailpipe carbon emissions relative to an equivalent fleet of Class 8 diesel trucks. Under the 10% HFCT adoption scenario, the optimized truck flow yields a daily vehicle miles traveled (VMT) of 55,952,713 miles across the U.S. highway network.

According to U.S. Environmental Protection Agency (2025), diesel combustion produces 10.21 kg of CO_2 per gallon. With a typical fuel economy of 5.7 mpg for Class 8 diesel trucks (U.S., Department of Energy, 2025), this corresponds to an average tailpipe emission factor of approximately 1.8 kg CO_2 per mile. Multiplying this factor by the HFCTs VMT provides an estimate of the reduced daily tailpipe diesel emissions of 100,714,883 kg of CO_2 per day, which is about 10% of the daily CO_2 emissions from a diesel fleet of medium and heavy duty trucks in the U.S. (U.S. Environmental Protection Agency, 2024). This is as expected. From a life cycle perspective, if green hydrogen production is adopted, even greater total life cycle CO_2 emissions reductions can be achieved from HFCTs.

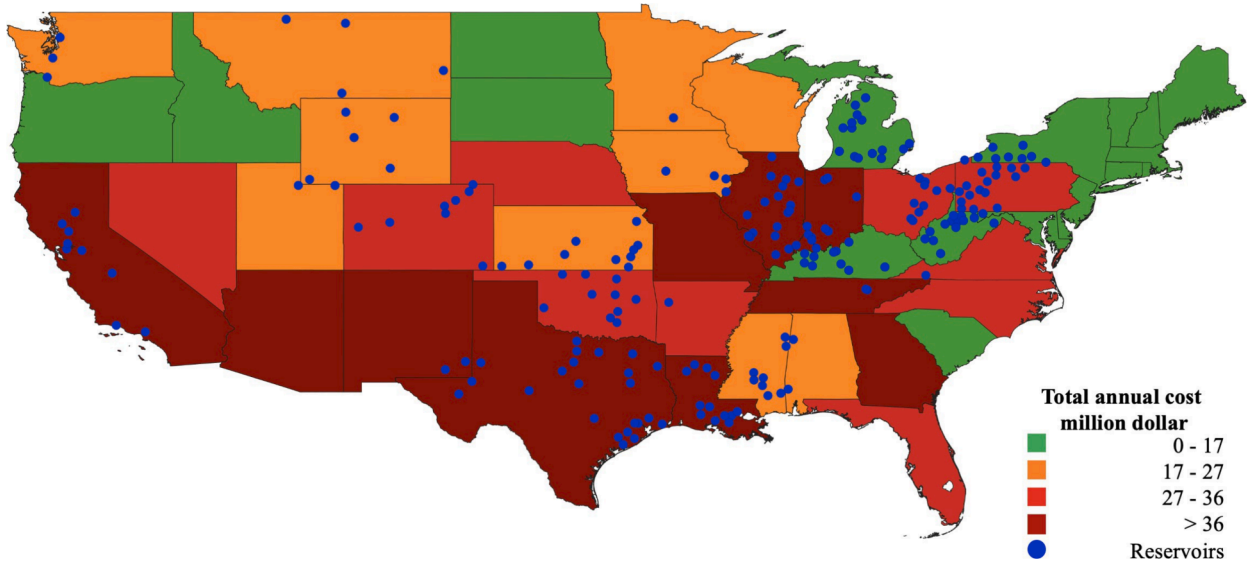

Fig. 11. Annual total cost by state.

Table 5
Annual cost breakdown of the top 10 states.

State	Total cost	HRS capital cost	Number of HRS	Delivery cost
TX	103,493,979	69,016,955	15	34,477,024
CA	85,597,636	46,011,303	10	39,586,333
AZ	61,078,569	18,404,521	4	42,674,048
GA	58,837,177	18,404,521	4	40,432,656
TN	57,626,340	23,005,652	5	34,620,688
NM	55,709,721	18,404,521	4	37,305,200
IL	50,746,972	36,809,043	8	13,937,929
LA	44,038,206	27,606,782	6	16,431,424
IN	40,204,073	18,404,521	4	21,799,552
MO	40,076,761	18,404,521	4	21,672,240

5. Sensitivity analysis

5.1. Driving range

We vary the HFCTs driving range from 500 to 1,000 miles while keeping all other parameters the same as in Table 4. The distributions of HRSs are shown in Fig. 12, where the diamond refers to the new HRS compared to baseline configuration, and the dash line circle indicates HRSs that are removed compared to the baseline configuration. Colors represent the refueling demand of the baseline HRSs and new HRSs. As the HFCTs driving range increases, the required number of HRSs significantly decreases—from 140 HRSs at a 500-mile range to just 75 HRSs at a 1,000-mile range, highlighting the reduced need for HRSs density with extended driving range. In Fig. 12, we also observe that most existing and new HRSs operate at high capacity, indicating high refueling demand rates at the HRSs.

