

A multi-optimization model for the design of hydrogen supply chains.

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Abstract. This paper presents a multi-objective optimization models which operating as time processes (2025-2035) for the design of hydrogen supply chain. The feasibility of the models are illustrated through a detail case study of Dalian, China. Furthermore, the case is evaluated with the total daily costs and CO₂ emissions reduction constraints. The results show that with the increase of hydrogen demand, considering the environmental factors, SMR are mostly applied in hydrogen production link. Shahekou and Pulandian grids are suitable for the constructions of hydrogen production units. Tank trucks are the main modes of hydrogen transportation. The proposed design models can provide policy-makers with the selection of infrastructures pathways for strategic dynamic hydrogen development planning.

1 Introduction

At present, developed countries have incorporated hydrogen energy into their energy development strategies and regarded it as one of the key sources of energy to achieve low-carbon social development goals. China has also attached great importance to the development of hydrogen energy industry. Great progress has been made in technological innovation and application of terminal products and infrastructure construction. Hydrogen fuel cell for vehicle will be an important development direction of hydrogen utilization in the future. Nowadays, developed countries such as Europe, America and Japan have supported the research, development, demonstration and commercial application of fuel cell technology through formulating medium - and long-term development plans. However, the source of hydrogen is a key issue to the commercialization of fuel cell vehicles. Hydrogen production, storage and transportation and infrastructure construction are important factors for fuel cell vehicles from research demonstration to small-scale demonstration operation, to preliminary commercialization and application, and finally to large-scale application [1-5]. Therefore, the construction of hydrogen energy industry chain is very important.

This paper presents a multi-objective optimization models which operating as time processes (2025-2035) for the design of hydrogen supply chain. The models are illustrated through a detail case study of Dalian, in China. And the case is evaluated with the total daily costs and CO₂ emissions reduction constraints.

2 The optimization model of hydrogen supply chain^[6]

The hydrogen industry chain covers hydrogen production, storage, transportation and application. The cost model of hydrogen production is calculated as follows:

$$PC = \sum_{g,p,f} \left(\frac{PCC_{p,f} NPF_{g,p,f} AF_p}{OP} + PR_{g,p,h,f} UPC_{p,f} \right) \quad (1)$$

Where PCC_{pf} is the capital cost of establishing plant type p producing product form f and UPC_{pf} is the unit production cost for product. NPF_{gpf} denotes the number of production plant . AF_p is an annuity factor for facility p, OP represents the operating period.

The fuel (FC), labor (LC) and maintenance (MC) costs associated with the delivery distance can affect the operation costs. Therefore, the total delivery cost is represented as:

$$TC = \sum_{g,g',t,f} \left(\frac{TCC_{t,f} NTF_{g,g',t,f} AF_t}{OP} \right) + FC + LC + MC \quad (2)$$

Where TCC_{tf} denotes the capital cost of transport mode t for the distribution of hydrogen in form f. $NTF_{gg'tf}$ is the number of transport mode. AF_t is an annuity factor for transport mode t.

$$NTF_{g,g',t,f} \geq Q_{g,g',t,f} \left(\frac{2Dis_{g,g',t}}{SP_t} + LUT_t \right) / (TMA \cdot TCap_{t,f}) \quad (3)$$

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$Dis_{gg't}$ is the average distance travelled by transportation mode t . SP_t denotes the average speed. LUT_t is the load/unload time. TMA_t is availability time. $TCap_{t,f}$ is the capacity .

$$FC = \sum_{g,g',t,f} \frac{FP_t}{FE_t} 2Dis_{g,g',t} Q_{g,g',t,f} / TCap_{t,f} \quad (4)$$

FP_t represents the fuel price, FET_t is the fuel economy.

$$LC = \sum_{g,g',t,f} DW_t Q_{g,g',t,f} \left(\frac{2Dis_{g,g',t}}{SP_t} + LUT_t \right) / TCap_{t,f} \quad (5)$$

Where DW_t represents driver wage, who drives transportation mode t .

$$MC = \sum_{g,g',t,f} ME_t 2Dis_{g,g',t} Q_{g,g',t,f} / TCap_{t,f} \quad (6)$$

ME_t denotes the maintenance cost for transportation mode t .

