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The future of hydrogen infrastructure for fuel cell vehicles in China and a case of application in Beijing

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Abstract

In the paper the future of hydrogen infrastructure for fuel cell vehicles in China is discussed. It is believed that, China should make different plans of hydrogen infrastructure during different periods and in different regions. Besides, a case of application in Beijing is studied to find the best plan for Beijing to develop hydrogen infrastructure in 2008 when Olympic Games will be held. In the study of that case, 11 feasible plans are designed at first according to the current technology of production, storage and transportation of hydrogen in China. After that, the energy, environmental and economic performances of these plans are evaluated with "life cycle assessment". Finally, the best plan in the case is picked out from all the aspects of energy, environment and economy.

Keywords: Hydrogen infrastructure; Fuel cell vehicles; Life cycle assessment

1. Introduction

In 50 years in the future, the total amount of automotive vehicles in China will be multiplied by 15 times as many as the current amount (see Table 1). It will increase the demand to liquid fuels and cause serious environmental pollution. To solve the problem, developing fuel cell vehicles will be a promising solution because fuel cell vehicles, fueled by hydrogen, can realize nearly zero emissions.

The hydrogen infrastructure is prerequisite to the development of fuel cell vehicles. It is very important to study the production, storage and transportation of hydrogen with current technologies. In China, the main technologies of producing hydrogen include natural gas steam reforming (NGSR), coal gasification, and water electrolysis, and hydrogen can be stored and transported in three manners: hydrogen gas, liquid hydrogen and hydride.

2. The future of hydrogen infrastructure in China

In order to build up the hydrogen infrastructure reasonably, the goals of development of fuel cell vehicles must be considered on the situation of resources, environment, energy supply and technical economy in China. In the near future, the purpose of development of fuel cell vehicles in China is to solve the problem of pollution in big cities. Besides, there will be other problems to be solved, such as improvement of the efficiency of energy utilization and development of independent intellectual property.

However, it is impossible for China to establish unified hydrogen infrastructure for fuel cell vehicles throughout the country. This problem has to be studied in view of "time" and "space".

From the aspect of time, the appropriate hydrogen infrastructure should change with the energy structure of China and the technologies of producing, storing and transporting hydrogen. Coal dominates the energy structure of China, so the production of hydrogen via coal is more suitable than that via other primary energy sources, in spite of its low efficiency in utilization of energy and unsatisfactory environmental performance. With the change of the energy

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Table 1
Numbers of automobiles in China ($\times 10,000$)

Predicted by	Time scale						
	2000	2005	2010	2015	2020	2030	2050
Tsinghua University	1600	2000	3000	4500	6000	10,000	30,000
SETC[a]		2918–2315	3100–3315	4435–4719			
Tianjin Automotive Center		2271	3434				
Tongji University		2900–3500		5480–6970			
Shanghai Jiao Tong University		3300	6930				
CNAIC[b]		1916	3057		6041		In 2043, 27,900

[a] SETC: State Economic and Trade Commission, People's Republic of China.

[b] CNAIC: China National Automotive Industry Corporation.

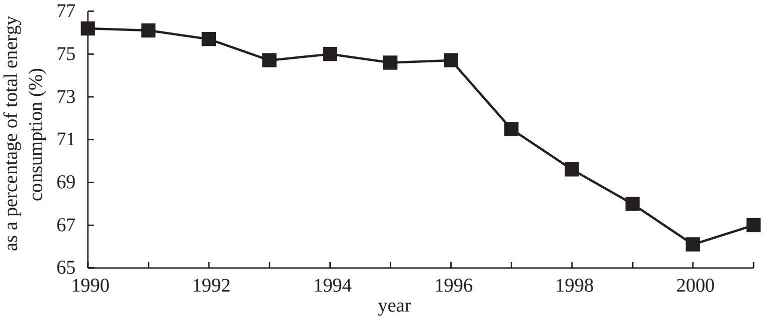

Fig. 1. The proportion of coal in energy structure of China (1990–2001).

structure, the proportion of coal will decrease (see Fig. 1) [1], and the proportion of hydrogen production via other primary energy sources (natural gas, renewable energy, etc.) will increase simultaneously. On the other hand, the progress of technologies of producing, storing and transporting hydrogen will also change the hydrogen infrastructure. For example, the energy density of liquid hydrogen is higher than that of hydrogen gas, but liquid hydrogen is not always better in storing and transporting hydrogen than hydrogen gas, because the energy consumption in liquefaction is enormous. If the energy consumption in liquefaction is reduced greatly, liquid hydrogen will probably become the best way of storing and transporting hydrogen.

From the aspect of space, the appropriate hydrogen infrastructure will be different in different regions in China. For example, in East China where renewable energy (waterpower, wind energy, etc.) is not rich, production of hydrogen via fossil fuel will be the first choice. But in West China where waterpower and wind energy are abundant, production of hydrogen via renewable energy will be the first choice. On a higher level, the abundant renewable energy of West China can be converted into hydrogen energy by water electrolysis, and then transported to East China, where the demand of energy is great.