As shown in Table 6 and Fig. 13. The total cost decreases steadily by 61% as the driving range increases from 500 to 1,000 miles. This reduction is primarily attributed to fewer HRSs and lower hydrogen delivery cost as HFCTs can travel longer distances. Furthermore, the non-linear nature of the capital cost curve suggests that the nonlinear decrease of the number of HRSs over driving range. Notably, hydrogen delivery costs by truck exhibit a steeper decline than HRS capital costs. This suggests that the effect of decreased hydrogen refueling demand is much greater than that of decreased number of stations on hydrogen delivery cost by truck, as a result of increased driving range.

Table 6 details the total cost and cost breakdowns by driving range. The HRS capital cost, while decreasing in absolute terms as HFCTs driving range increases, becomes larger in share from approximately 52% at a 500-mile range to 71% at a 1,000-mile range. This indicates that as HFCTs technology advances and vehicle driving range improves, the high capital investment in HRSs building will play an even greater role in HFCTs deployment.

Compared to pipeline-based hydrogen delivery, truck-based hydrogen delivery consistently dominates in the hydrogen delivery cost. In the baseline scenario of a 500-mile driving range, truck-based delivery accounts for over 90% of the total hydrogen delivery

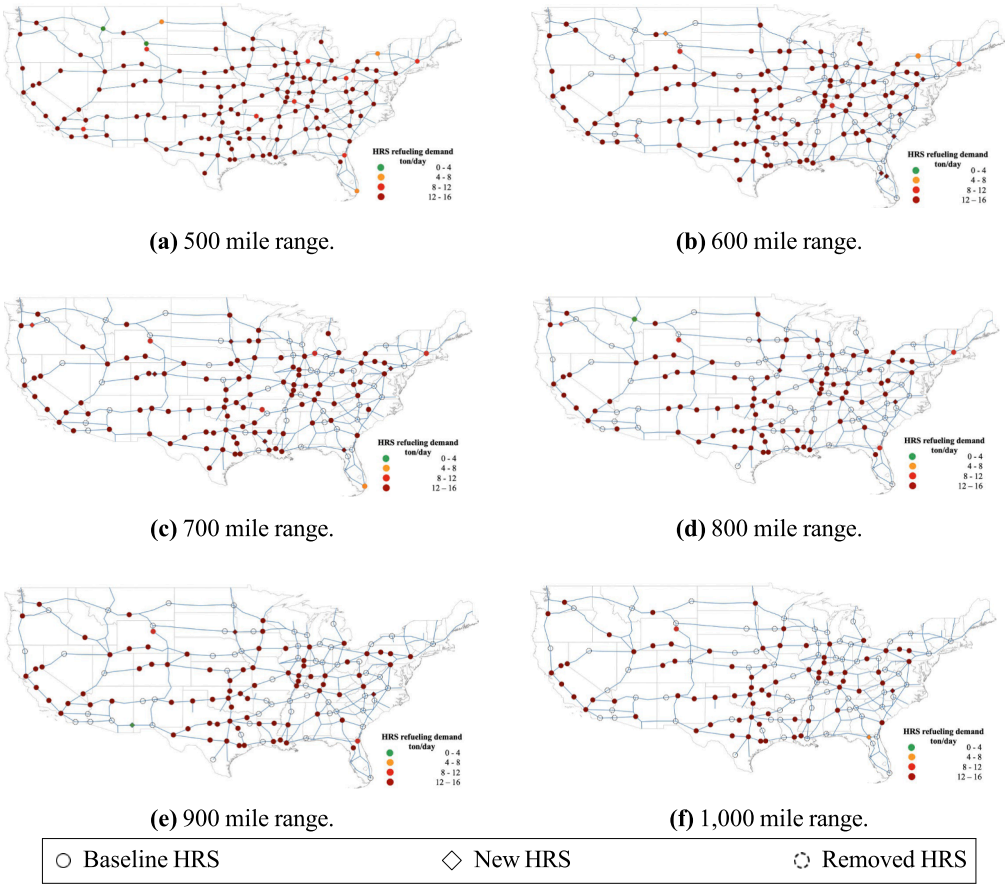

Fig. 12. HRSs distributions under different HFCTs driving range using Fig. 12a as the baseline.

Table 6
Cost breakdown under different HFCTs driving range.

