

Models and Methods for Planning Hydrogen Supply Chain Systems

Han Liu and Jing Ma, *Senior Member, IEEE*

Abstract—Hydrogen is becoming an important candidate for replacing fossil fuels in the future energy economy. As such, efficient hydrogen supply chain system planning and the promotion of its large-scale civilian and commercial applications are needed. To identify research gaps in the field, this study reviews models and methods for planning hydrogen supply chain systems that have been employed over the past 15 years. Significant decision aspects and objectives in the hydrogen supply system are presented. Thereafter, problem types, modeling techniques and solution methods are analyzed and classified based on their individual characteristics. Finally, potential directions promoted by economic factors are recommended for future research.

Index Terms—Hydrogen, planning model, supply chain system, solution method.

I. INTRODUCTION

THE decline in fossil energy is an immense challenge to the ecosystem. In the future energy economy, hydrogen will become an important candidate to replace fossil fuels due to its physical properties [1]. Hydrogen can be produced by either traditional or novel technologies in chemical and electrochemical processing. Before using hydrogen gas, compounds containing hydrogen must be chemically converted to molecular H_2 [2]. Therefore, hydrogen is a medium capable of storing energy converted from main energy sources into a chemical form. Additionally, this utilization is not limited by the second law of thermodynamics because the energy does not undergo thermal cycling. Conversely, by operating in an electrochemical reaction, a fuel cell can generate the most available energy due to its higher conversion efficiency. In addition, hydrogen reacts with oxygen to release energy and water without releasing carbon dioxide, the typical byproduct of fossil fuel combustion. Therefore, hydrogen can mitigate the release of the gases and compounds that cause climate change, and which are harmful to humans (e.g., nitrogen oxides, sulfides, and particulates) [3]. Despite the advantages mentioned above, the use of hydrogen as an energy carrier is still limited

by several shortcomings. For example, the acquisition of hydrogen requires additional chemical processes. Furthermore, even though the use of hydrogen has been prevalent in the chemical industry for decades, economic systems still lack the maturity necessary for large-scale hydrogen production.

The hydrogen energy supply chain system includes various key links such as production, transportation, storage, and the distribution of hydrogen energy along multiple paths. Modeling the interaction between different components complicates the problem. Optimization-based methods are especially influential in understanding these technologies and spatial interactions. The present study reviews models and methods related to the hydrogen energy supply chain system that have been published in scientific journals over the past 15 years. It also provides suggestions for gaps in the existing literature, as well as future research directions. We included 100 articles in our classification process. The individual characteristics of the models and the method for planning the hydrogen supply chain system are listed in the Appendix.

Figure 1(a) lists the journals published between 2005 and the first quarter of 2020 that this review references. *International Journal of Hydrogen Energy* is a comprehensive journal that publishes most of the scholarly articles on hydrogen supply chain system planning. In addition, Figure 1(b) provides information on chronological changes in the number of articles. Research interest in this topic has been growing over the past several years. This objectively reflects the maturity of hydrogen energy application across several fields.

The remainder of this paper is organized as follows. Section I discusses the research background, publication journals, trends, and application areas involved in planning the hydrogen supply chain system. Sections II, III, and IV introduce the decision-making aspects, objective functions, and model types in the literature. Section V provides solutions to the proposed problems. In this last section, potential areas of future research are suggested.

II. PLANNING DECISIONS

The main characteristics of the hydrogen supply chain are related to the problems of small decentralized or medium to large-scale centralized hydrogen production facilities, transportation modes, and large storage facilities. Systematic decisions in planning are presented as follows.

A. Production Plants

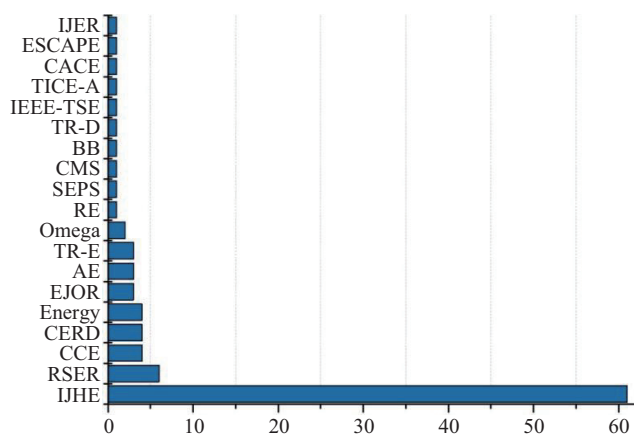
Hydrogen energy production plants are important facilities for producing industrial hydrogen energy. Since 2018, most

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H. Liu is with Research Institute of Emergency Science, China Coal Research Institute CCRI, China Coal Technology & Engineering Group (CCTEG), Beijing 100013, China.