Besides, the future of hydrogen infrastructure for fuel cell vehicles in China will be discussed in detail according to the variety of primary energy sources.

2.1. *Coal*

The production and consumption of coal of China are the largest in the world. Coal dominates about 60% of primary energy consumption in China [1]. The resource of coal in China is very abundant, but the distribution of coal mines is unbalanced, most of which are located in Shanxi, Inner Mongolia, Shaanxi, Guizhou, Ningxia and Anhui Provinces (see Fig. 2) [2]. In the planning of hydrogen infrastructure, these features have to be considered carefully.

There are many ways to get hydrogen via coal.

The simplest way is to electrolyze water with the electricity generated from coal. However, its energy consumption is too high. Therefore, this way to get hydrogen is only practical in the regions where no other ways are convenient.

In the near term, hydrogen can be obtained from discharge gas and purge gas by pressure swing absorption or low-temperature separation in ammonia synthesis and methanol synthesis using coal as raw materials. For example, hydrogen consists up to 50–60% of discharge gas from ammonia synthesis plants, and 180–250 Nm^3 of discharge gas can be obtained per ton ammonia [2]. It is a practical and economical way to gain hydrogen in some areas, such as Shanghai, where the estimated amount of recoverable hydrogen is 3×10^9 $\mathrm{Nm}^3/\mathrm{yr}$ [2].

In another respect, methanol can be synthesized, stored and transported easily. And then, hydrogen can be produced

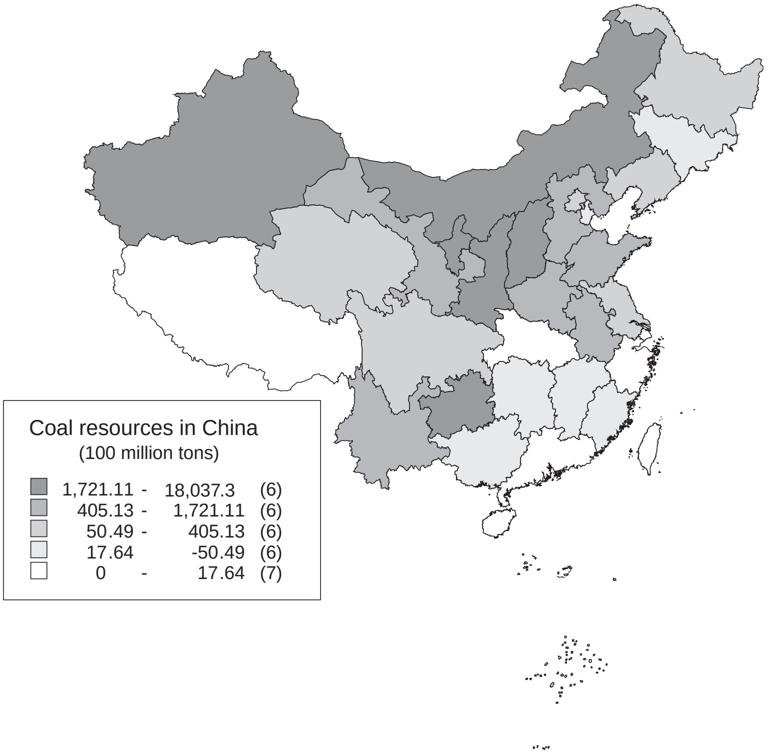

Fig. 2. The distribution of coal mines in China.

via methanol reforming in refueling stations or onboard. At present, the capacity of production of methanol via coal has already become rather great. For example, the annual yield of methanol in Shanxi Province is 1.6×10^5 ton [2]. Besides, great progress in the development of methanol reformer has been realized in China. Therefore, this way to obtain hydrogen is also feasible.

In a long run, producing hydrogen directly via coal gasification will become the most important way in China. However, it must be polygeneration process with the production of electricity, chemical products, liquid fuels and together with hydrogen. Although the main energy sources in the world has changed from coal to petroleum, and then from petroleum to natural gas, the development of polygeneration technology taking coal gasification as the core makes it possible that coal will be the linkage from the times of coal to the times of hydrogen energy.

2.2. Natural gas

The total reserve of natural gas is 39 trillion Nm^3 in China [3]. There are many technologies to produce hydrogen via natural gas, such as steam methane reform (SMR), partial oxidization (POX), and auto thermal reform (ATR), which can be applied in central factory or refueling stations.

However, large-scale gas fields are mostly located in Northwest China, while the current infrastructure for natural gas transportation and distribution is so weak that hinders large-scale utilization of natural gas. The 10th Five-Year Plan of China will carry out the West–East Natural Gas Transmission Project to transport natural gas from Xinjiang Uygur Autonomous Region to Shanghai. This makes it possible to produce hydrogen from natural gas in the areas along the line of West–East Natural Gas Transmission Project besides the habitats of natural gas in the near and medium term. In the long term, however, it is impractical to produce hydrogen from natural gas in China for the rarity of natural gas.