Range (mile)	Total cost ($)	HRSs	HRS capital cost	HRSs (%)[a]	Delivery cost	Pipeline cost	Truck cost	Truck (%)[b]
500	1,249,073,334	140	644,158,248	51.6	604,915,086	52,942,383	551,972,703	44.2
600	1,020,710,103	120	552,135,641	54.1	468,574,462	46,919,288	421,655,174	41.3
700	836,977,452	106	487,719,816	58.3	349,257,636	41,367,434	307,890,202	36.8
800	689,234,600	92	423,303,992	61.4	265,930,608	37,216,620	228,713,988	33.2
900	579,275,339	84	386,494,949	66.7	192,780,390	32,172,173	160,608,216	27.7
1000	486,098,703	75	345,084,776	71.0	141,013,927	28,447,605	112,566,322	23.1

[a] Percentage of HRS capital cost over total cost.
[b] Percentage of truck delivery cost over total cost.

cost. While this percentage declines with extended range, it remains at over 80%. So expanding the pipeline infrastructure and improving the blending/separating technology between natural gas and hydrogen will further cut down the hydrogen delivery cost.

The disproportionately high share of truck-based hydrogen delivery costs points to the “last mile” challenge in hydrogen distribution. While pipelines are critical for long-distance bulk delivery, the regional distribution of hydrogen from production hubs or reservoirs to individual HRS will likely continue to rely on truck delivery. Therefore, improving HFCTs driving range can be an effective solution to significantly reducing truck-based hydrogen delivery cost. Strategically locating hydrogen production close to high-demand sites is another plausible solution.

In summary, the experiment results demonstrate that pipelines are indispensable for reducing the overall burden of hydrogen delivery costs, but the efficiency of the truck-based hydrogen delivery remains a critical area for improvement.

5.2. Station capacity

We further examine the impact of the HRS capacity on the number of HRSs and total cost. The distributions of HRSs under different

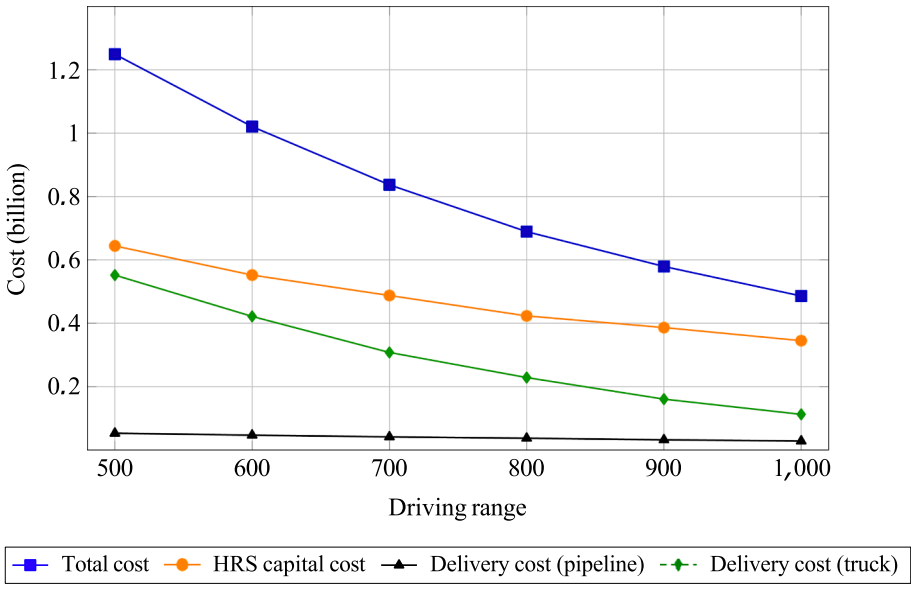

Fig. 13. Total annual cost and breakdown under different HFCTs driving range.

HRSs capacities are shown in Fig. 14. We find a significant reduction in the number of HRSs as the HRS capacity increases from 16 to 44 tons, as shown in Table 7. When HRS capacity is limited, more HRSs are needed to meet the HFCTs refueling demand. However, a plateau effect is observed from Fig. 15: beyond 40 tons, further increasing the HRS capacity does not reduce the number of HRSs. This plateau is primarily due to the assumptions of fixed system-wide HFCTs demand and constant HFCTs driving range. Consequently, the refueling demand remains approximately constant regardless of the routes chosen by HFCTs. A certain minimum number of HRSs is always needed to serve the refueling demand. Another observation is that increasing the HRS capacity mainly reduces the cost of truck-based hydrogen delivery. This occurs because larger capacities enable more hydrogen to be delivered to candidate HRSs with lower associated truck delivery costs.

A tradeoff between the number of HRSs and the utilization rate is observed in Fig. 15. The utilization rate is defined as the ratio of the total HRS refueling demand to the total station capacity across all HRSs. Notably, at lower capacities, utilization rates are significantly higher. At the 24-ton sweet spot, the utilization rate remains at 90%, suggesting efficient station usage while still maintaining an optimal cost. However, unlike the driving range sensitivity analysis, increasing the HRS capacity also results in fewer HRSs, but these HRS generally operate at lower utilization rate, and the utilization rate decreases faster as station capacity increases. This tradeoff between number of HRSs and utilization rate also reinforces the conclusion that limited HRS capacity imposes a substantial constraint on HFCTs operational efficiency. At the baseline scenario, though the utilization rate is the highest, the station capacity limitation leads to higher capital investment due to the need for more HRSs and necessitates more frequent refueling stops for HFCTs. While the act of refueling itself may be relatively fast, frequent stops can reduce overall logistical efficiency.