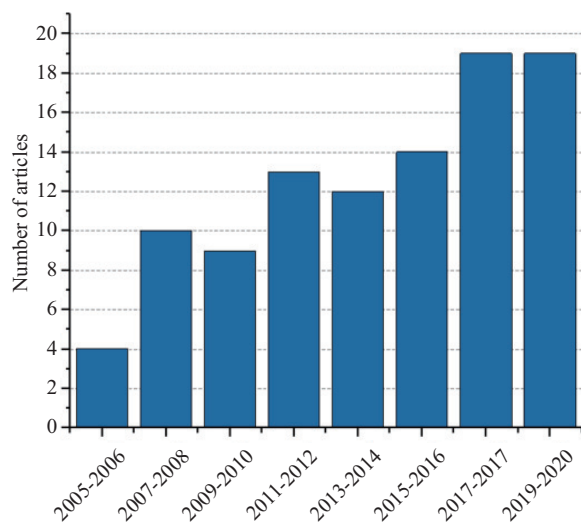
J. Ma (corresponding author, email: hdmajing@163.com) is State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China.

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(a) Publications per journal

IJER: International Journal of Energy Research; ESCAPE: European Symposium on Computer Aided Process Engineering; CACE: Computer Aided Chemical Engineering; IEEE-TSE: IEEE Transactions on Sustainable Energy; TICE-A: Trans IChemE, Part A; TR-D: Transportation Research Part D; BB: Biomass and Bioenergy; CMS: Computational Management Science; SEPS: Socio-Economic Planning Sciences; RE: Renewable Energy; TR-E: Transportation Research Part E; AE: Applied Energy; EJOR: European Journal of Operational Research; CERD: Chemical Engineering Research and Design; CCE: Computers and Chemical Engineering; RSE: Renewable and Sustainable Energy Reviews; IJHE: International Journal of Hydrogen Energy



(b) Publications every two years

Fig. 1. Overview of (a) publications per journal and (b) publications every two years.

hydrogen has been converted from fossil fuels through natural gas steam reformation, partial methane oxidation, or coal gasification. Other methods of hydrogen production include biomass gasification and water electrolysis. Designed technologies primarily include steam methane reforming (SMR), coal gasification (CG), biomass gasification (BG), and water electrolysis (WE) [4]. Among the two production forms, liquefied and compressed H_2 production (i.e. LH_2 or CH_2), the former is cheaper due its capital and energy intensive processes.

Optimal decision-making in production plants (e.g., the location, type, capacity and quantity of the production plant, as well as its production capacity) can minimize the hydrogen supply chain's capital and operating costs. Almansoori and

Shah found that more production plants are needed in areas with higher population densities, and that steam methane reforming plants have been built in various areas due to their lower production costs [5]. Another study optimized the locations of four plants with different production capacities by considering the scale effect on hydrogen energy's production capacity [6], [7]. Kim *et al.* analyzed the effects of multiple production types and locations on the hydrogen energy facility risk index [8]. Konda *et al.* determined the expansion scale of existing production plants based on existing production plant data, technology and economic data, and the number, type, location and capacity of new plants in future time periods [7].

B. Terminal Facilities

In the case of centralized hydrogen production, the terminal facility is an intermediate facility for hydrogen delivery to the end user. This includes the transmission and distribution facilities that process hydrogen from the production plant to the city gate and the transportation to the gas station or other end users. Decisions on terminal facilities influence energy use and emission targets [7]. For example, in a wind-based hydrogen supply system, the amount of hydrogen transported or stored in the terminal can be optimized by determining the number of hydrogen terminals [9]. Parker *et al.* designed an energy production and distribution system by deciding the terminal's mode, location and capacity. Four separate rice straw availability scenarios were matched with four hydrogen demand scenarios. The results showed that terminal cost dominated the total cost when rice straw availability was 75% or hydrogen demand in urban areas was 10% [10]. Talebian *et al.* proposed a space-time optimization method for the hydrogen fuel supply chain, in which the gas compression device and the liquefaction plant were integrated into the central production plant [11].