The price for the primary energy source is calculated as follow:

$$PES = \sum_{g,g,p,e} (PESAv_{g,g,p,e} (ESDIS_e Dis_{g,g} + ESCost_e)) + \sum_{g,p,e} PESI_{g,p,e} ESICost_e \quad (7)$$

Where $ESICost_e$ represents the energy source e import price, $ESCost_e$ denotes local generated energy source e price, $ESDIS_e$ is the delivery price for energy source e , and $Dis_{g,g}$ is the distance between grid point.

The storage facility can store hydrogen in different types depending on its physical form. Each storage facilities involve type, number, capacities and locations decision variable.

$$SC = \sum_{g,s,f} \left(\frac{SCC_{s,f} NSF_{g,s,f} AF_s}{OP} + USC_{s,f} ST_{g,f} \right) \quad (8)$$

$$ST_{gf} = \beta DT_{gf} \quad \forall f, g \quad (9)$$

Where SCC_{sf} denotes the capital cost of establishing storage type storing product form f , and USC_{sf} is the unit storage cost . NSF_{gsf} is the number of storage facility. AF_s is annuity factor for storage facility s . ST_{gf} is the total average inventory of product form f in grid g . β is storage holding period-average number of days worth of stock.

3 A multi-objective optimization model

The multi-objective optimization includes economic and environmental effects in the following:

$$CE_{optimal} = \min \{ \lambda_1 TotalCost + \lambda_2 TotalCO_2 \} \quad (10)$$

λ_1 and λ_2 is the weight factor.

The first objective function consists of the production (PC), storage (SC), and transportation costs (TC) and the energy source costs (PES) are included as given by:

$$TotalCost_{optimal} = \min \{ PC + SC + TC + PES \} \quad (11)$$

The total daily CO₂ emissions are associated with production plant, storage facility and transportation of HSC network as follows:

$$CO_{2optimal} = \min \{ PCO_2 + SCO_2 + TCO_2 \} \quad (12)$$

And the total CO₂ emission generated by the HSC operation (CO₂E) is given as:

$$CO_2E = CO_2EP_{g,p,f} + CO_2ET_{g,g',t,f} + CO_2ES_{g,s,f} \quad (13)$$

Where CO_2EP_{gpf} denotes the CO₂ emission generated by the production facility, $CO_2ET_{g,g',t,f}$ is the CO₂ emission generated by the t th distribution mode and CO_2ES_{gsf} is the total CO₂ emission produced by storage sites.

In above equation,

$$CO_2EP_{gpf} = PT_{gpf} CEF_{pf} \quad \forall g, p, f \quad (14)$$

$$CO_2ET_{g,g',t,f} = \sum_{g,g',t,f} 2Dis_{g,g',t} NTF_{g,g',t,f} GET_t \quad (15)$$

$$CO_2ES_{g,s,f} = \sum_{g,s,f} ST_{g,s,f} GES_f \quad (16)$$

CEF_{pf} is the CO₂ emission factor for each hydrogen technology. TEF_t is the emission factor associated to transport mode t . GES_f is the amount of CO₂ emission in the form f in storage s .

4 An optimization analysis—Dalian in China

Dalian was taking as a detail cases in this study, which was divided into 9 grids, including Zhongshan, Xigang, Shahekou, Ganjingzi, lvshunkou, Jinzhou, Wafangdian, Pulandian, Zhuanghe. Hydrogen can be produced in each grid through production facilities to satisfy its hydrogen demand. The remaining hydrogen can be transported to other grids through the transportation network. In this paper, the fuel cell vehicle is assumed to be a proton exchange membrane fuel cell vehicle. The number of fuel cell vehicles was estimated based on the year-to-year permeability of FCEV. A multi-objective optimization model was established with the lowest economic cost and environmental emission constraints.

On the basis of fully considering the energy resources of Dalian and the characteristics of each hydrogen production technology, four hydrogen production units were selected in this study: steam methane reforming (SMR), coal gasification (CG), hydro-electrolysis (WE) and biomass gasification (BG).

The optimization results in 2025 are shown in Table 1: In order to meet the hydrogen demand, 16 hydrogen production plants should be built in Dalian, and they are mainly based on SMR hydrogen production technologies. Furthermore, the production facilities optimized to be constructed in these grids are all small scales.