With respect to cost, Fig. 16 suggests a “sweet spot” at the 24-ton HRS capacity, where the benefits of fewer HRSs and optimized delivery outweigh the linearly increasing HRS capital cost. Beyond this 24-ton threshold, the rising HRS capital cost becomes the dominant factor, leading to an increase in the total cost. This observed non-monotonic trend results from a critical tradeoff between the hydrogen delivery cost and the HRS capital cost. Although the HRS capital cost increases linearly with capacity, the initial reduction in the hydrogen delivery cost—particularly associated with truck-based delivery—offsets this increase. Specifically, the analysis shows that while the cost of pipeline-based delivery remains relatively stable, the cost of truck-based delivery decreases by $150.7 million, which significantly outweighs the $66.7 million increase in the HRS capital cost. This suggests that larger and optimally located HRSs can serve more HFCTs while reducing truck-based delivery cost.

5.3. Delivery cost

As discussed in Section 4.1.2, both pipeline-based and truck-based hydrogen delivery exhibit a range of unit delivery costs. To assess the sensitivity of our results to this variability, we further evaluate the outcomes under the upper and lower bounds of the delivery cost range. We consider the following four scenarios: (1) best pipeline unit cost and best truck unit cost, which serves as the lower bound; (2) worst pipeline unit cost and worst truck unit cost, which serves as the upper bound; (3) best pipeline unit cost and worst truck unit cost, which serves as the highest truck cost; (4) worst pipeline unit cost and best truck unit cost, which serves as the highest pipeline cost. Scenarios 1 and 2 set the lower and upper bounds of total cost, while scenarios 3 and 4 show the best and worst shares between pipeline and truck. All of the other parameters remain consistent with the baseline setting. The unit delivery cost of each scenario is shown in Table 8.

The result is shown in Table 9 and Fig. 17. Across the four bounds tests, the total cost ranges from $1.04 to $1.52 billion. While the

(a) 16 ton capacity.

(b) 20 ton capacity.

(c) 24 ton capacity.

(d) 28 ton capacity.

(e) 32 ton capacity.

(f) 36 ton capacity.

(g) 40 ton capacity.

(h) 44 ton capacity.

Fig. 14. HRSs distributions under different HRS capacity.

optimal number of HRSs remains nearly constant and capital expenditure changes only slightly, the composition of costs shifts substantially with delivery costs. Within delivery costs, truck-based hydrogen delivery is the dominant component across all scenarios, ranging from 93.8% to 78.9%. This dominance explains the asymmetric sensitivity between truck and pipeline costs. Because truck delivery consistently represents the majority of delivery spending, even moderate changes in truck unit prices translate almost directly into total cost variations. In contrast, comparable changes in pipeline prices exert a much weaker effect due to their smaller base share. For example, comparing scenario 3 to scenario 4 shows that nearly the entire cost difference stems from the truck component, whereas

Table 7
Cost breakdown under different HRS capacity.

Capacity (ton)	Total cost ($)	HRSs	HRS capital cost	HRSs (%)	Delivery cost	Pipeline cost	Truck cost	Truck (%)
16	1,249,073,334	140	644,158,248	51.57	604,915,086	52,942,383	551,972,703	44.19
20	1,184,646,849	117	672,915,313	56.80	511,731,536	54,233,710	457,497,826	36.82
24	1,165,360,787	103	710,874,638	61.00	454,486,149	53,201,740	401,284,409	34.43
28	1,196,349,672	92	740,781,986	61.92	455,567,686	54,503,467	401,064,219	33.52
32	1,219,679,132	86	791,394,420	64.89	428,284,712	53,618,108	374,666,604	30.72
36	1,278,899,810	83	859,261,092	67.19	419,638,718	53,130,409	366,508,309	28.66
40	1,318,041,409	81	931,728,895	70.69	386,312,514	53,864,652	332,447,862	25.22
44	1,403,122,770	81	1,024,901,785	73.04	378,220,985	53,573,682	324,647,303	23.14