C. Storage Facilities

Storage technologies include compressed gas hydrogen storage (CH_2S) and liquid hydrogen storage (LH_2S). Due to hydrogen's low boiling point (approximately 20.268 K), achieving such a low temperature requires considerable energy in the form of LH_2S [12]. Pan *et al.* considered generation-load uncertainties and conducted dynamic planning for seasonal storage facilities with varying pressures in an electricity-hydrogen integrated energy system [13]. To optimize the design of a hybrid energy storage system composed of super capacitors and hydrogen subsystems, Mohseni and Brent proposed a meta-heuristic drive model, and evaluated the economic feasibility of storage and utilization technologies [14]. Alain *et al.* evaluated the location of an underground storage cavity in France from the perspective of economic and technological feasibility [15]. They found that when the penetration rate of renewable energy reached 50%–70%, extensive underground storage facilities are needed to meet the demand for hydrogen energy. Samsatli and Samsatli proposed a general space-time model to determine the location and size of hydrogen storage facilities, and the amount of energy generated and converted [16]. When designing the H_2 supply network, Han *et al.* properly controlled storage facility distribution activities and

maintained products at time intervals to meet local hydrogen needs [4].

D. Fueling Stations

Fueling infrastructures are essential to hydrogen-powered vehicles. A hydrogen refueling station needs to meet the following requirements: Compressed hydrogen needs to be supplied through a high-pressure hydrogenation system; compressed oxygen needs to be exchanged from empty storage tanks to full tanks (similar to the exchange in butane or propane tanks); liquid hydrogen must be distributed through transmission pipelines or exchanged to low-temperature storage tanks. Hydrogen refueling stations can receive compressed or liquid hydrogen through either trucks or pipelines. Their electricity can be derived from power grids, wind turbines, or photovoltaic cells.

Fueling station-related decision variables include position, size, and type. A fueling station's location determines its distance from the production facility and the storage facility. As such, it is a factor in hydrogen energy transportation costs. A fueling station's size determines its capacity and affects the flow of the transportation vehicle or pipeline. These factors affect all aspects of the lifecycle cost of hydrogen energy. Li *et al.* optimized the location, number and size of fueling stations in the hydrogen supply network, and made decisions on the types of fueling stations that either rely on delivery or produce hydrogen on-site [17]. By considering the hydrogen life cycle cost, Sun *et al.* coordinated the optimization of fueling station locations and scale with the objective of minimizing hydrogen user costs [18]. By extending the p-median model and applying Beijing's multivariate data, Lin made a decision on the location and coverage radius of the fueling station [19]. Hosseini and MirHassani proposed a two-stage stochastic programming model to optimize the location of permanent stations and possible future portable stations [20]. Zhao *et al.* expanded the Flow Refueling Location Model (FRLM) and optimized hydrogen battery power station locations by considering user access to changes in power along the start-end point [21]. Honma and Kuby argued that increasing facilities' coverage during hydrogen energy facility planning reduces vehicle travel time. This provides potential solutions for reducing travel time and fuel consumption [22].

E. Transportation Vehicle

Hydrogen travels in various transportation vehicles, such as tanker trucks, tube trailers, railway tanks and tanker ships. Unlike the railway tanks that operate in a closed network, tank trucks that use road infrastructure are more flexible. Especially in emergencies, they are easier to dispatch and can be efficiently deployed to end-users at any time [5]. Each transportation vehicle has its own transportation capabilities. The capacity of most compressed hydrogen tube trailers is around 1000 kg. This is one-fifth as much hydrogen as cryogenic tankers carry [12]. Compressed natural gas trucks are often used in supply networks with lower demand or smaller site capacities [23].

Hydrogen energy transport trucks have varying hydrogen energy pressure, polymerization conditions, carrying capacity,

traveling speeds and transportation costs. This affects hydrogen energy transportation costs. Dominković *et al.* compares the transport sectors of four renewable energy sources—biofuel, hydrogen, synthetic fuel (electronic fuel) and electricity. Although the construction of hydrogen energy has advantages in reducing air pollution and carbon dioxide emissions, large-scale implementation of hydrogen-powered transportation systems may be economically inefficient due to the capital costs of new infrastructures [24]. Since the price of an oil tanker is almost twice that of a trailer, the effects of two transportation modes on transportation funds and operating costs in different scenarios warrant consideration: trailers transporting GH_2 , and oil tankers transporting LH_2 [25]. Distributed demand is cheaper than highly dispersed demand, and this may enhance the practical application of gaseous hydrogen.