Table 1 Hydrogen production optimization for HSC network design 2025

Grid	Technology	Scale	Number	Amount(kg d-1)
Zhongshan	SMR	Small	1	7991
Xigang	SMR	Small	1	6403
Shahekou	SMR	Small	2	14237
Ganjinzi	SMR	Small	2	19407
Lvshunkou	SMR	Small	1	4542
Jinzhou	SMR	Small	2	14205
Wafangdian	SMR	Small	3	20411
Pulandian	SMR	Small	2	18669
Zhuanghe	SMR	Small	2	18406

It can be also seen from the Table 1 that each grid has its own hydrogen production plant, which can completely satisfy their hydrogen demand. Consequently, there is no hydrogen transported between grids. Furthermore large-amount production facilities are optimized to be constructed in Wafangdian grid.

The optimization results of 2030 in Table 2 and Table 3 show that hydrogen production plants need to be constructed in Shahekou and Pulandian grid of Dalian, . With the increase of hydrogen demand, the production plants are mostly medium scale. The result is obviously different from the plans of 2025, which is mainly small scale plants. Furthermore, considering the environmental factors, the selection of SMR hydrogen production technology is the main hydrogen production technology in all the grids. The reason is that CG has high CO₂ emission factor, although it can be produced easily from economic viewpoints. Additionally, hydrogen transport facility is mainly tank truck. The amount of hydrogen transportation are obviously increased and the number of transport facilities are 8 in all grids. This means that with the increase of hydrogen demand, the comprehensive evaluation of economic and environmental can be obtained through hydrogen allocation between each grids.

Table 2 Hydrogen production optimization for HSC network design 2030

Grid	Technology	Scale	Number	Amount(kg d-1)
Shahekou	SMR	Medium	1	142853
Pulandian	SMR	Medium	1	93989

Table 3 Hydrogen Transportation optimization for HSC network design 2030

From	To	Type	Number	Amount(kg d-1)
Shahekou	Zhongshan	Tank truck	1	16155
	Xigang	Tank truck	1	12944
	Ganjingzi	Tank truck	1	39235
	Lvshunkou	Tank truck	1	8326
	Wafangdian	Tank truck	2	37410
Pulandian	jinzhou	Tank truck	1	26037
	zhuanghe	Tank truck	1	33736

The optimization results of 2035 are shown as Table 4 and Table 5: in order to meet the hydrogen demands, four hydrogen production units should be constructed in Dalian. And Shahekou, Ganjingzi, Jinzhou and Pulandian grids are suitable for the construction of medium-scale hydrogen production units. The hydrogen production technologies are mainly SMR technologies.

Table 4 Hydrogen production optimization for HSC network design 2035

Grid	Technology	Scale	Number	Amount(kg d-1)
Shahekou	SMR	Medium	1	104874
Ganjingzi	SMR	Medium	1	71305
Jinzhou	SMR	Medium	1	101931
Pulandian	SMR	Medium	1	117621

It can be also seen that the hydrogen transportation and allocation between the grids can not satisfy the increasing hydrogen demand. Therefore the number of hydrogen transportation units are increased compared with that in 2030. Hydrogen transport facility is mainly tank truck which is consistent with 2030. The hydrogen can be transported from Shahekou grid, Ganjinzi grid, Jinzhou grid and Pulandian grid to other areas. In particular, the amount of hydrogen which transported from Jinzhou grid to Wafangdian grid is the largest.

Table 5. Hydrogen Transportation optimization for HSC network design 2035

From	To	Type	Number	Amount(kg d-1)
Shahekou	Zhongshan	Tank truck	1	26994
	Xigang	Tank truck	1	21626
	Ganjingzi	Tank truck	1	4081
	Lvshunkou	Tank truck	1	4081
	Ganjingzi	Lvshunkou	Tank truck	1
Jinzhou	Wafangdian	Tank truck	1	58427
Pulandian	Wafangdian	Tank truck	1	4081
	Zhuanghe	Tank truck	2	56368

5 Conclusion

In this paper, a multi-optimization model operating as time processes (2025-2035) for hydrogen infrastructure plan has been proceeded in Dalian, China. The two objectives considered were cost and environmental impact. Four types of technologies to produce hydrogen were evaluated, namely steam methane reforming (SMR), coke oven gas hydrogen production (COG), hydro-electrolysis (WE) and biomass gasification (BG). From the economic and environmental view point, this study showed that, SMR are mostly selected and applied in hydrogen production plant. While Shahekou and Pulandian grids are suitable for the construction of hydrogen production units. Meanwhile, with the increase of hydrogen demand, the multi-objective optimization can be obtained through hydrogen allocation between each grids. Additionally, tank trucks are the main modes of hydrogen transportation.

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