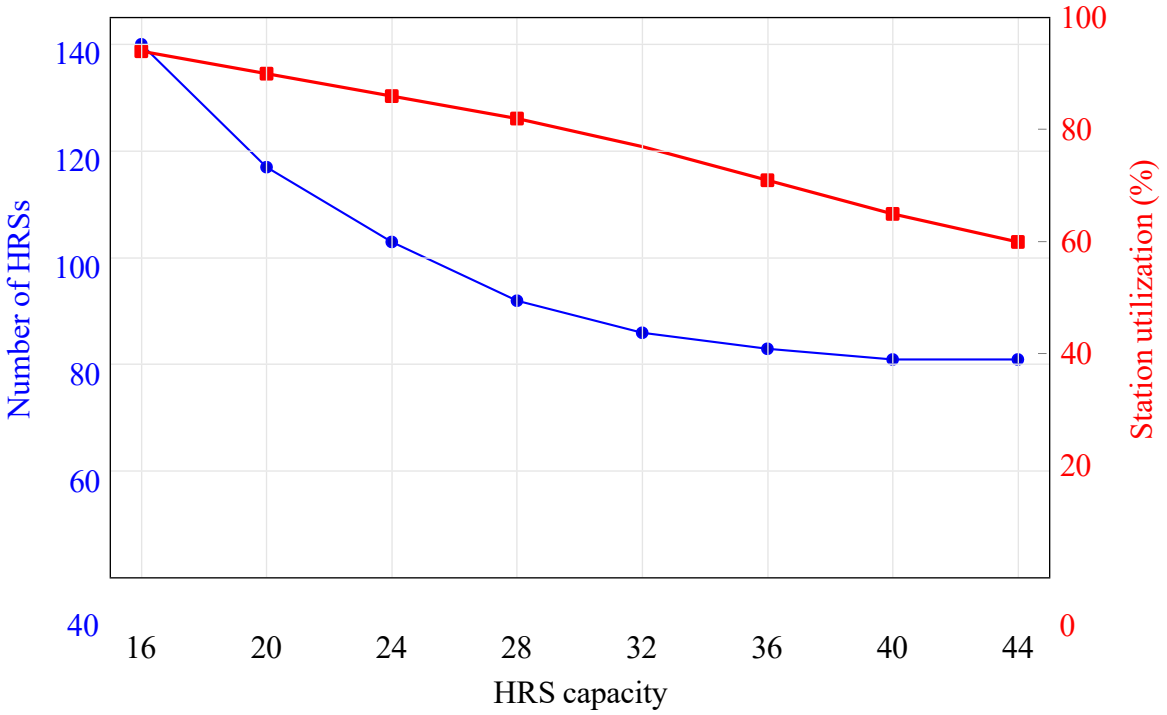

Fig. 15. Number of HRSs and utilization rate under different HRS capacity.

the pipeline component contributes only a modest $0.042 billion reduction. Similarly, moving from scenario 1 to scenario 2 more than doubles delivery expenditure, yet the increase in capital cost is limited to just $0.014 billion. Overall, the results highlight that truck delivery cost is the primary driver of cost variability, while pipeline delivery cost plays only a secondary role. Moreover, because the optimal HRS layout is largely invariant to delivery price bounds, the system has limited flexibility to offset rising truck cost through HRSs siting reconfiguration.

5.4. Truck-only delivery

To further evaluate the advantages of pipeline-based hydrogen delivery, we examine an alternative scenario in which hydrogen is delivered exclusively by truck from production hubs to candidate HRSs. This scenario reflects a potential real-world constraint in early infrastructure deployment stages. Consistent with the methodology described in Section 4.1, we calculate the 547 shortest distances between each of the seven hydrogen production hubs and all candidate HRSs, and retrieve the minimum distance to each candidate HRSs as the input distance. Using these distances and the unit truck delivery costs from Table 3, we compute total truck-based delivery costs. All other model parameters and assumptions are held constant to ensure consistency and comparability.

The results are summarized in Fig. 18 and Table 10. The results of the truck-only delivery scenario reveal a stark contrast with the mixed delivery scenario, with a substantially higher total system cost. When comparing with the mixed delivery scenario which combines pipeline and truck delivery, several key findings emerge: Across all HRSs capacities, the total cost in the truck-only delivery scenario is found to be 38.0% to 48.9% higher than those in the mixed delivery scenario. Furthermore, the optimal total cost in the truck-only scenario occurs at a 20-ton HRS capacity, amounting to approximately $1.73 billion. In contrast, the total cost under the mixed delivery scenario is $1.16 billion when the HRS capacity is at 24 tons. This significant cost difference underscores the economic