F. Supply Routes

Route selection may also affect a road network's traffic flow pattern, and thus affect transportation costs. When social traffic flow is heavy, energy transportation vehicles must avoid congested roads to ensure transportation is cost-effective and safe. The flow's impact balances the efficiency of energy transportation and the normal operation of social vehicles [26]. In the multi-class user equilibrium (UE) framework, Miralinaghi *et al.* reduced transportation costs by making decisions about transportation vehicle paths under uncertain conditions. However, they assumed that the transportation vehicle would stop and refuel only once along the way. This was done to simplify the model [27]. The results showed that the robust decision-making scheme could reduce average driving time in the system by 6%, 7% and 14% under various demand characteristics. From the perspective of convenience and coverage, a node-based and path-based location model of urban hydrogen refueling stations has also been proposed [22]. Zhao *et al.* extended the Freeway Traffic Capture Method (FTCM) to evaluate the effect of user routes on road intersection accessibility in the initial stage of hydrogen energy construction [21].

G. Pipes

Unlike hydrogen energy transportation by gas trucks and liquid cryogenic trucks, pipes are rarely utilized in early infrastructure construction, due to their high costs. However, as the hydrogen energy demand market matures, pipes are gaining cost advantages over transportation vehicles in hydrogen energy transportation. Therefore, research into pipe location, length, and capacity is needed. Yang and Ogden provided a calculation method for pipe flow according to hydrogen energy pipes' diameter, length, pressure, inclination angle and capacity [23].

Pipeline capital costs include materials, installation, access and licensing. Each pipeline's flow rate can be calculated by dividing the total demand peak by the number of clusters. The pipeline length can be assumed to be the average distance from the demand center to all demand points. In the context of integrating wind, electrical and hydrogen energy, Ball *et al.* optimized the location, capacity and route of Great Britain's hydrogen network pipeline [28]. Andre *et al.* conducted a

comparative cost assessment of trucks and pipelines. Various algorithms have also been applied and compared at three levels of hydrogen pipeline planning (city scope, regional scope, and national scope) [29]. André *et al.* analyzed the hydrogen energy pipeline network location and scale in Northern France by analyzing hydrogen energy market share. They concluded that large-scale hydrogen energy networks can cut costs when hydrogen energy accounts for over 10% of the vehicle energy market [30]. Using the Southwestern United States as the background, Johnson and Ogden optimized the pipeline facilities of the unicom hydrogen manufacturing plant and user center. They found that nearly one-third of the pipelines had sub-standard design during construction [31].

III. OBJECTIVE FUNCTION MEASURES

With the increasing complexity and multiplicity of hydrogen supply planning, objective factors, such as facility costs, carbon emissions, system safety, and investment have been optimized. They are analyzed in the ensuing sections.

A. Facility Costs

The high costs of hydrogen energy infrastructure can challenge hydrogen energy commercialization. Facilities costs include general facilities, project permit costs and land. Among facility types, WE are the most expensive, followed by BG, CG and SMR. Facility size and capacity also affect facility costs. For a new plant, total operating and maintenance costs are typically equal to 6% of capital expenditures [7]. For example, building a hydrogen power station in California can cost up to \$4.6 million. The current average cost of the 46 existing sites is \$2.2 million [32]. Platform equipment, manufacturing, procurement, site preparation, and construction account for the bulk of the costs.

B. Transportation Costs

The costs related to transport units are fuel and wage costs, logistic costs, and capital costs of truck components which may include the cab, the undercarriage and the tube. Fuel cost is related to the type, capacity, travel distance, and energy price of the vehicles that are carried. The transportation capital cost of transmission and distribution can be calculated based on the number of transportation units. The number of transportation units is related to factors such as capacity of the truck/trailer, transportation distance, speed, loading/unloading time and transportation mode. The capital costs of a tanker truck are higher than those of a tube trailer (approximately \$800,000 and \$300,000 per unit, respectively). This is because of the expensive LH₂ container on the tanker truck [5].

In the path-based approach, demands are represented by pairs of origin and destination (O-D) points on trips which guide the vehicles' routes. The original flow-capturing location model (FCLM) aims to maximize the traffic flow through p facilities [33]. When a single facility is located on any location on the path, this path's O-D demand is considered covered. Due to the difference in trucks' hydrogen energy pressure, polymerization conditions, carrying capacity, delivery speed and transportation costs during hydrogen energy transportation, Lahnaoui analyzed the costs of four compressed gas

trucks (250, 350, 500 and 540 bar) [34] [35]. Gim *et al.* concluded that the centralized hydrogen production process has the advantage of cost-effectiveness. They developed a strategy to minimize hydrogen transportation costs [36]. Lahnaoui proposed a levelized cost of transporting hydrogen (LCOTH) model. As the transportation capacity decreases and the travel distance increases, the target cost continues to rise [35]. The lowest equipment deployment costs are also provided for various compressed gas truck (CGT) pressure levels.

C. Storage Costs

Various hydrogen storage methods determine capital costs. Common hydrogen energy storage methods include underground, compressed gas, liquid and metal hydride. For underground storage, capital costs include cave costs and compressor costs. Underground hydrogen storage in a salt cave, which is formed by dissolving salt in evaporated formations, is a technically feasible option for large-scale electricity storage. The shape and size of the cavity can be controlled due to the mature leaching technology. Electrolysis costs account for over 80% of the total costs of integrated production and underground hydrogen storage facilities [15], of which electricity costs account for the main share.

The cost of compressed hydrogen storage includes water cooling and compressor power requirements. These are calculated based on the hydrogen compression power and cooling requirements. For liquid hydrogen storage, capital expenditures include the cost of insulated dewars. However, the liquefier is usually considered a separate conversion technology. For metal hydrides, capital costs include hydride materials and integrated heat exchangers for storing and releasing hydrogen in the form of hydrides.

There are three stages in the hydrogen storage operational process: charging, maintaining and discharging. For example, most of the operating costs of compressed gaseous hydrogen storage and underground storage are from the compression process. To store liquid hydrogen, the liquid hydrogen needs to be kept at a very low temperature to prevent evaporation. For metal hydride storage, the adsorption and desorption processes are difficult and costly.

D. Carbon Externalities

Carbon emissions in the hydrogen supply chain network derive primarily from the hydrogen production link [17]. The global warming potential (GWP) is associated with the absorption of atmospheric heat radiation caused by a network's greenhouse gas emissions. It indicates the overall carbon

emissions effect. The total GWP comes from the energy consumption of various facilities in the network. Almaraz *et al.* calculated the total energy consumption of production facilities, storage facilities and transportation facilities to obtain the total GWP [37].

E. Pipe Costs

While modes of road transportation, such as trucks and trailers provide flexibility, pipelines can provide economies of scale. As demand grows, pipelines may eventually become the preferred mode of transportation. The large-scale

industrial application of hydrogen began in 1938, when a 240 km long pipeline, which could transport 250 million m³ of hydrogen per annum, was built in the Ruhr Valley. At present, the lengths of the hydrogen pipeline networks in Western Europe and the United States are 1,500 km and 900 km, respectively: South America and Thailand also have small pipeline networks. These consist of ordinary steel pipes with diameters ranging from 100 mm to 200 mm [1]. These pipelines transport hydrogen from the production site (usually generated by methane steam reforming, ethylene cracking, or chlor-alkali electrolysis to hydrogen). Their transportation pressure ranges from 0.34 MPa to 10 MPa. The French Air Liquide Company's pipeline network covers France, Northern Europe and the United States. The United Kingdom and the United States also have maturing pipeline networks. The construction costs of a compressed-gaseous hydrogen energy network are eight times the construction costs of a liquid hydrogen energy network. Transport container capacity is a major cost. Another is that gaseous hydrogen's low energy density causes higher storage and distribution costs in compressed-gaseous hydrogen networks [5]. The delivery cost in each time period is calculated based on the ratio of the total expenditure within the network to the total production volume in that time period. Considering how pipelines benefit from economies of scale, radical changes in network topology may occur by 2050 [7]. If there is sufficient demand, investors may gain enough confidence to invest in deploying a dedicated pipeline infrastructure to produce long-term benefits.

F. Safety

Hydrogen is flammable, but because it is light, it tends to rapidly diffuse when it leaks. Only in a closed space without proper ventilation is there a real risk of burning. When hydrogen and air form a flammable cloud, an explosion may occur. Safe hydrogen use requires leak prevention. This means that appropriate ventilation systems require detectors. Appropriate design features such as roof-top installation of hydrogen tanks should also be considered.

Safety is crucial to the confident development of hydrogen energy use. Due to varying national conditions, countries issue their own hydrogen energy safety standards. In the United States, hydrogen technology safety guidance is regulated by the National Fire Protection Association (NFPA). It provides basic guarantees for the generation, installation, storage, piping, use and disposal of air in the form of compressed gas or cryogenic liquid [38]. Kim *et al.* developed expressions to evaluate total risk in hydrogen energy systems. They found that the risk index is correlated with the number of hydrogen facilities, the risk level, and the population near where the facilities are located [8].