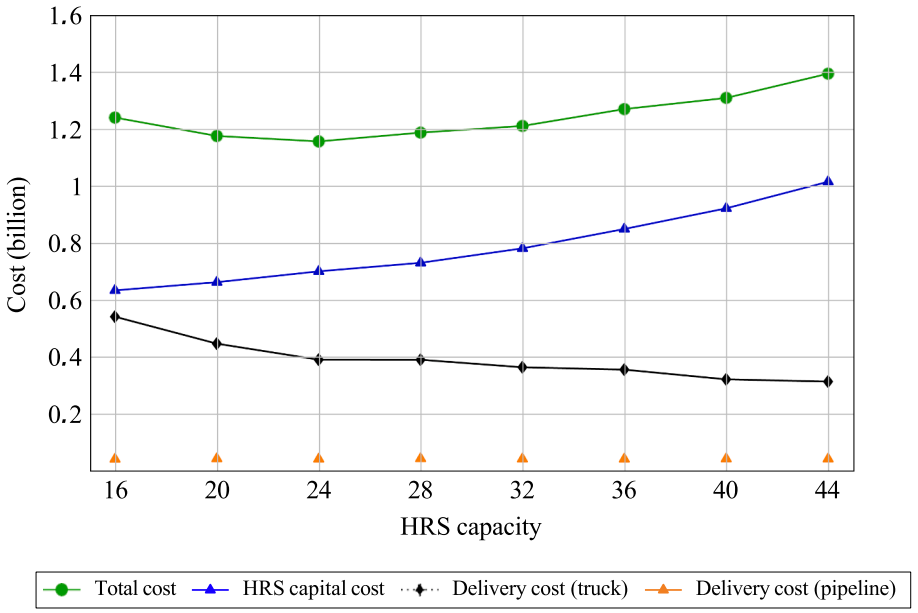

Fig. 16. Cost composition under different HRS capacity.

Table 8
Unit delivery cost breakdown under baseline and alternative scenarios.

Scenario	Pipeline $/(*ton·mile*)	Truck (0–62 mile) $/*ton*	Truck (62–311 mile) $/*ton*	Truck (>311 mile) $/*ton*
Baseline	0.2	500	1,500	2,000
Lower bound	0.19	100	1,000	2,000
Upper bound	0.35	1,000	2,000	2,200
Highest truck cost	0.19	1,000	2,000	2,200
Highest pipeline cost	0.35	100	1,000	2,000

Table 9
Cost breakdown under different delivery cost bounds.

Scenario	Total cost ($)	HRSs	HRS capital cost	HRSs (%)[a]	Delivery cost	Pipeline cost	Truck cost	Truck (%)[b]	Ratio[c]
Baseline	1,249,073,334	140	644,158,248	51.57	604,915,086	52,942,383	551,972,703	44.19	10.42
Lower bound	1,035,921,993	138	634,955,988	61.29	400,966,005	50,842,769	350,123,235	33.80	6.89
Upper bound	1,517,815,529	141	648,759,379	42.74	869,056,150	91,767,208	777,288,942	51.21	8.47
Highest truck cost	1,465,696,337	139	639,557,118	43.64	826,139,219	51,368,097	774,771,122	52.86	15.09
Highest pipeline cost	1,077,576,587	138	634,955,988	58.92	442,620,600	93,480,822	349,139,778	32.40	3.73

[a] Percentage of HRS capital cost in total cost.
[b] Percentage of truck delivery cost in total delivery cost.
[c] Ratio of truck delivery cost to pipeline delivery cost.

infeasibility of a large-scale, truck-only hydrogen delivery, establishing pipeline infrastructure as a foundational requirement rather than an optional enhancement.

6. Policy implications

The findings from our numerical experiments and sensitivity analysis provide several key insights into the design of hydrogen refueling infrastructure for long-haul freight transportation, particularly when considering the integration of existing pipeline infrastructure and truck-based hydrogen delivery.

First, leveraging the existing pipeline infrastructure can lead to significant cost savings. The integration of pipeline-based hydrogen delivery presents a transformative opportunity to reduce the total cost of hydrogen refueling infrastructure for long-haul freight. In the mixed delivery scenario, total costs are reduced by up to 49.1% compared to truck-only delivery scenario. Therefore, leveraging existing pipeline networks substantially lowers delivery costs and enhances the overall economic viability of hydrogen distribution.

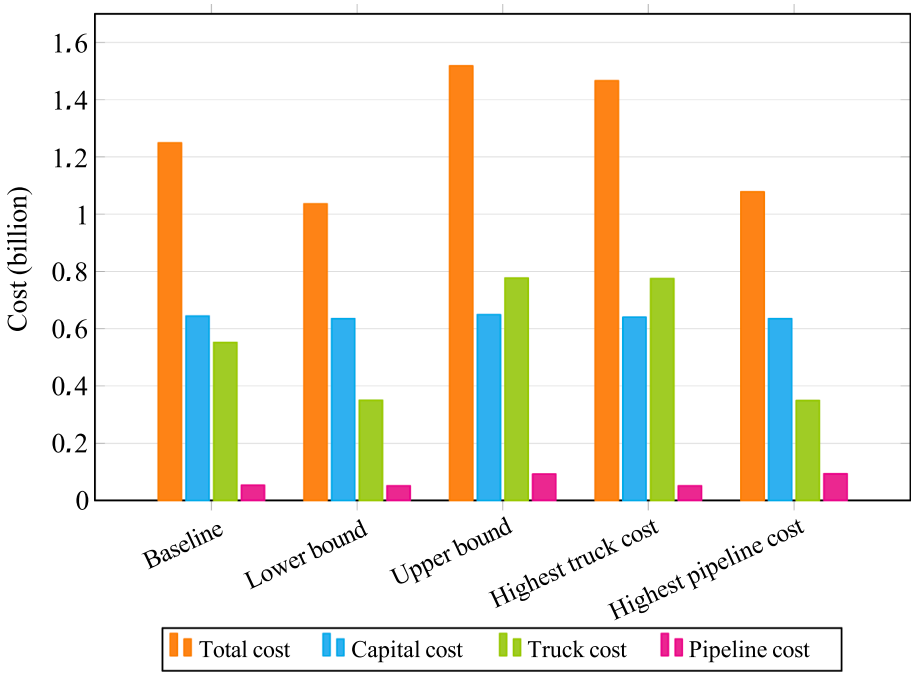

Fig. 17. Cost components under different delivery cost scenarios.