G. Technological Investment

Technology refers to the equipment used for hydrogen resource conversion, storage, and transmission. A technology may be provided at different capacity scales, which may vary from the household to the industrial scale. They are characterized by a set of conversion factors that define efficiency through the ratio of each resource generated and consumed by

technical operations. Any resource can serve as a technology input or output, so that optimization can employ the most effective conversion path [16]. Storage and transportation are considered "technology" in order to facilitate the modeling of resource needs and losses.

IV. PROBLEM TYPES AND MODELING TECHNIQUES

As shown in the APPENDIX, models can be divided into either single objective or multiple objective models, according to the number of objectives in their respective scholarly publications. The majority are multiple objective model accounts because the planning model for a hydrogen supply chain system involves manifold optimization factors.

A. Pathway Models

The large-scale civilian use of hydrogen energy is still in its nascent stage. As such, there are multiple technical options for hydrogen production, storage, and distribution. This poses challenges in choosing hydrogen supply channels. In addition to technical factors, indicators, such as cost, feasibility, reliability, environmental impact, safety and social impact, should also be considered when evaluating long-term approaches [39]. In many pathway models for planning a low-carbon economy, energy storage issues often lack detailed modeling (International Energy Agency, 2014). This may be a limitation on reliable energy supply systems.

B. Optimization Models with Uncertainty

Dangers which may cause doubt about hydrogen energy's reliability are hidden in its production, transportation and utilization. To increase the feasibility of hydrogen energy as a renewable energy source in the future, the most important issue is to improve its reliability by means of optimization. Agnolucci *et al.* proposed an uncertainty model for spatial hydrogen infrastructure planning which tests the uncertainties related to the characteristics and evolution of hydrogen demand, and the availability of technology and resources [25]. Botterud *et al.* used a Monte Carlo simulation to describe uncertainties in hydrogen and electricity prices. They applied a real-options method to assess the return on investment in nuclear hydrogen plants which convert electricity and hydrogen [40]. As such, the expected profits and overall financial risk can be balanced by adjusting a product's flexibility.

C. Coverage Models

Coverage models are derived from emergency location models. They include the Location Set Covering Problem (LSCP), Maximal Covering Location Problem (MCLP), and their extended forms. MCLP, which covers maximum demand points using limited resources, is mostly applied in hydrogen supply chain system planning. Zhao *et al.* proposed a multi-scale coverage optimization framework for locating gas stations. It effectively provides information on early stage hydrogen fuel infrastructure plans [21].

D. Transportation Models

Transportation models are designed to meet customer needs while minimizing transportation costs. They are a means

of choosing the best way to distribute product distribution from multiple factories or warehouses to multiple destinations. The original transportation model used linear programming to analyze logistics management issues. In order to accurately estimate the number of fuel cell vehicles and the required hydrogen, Gim *et al.* projected hydrogen demand and transportation distances into 2040, and employed Lawrence Lawton's diffusion model for a hydrogen transportation plan arrangement [36]. The results showed that pipelines solution can minimize total hydrogen transportation costs over the long term.

E. Life Cycle Models

The hydrogen system's life cycle is usually composed of a series of stages adjusted by management decisions. These can serve as evaluation methods for renewable energy optimization. Sabio *et al.* developed a multi-objective mixed integer linear program (MILP) [41] which measures eight life cycle assessment indicators. In this way, it quantifies hydrogen infrastructure's environmental performance across life cycle damage categories.

F. Forecasting Models

One of many forecasting models, the MARKAL model, can provide effective analysis for establishing long-term forecasts of optimal energy mix and technological change. Krzyzanski *et al.* predicted the long-term impact of increased transportation demand, and concluded that the consumption of major resources (i.e., fuels) and increases in carbon dioxide emissions come primarily from road vehicles [42].

G. Dynamic Programming Models

The storage and transportation system is dynamic, and it is usually necessary to capture its state characteristics every hour, or in even shorter intervals, for accurate modeling [16]. Duigou *et al.* analyzed the technical and economic feasibility of large-scale hydrogen underground storage from static and dynamic perspectives [15]. The static model simulated the operations of a storage facility with a simplified annual total value, while the dynamic model simulated the operations of a storage facility over an interval of one year; the two models are independent and complementary in a well-designed framework.

In recent years, seasonal storage of hydrogen in vehicles has become a hot research topic. Due to the inconsistent characteristics of energy storage and energy consumption in some countries, relying on seasonal storage can promote energy efficiency. For example, wind power generation in Germany peaks in winter, while solar power in the northern hemisphere reaches its maximum in summer. Seasonal storage can narrow the gap between fluctuations in renewable energy generation from winter to summer [43]. Therefore, seasonal storage has a high storage capacity, and annual charging cycles are minimal.

From an economic perspective, seasonal storage systems can prevent huge energy waste with limited capacity costs.

V. SOLUTION APPROACH

This section presents exact and heuristic methods, sim-

ulation and other techniques for solving hydrogen supply planning problems.

A. Exact Methods

Most hydrogen supply chain system planning models in small size problems are formulated as LP or MILP. These can usually be efficiently solved by commercial software, such as CPLEX [9], [19], [22], [36], [44]–[51], [70], and [107], [108] LINGO or GAMS [8], [28]. For some MIP problems, the decomposition method has proven applicable for obtaining satisfactory solutions with relative small gaps [16]. The cutting-plane method has also been used to solve robust optimization models under demand uncertainties [27].

B. Heuristic Methods

Heuristic methods, such as genetic algorithms, are also prevalent in large-scale and complex planning problems. Lin proposed the p -median model for fueling stations, and designed a hybrid heuristic method consisting of a genetic algorithm, an annealing algorithm, and the greedy algorithm to achieve rapid convergence when solving this integer programming problem [19]. Mohseni and Brent proposed an optimized design model for a hybrid energy storage system composed of super capacitors and aluminum hydroxide [14]. By comparing the efficiency of 20 metaheuristic calculations in the Hydro Micro-Grid planning research, they found that the Moth-Flame Optimization Algorithm can obtain near-global optimal solutions to the problem [14]. By applying PID (Proportion, Integration and Derivative coefficient) control logic to the hydrogen supply system, Cho *et al.* simulated the controlling of the dynamic process of discharging hydrogen from metal hydride tanks under various operating conditions. They also derived typical hydrogen consumption demands for fuel cell systems [52].

C. Simulations

Based on mathematical theory, simulation modeling compares alternatives and solutions to problems, as well as tests and hypotheses. It also infers processes. It is possible that the development of hydrogen supply system planning models and information technology are parallel. Therefore, simulation has potential as an effective tool for studying complex systems. In order to reliably optimize electrolyzer operations, Zhou and Francois simulated the electrolyzer and auxiliary control system [53]. The experimental results characterize the relationship between different physical quantities, and highlight the relationship between the change domain and physical quantities. Contreras *et al.* simulated energy consumption in the road transport sector in Madrid from 2010 to 2050 according to vehicle fuel types, and conducted market penetration analysis of hydrogen usage [54].

D. Other Approaches

There are several other approaches to designing a hydrogen supply chain. For example, Almaraz presented the TOPSIS (Technique for Order Preference by Similarity to Ideal Situation) model on the Pareto frontier and used the same weighting factors to determine cost, safety and environmental

standards [37]. They optimized the multi-objective functions of economic, environmental and safety indicators, and solved important decisions including factory productivity and storage inventory, hydrogen energy flow and transportation routes.

CONCLUSION

This paper presents an overview of research into planning hydrogen supply chain systems. Separate sections are dedicated to analyzing and classifying the models and methods of selected papers to identify research gaps in this field. The hydrogen energy conversion, storage and utilization system is an effective, reliable, continuous and independent system that

replaces the current centralized energy system based on fossil energy. Such a replacement could have an immense effect on the global macro economy. From a technical perspective, many problems have yet to be resolved, such as the efficient storage of hydrogen at normal temperatures and pressures, as mentioned in the referenced articles. However, the economic benefits engendered by market demand could accelerate technological upgrades. The introduction of a hydrogen energy system will be a breakthrough in addressing human health, political conflict and energy shortages. Therefore, while implementing this new energy system, it is necessary to analyze its life cycle, and to estimate and budget for its tangible benefits.