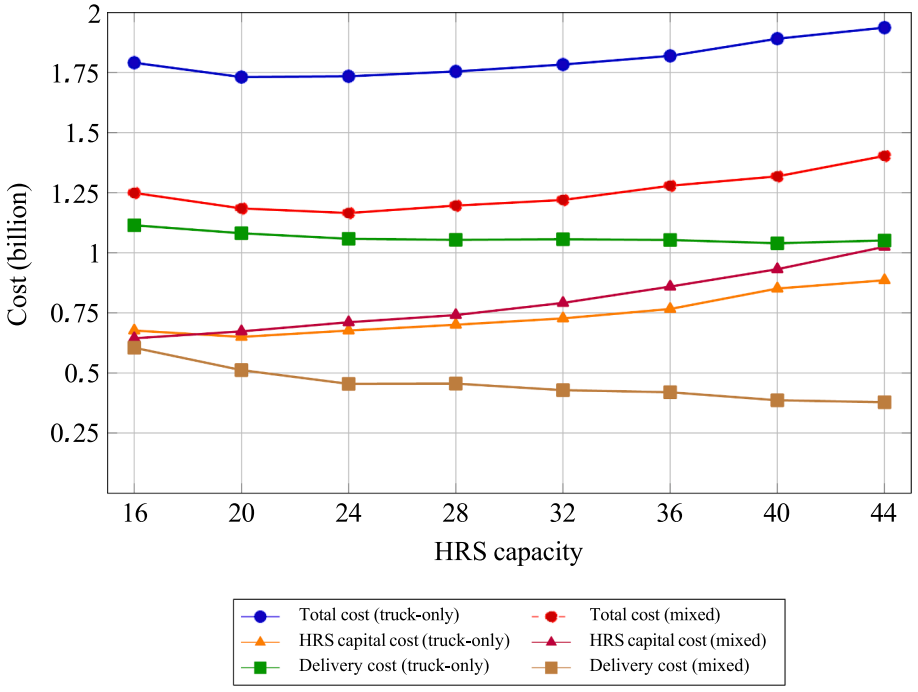

Fig. 18. Cost composition under truck-only and mixed delivery scenarios.

Consequently, maximizing pipeline infrastructure utilization presents a promising strategy to mitigate costs and improve long-term economic feasibility. Looking ahead, hydrogen pipeline can be exclusively built based on current natural gas pipeline network to substitute truck-based delivery in long-term hydrogen adoption development. The U.S. operates approximately 1,600 miles of hydrogen pipelines, predominantly located along the Gulf Coast (U.S. Department of Energy, 2017). These pipelines are designed to deliver hydrogen gas in a manner similar to natural gas pipelines, but they are exclusive to hydrogen rather than shared with other

Table 10
Cost breakdown under truck-only delivery scenario.

	Truck-only Scenario					Mixed Scenario	
Capacity (ton)	HRSs	HRS capital cost	HRSs (%)	Delivery cost	Total cost	Total cost	Cost ratio[a]
16	147	676,366,161.1	37.8	1,114,354,552	1,790,720,713	1,249,073,334	1.43
20	113	649,909,661.6	37.5	1,081,276,310	1,731,185,972	1,184,646,849	1.46
24	98	676,366,161.1	39.0	1,058,063,383	1,734,429,544	1,165,360,787	1.49
28	87	700,522,095.4	39.9	1,053,837,546	1,754,359,642	1,196,349,672	1.47
32	79	726,978,594.9	40.8	1,056,357,778	178,336,373	1,219,679,132	1.46
36	74	766,088,202.9	42.1	1,053,165,340	1,819,253,543	1,278,899,810	1.42
40	74	851,209,114.3	45.0	1,039,636,100	1,890,845,214	1,318,041,409	1.43
44	70	885,717,591.9	45.7	1,051,152,735	1,936,780,327	1,403,122,770	1.38

[a] Ratio of the total cost under the truck-only delivery scenario to that under the mixed delivery scenario.

gases. In the future, new, dedicated hydrogen pipelines could be strategically aligned along existing natural gas pipeline corridors to facilitate direct, high-capacity hydrogen delivery, thereby enhancing the efficiency and reliability of the hydrogen supply chain.