APPENDIX

TABLE I

INDIVIDUAL CHARACTERISTICS OF MODELS AND METHODS FOR THE PLANNING OF THE HYDROGEN SUPPLY CHAIN SYSTEM

Ref.	Decision variable								Objective function						Type	
	PP	TF	SF	FS	PL	TV	SR	FC	TC	SC	CE	PC	SA	S		M
55	*	*		*				*			*				*	MILP
5	*	*	*			*		*	*						*	MILP
57				*				*	*		*	*			*	DP
28	*													*		
39											*			*		LP
58	*	*						*			*				*	DP
6	*	*					*	*				*			*	MIP
44	*		*			*		*	*				*		*	MILP
42														*		MIP
60	*		*			*		*	*	*					*	MILP
61				*			*		*					*		MILP
62	*		*			*	*	*	*							MILP
54						*										DLP
53	*															
63				*				*							*	NLP
33				*			*							*		MILP
64								*			*				*	MIP
10	*	*	*	*		*	*	*	*	*		*			*	MINLP
66		*		*				*						*		
31	*				*			*				*			*	MILP
8	*		*			*						*				LP
67	*		*	*	*			*	*						*	MILP
7	*							*	*						*	MILP
36									*					*		LP
41	*		*			*		*	*		*	*			*	MILP
4	*		*				*	*	*	*					*	MILP
70				*						*					*	DP
72								*			*	*			*	MIP
73				*							*				*	MIP
37	*		*			*		*	*	*	*		*		*	MILP
29	*				*							*			*	MINLP
52	*									*						
75	*		*			*	*	*	*	*	*		*		*	MILP
25	*		*	*		*		*	*		*	*			*	MILP
76	*				*	*		*	*						*	LP
77								*	*		*	*			*	DLP
78	*		*		*	*		*	*						*	MILP
80	*		*			*		*	*	*			*		*	MILP
30					*	*		*	*			*			*	
16	*		*				*	*	*	*	*				*	MILP
82	*		*	*		*	*	*	*	*	*		*		*	MILP
83	*		*			*		*	*	*					*	SMIP
84				*			*							*		LP
20				*			*							*		MIP
9	*	*	*	*		*		*	*						*	MILP
45	*	*	*				*	*	*	*	*	*			*	MILP
46	*		*		*			*	*	*					*	MILP
47	*		*			*	*	*	*	*					*	MILP
48						*		*	*						*	MILP
49	*		*				*	*	*	*					*	MILP
50	*		*	*	*	*	*	*	*	*	*				*	MILP
86	*					*	*	*	*		*				*	MILP

TABLE I
(CONTINUED)

Ref.	Decision variable								Objective function							Type
	PP	TF	SF	FS	PL	TV	SR	FC	TC	SC	CE	PC	SA	S	M	
87	*														*	
88								*		*					*	MILP
89	*		*			*		*	*	*	*				*	MILP
90				*		*		*	*	*					*	MILP
91				*			*							*		MINLP
92	*		*			*	*		*	*		*			*	MILP
27				*			*	*	*						*	MINLP
15	*		*			*										
94	*		*		*	*							*	*		
43						*		*	*	*					*	
97	*		*			*	*	*	*	*					*	MILP
98	*		*			*	*	*		*	*				*	MILP
34	*		*						*	*					*	MILP
99							*								*	MILP
21				*			*							*		MIP
14						*		*								MIP
22				*			*		*					*		MIP
18			*					*							*	MIP
35			*			*		*	*	*					*	MIP
11	*	*	*			*		*	*		*					MIP
51	*		*	*		*		*	*	*	*					MIP
19				*					*					*		MIP
17	*			*		*	*	*	*		*				*	MILP
13	*		*					*		*					*	
106	*		*											*		SLP

PP: production plant; TF: terminal facility; SF: storage facility; FS: fueling station; PL: pipe location; TV: transport vehicle (i.e., trucks or railcars); SR: supply route; FC: facility cost; TC: transportation cost; SC: storage cost; CE: carbon externalities; PC: pipe cost; SA: safety; S: single objective; M: multiple objective.

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Han Liu received his B.S. degree in Transportation Engineering from Beijing University of Technology, Beijing, China, in 2008, and a Ph.D. degree in Transportation Engineering from Harbin Institute of Technology, Harbin, China, in 2018. He was a post-doctoral researcher at Tsinghua University and a visiting scholar at the University of Illinois at Urbana-Champaign. His research interests include integrated transportation and renewable energy development, transportation facility planning, and emergency vehicle routing optimization.



Jing Ma received his B.S. and PhD degrees from North China Electric Power University, China, in 2003 and 2008, respectively. He was a visiting research scholar at the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University from 2008 to 2009. He was a professor in the School of Electrical and Electronic Engineering, North China Electric Power University. He is currently a professor at School of Electric Power Engineering of Shanghai University of Electric Power, Shanghai, China. His major interests include power system stability and control.