In parallel, it is important to recognize that truck-based hydrogen delivery will continue to play a critical role in the foreseeable future. While hydrogen pipeline offers substantial potential for reducing long-distance delivery costs, their deployment requires long planning horizons, large upfront investments, and is most feasible along major corridors. In contrast, trucks provide flexibility to serve geographically dispersed or emerging demand centers where pipeline infrastructure is not yet available. Moreover, unless on-site hydrogen production at refueling stations is widely implemented, trucking will remain the default mode for last-mile distribution from production hubs or storage reservoirs. Given this inevitability, reducing the cost of truck-based hydrogen delivery deserves equal attention. Strategies could include adopting larger-capacity cryogenic trailers and streamlining logistics operations such as back-hauling. Advances in liquid hydrogen transport technologies may also lower costs and enhance scalability (Gjerløw et al., 2023). Focusing on these improvements not only complements pipeline expansion but also ensures that the hydrogen supply chain remains resilient during the transition phase.

Furthermore, advancements in both HFCTs driving range and HRS capacity technologies create powerful synergies that drive total cost reductions. Extending HFCTs driving range from 500 to 1,000 miles—achievable through improved fuel cell efficiency and lightweight composite tanks—reduces required HRSs count by 46% and reduce total infrastructure costs by 61%. Similarly, increasing HRS capacity can reduce total costs compared to the baseline scenario. Also, increased HRS capacity improves the readiness to meet future hydrogen refueling demand at higher market penetration levels. These findings highlight that coordinated R&D efforts aimed at developing longer-range fuel cell stacks and high-capacity HRSs systems are essential for the future widespread adoption of hydrogen technology.

Last, the financial challenges of hydrogen infrastructure underscore the critical need for government support and strategic policy implementation. Even with cost optimization through strategic HRSs placement and pipeline-based logistics, the overall investment requirement for nationwide hydrogen infrastructure remains substantially high. This cost burden poses significant barriers to private investors, especially during the early adoption phase when HFCTs penetration rates are still low and revenue streams are uncertain. To overcome these challenges, robust policy measures are necessary. Examples include direct subsidies for HRSs construction, tax incentives for both infrastructure developers and fleet operators, and favorable financing schemes such as low-interest loans or public–private partnerships. In addition, coordinated federal and state-level planning can help align HRSs deployment with the hydrogen production hubs and freight corridors, thereby maximizing infrastructure utilization and economic efficiency. Such targeted policy interventions will not only reduce financial barriers but also accelerate market confidence and enable the large-scale adoption of HFCTs in long-haul freight transportation.

7. Conclusions

In this study, we propose a strategic HRSs location model that integrates pipeline- and truck-based hydrogen delivery. The model is implemented to investigate HRSs planning along the interstate highway network in the continental U.S., with many insights generated to support national HFCTs deployment. The proposed approach advances the understanding of the economic feasibility of HRSs deployment for HFCTs, supporting decision-making regarding the optimal siting and HRSs capacities. We find that incorporating realistic HRS capacity limitations will significantly influence both the total system cost and the number of required HRSs. Moreover, pipeline-based hydrogen delivery demonstrates a clear cost advantage compared to truck-based delivery, highlighting its strategic importance. To further reduce infrastructure costs and promote hydrogen adoption, future efforts should focus on advancing hydrogen storage technologies and implementing targeted subsidy programs that support fuel cell vehicle deployment.

Based on the findings of this study, we propose the following directions for future research. First, heterogeneous HFCTs operation characteristics such as HFCT driving range, tank size, and fuel economy could be incorporated as data becomes available to fully operationalize heterogeneous fleet scenarios. The current model assumes homogeneous vehicle attributes. Future research could classify HFCTs into multiple categories and consider stochastic initial fuel states to enable more realistic and robust infrastructure planning, enabling more realistic and robust infrastructure planning strategies. Second, the current model could be strengthened by including hydrogen production capacity and pipeline delivery capacity. Due to data unavailability, the current model does not account for production capacity or pipeline throughput constraints. Incorporating these factors would provide a more comprehensive and

realistic assessment of hydrogen delivery feasibility. Third, future analysis could investigate the impact of demand uncertainties on the model results. While the current study relies on FAF5 projections as a robust freight demand input, we assume deterministic freight flows. In reality, long-haul truck demand exhibits considerable variability. Additional research may take into account demand uncertainty to capture a range of plausible operational outcomes and enhance the robustness of HRSs planning. Fourth, future research should develop advanced solution algorithms. Incorporating fleet heterogeneity and demand uncertainty will significantly increase computational complexity. Therefore, efficient methodologies are essential to ensure computational tractability when scaling to large-scale, real-world networks.

CRediT authorship contribution statement

Jialu Yang: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Danesh Hosseinpanahi:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Bo Zou:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jane Lin:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The FAF data is publicly available

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