2.3. Renewable energy

Renewable energy such as waterpower, solar energy, wind energy and biomass energy are clean and sustainable sources for hydrogen.

Waterpower is very abundant in China and exploitable waterpower is 3.78 hundred million kilowatt ranking the first in the world [3]. However, the current utilization of waterpower is only 9.1% of total amount [3]. Waterpower is mainly located in southwest, northwest and central of China, therefore, hydrogen can be produced by electrolyzing water with electricity from waterpower in these areas. This plan is also an initiative to a new method to storage redundant waterpower as hydrogen energy.

Table 2
The matrix of time and space for development of hydrogen infrastructure in China

Area	Time		
	Near-term 2002–2010	Medium-term 2010–2020	Long-term 2020–2030
North China: Beijing East China: Shanghai West China: Chengdu Central China: Taiyuan	**Beijing Case Study**		

Solar cell is one of the most promising technologies of power generation. China has abundant resources of solar energy. The annual solar radiation is more than 0.6 MJ/cm^2 in 2/3 of country lands [4]. With the development of the technology of solar energy utilization, the production of hydrogen by electrolyzing water with electricity from both solar energy and waterpower is an ideal plan in the long term.

In addition, hydrogen can also be produced via wind or geothermal energy where they are abundant.

In summary, it is necessary that China make different plans of hydrogen infrastructure during different periods and in different areas (taking some cities as representatives) according to the change of energy structure of China and the development of technologies of producing, storing and transporting hydrogen. Therefore, a matrix of time and space for development of hydrogen infrastructure in China can be given (see Table 2). Researchers should make specific plan of hydrogen infrastructure in specific location of the matrix, which will instruct the development of hydrogen infrastructure for fuel cell vehicles in China comprehensively, scientifically and objectively.

3. Beijing case study

In consideration of the 2008 Olympic Games and the fuel cell vehicles commercialization process for China [5], It is believed that the most possible time and space for the earliest commercialization of fuel cell vehicles in China are 2008 and Beijing. Therefore, Beijing is taken as the specific case in the paper to study what will be the best plan of hydrogen infrastructure for fuel cell vehicles. The location of the case in the matrix of time and space for development of hydrogen infrastructure is marked black (see Table 2).

3.1. Assessment tool

The tool to evaluate plans of hydrogen infrastructure in the paper is “life cycle assessment” (LCA) from environmental management [6]. LCA is a new, comprehensive and useful method to evaluate the energy, environmental and economic performances of activities, productions or processes from “cradle” to “grave”. Generally, LCA includes four steps: goal and scope definition, inventory analysis, impact assessment and improvement assessment.

3.2. Plan design

The hydrogen infrastructure for fuel cell vehicles include four spatially independent subsystems in the light of the order of hydrogen flow: the production subsystem (site and equipments of hydrogen production), the transportation subsystem (equipments of hydrogen transportation), the refueling subsystem (hydrogen refueling stations) and the utilization subsystem (fuel cell vehicles).

According to different technologies of producing, storing and transporting hydrogen [7–15], and the appropriate equipments and their matching [16], 11 feasible plans are designed (see Table 3; in the refueling and utilization subsystems, only the manners of storing and utilizing hydrogen are listed).

3.3. Goal and scope definition

(1) *Goal*: It is supposed that the 11 plans will be put into practice in 2008 Beijing Olympic Games, and 1 kg H_2 is taken as the unit to evaluate the energy, environmental and economic performances of the 11 plans in 20 years (life cycle of fuel cell vehicles [17]) from exploitation of raw material to utilization of hydrogen in fuel cell vehicles.

(2) *Scope*: According to the different sites where hydrogen is produced, the plans can be classified into three kinds: production in central factory (Plans 1–8), production on refueling stations (Plan 9 and 10), and reforming onboard (Plan 11). The system boundaries for every kind of plan are shown as Figs. 3–5.

3.4. Data collection for inventory analysis

Inventory analysis is the key step of LCA. In this step, many data need to be collected, such as material consumption, energy consumption factors and pollutant emission factors of all kinds of equipments, infrastructure and technologies; energy consumption factors and pollutant emission factors of raw material production; pollutant emission factors of electricity (secondary energy source) production, etc. How to get accurate and credible data coincided with the situation of China is very important and difficult in LCA. The following three principles will be taken into consideration during collection of data.

- The limitation of time and space for the technologies in the plans are considered, that is, 2008 and Beijing.
- The main data should come from China, and the data from other countries are taken as useful supplement.
- The simplification and editing criteria of data should be based on the impact of the data on results.

Table 3
11 plans of hydrogen infrastructure for fuel cell vehicles

Plan no.	Production subsystem	Transportation subsystem	Refueling subsystem	Utilization subsystem
1	Central factory: NGSR	Hydrogen gas cylinder by truck	Hydrogen gas cylinder	Hydrogen gas
2	Central factory: NGSR	Hydrogen gas by pipeline	Hydrogen gas tank	Hydrogen gas
3	Central factory: NGSR	Liquid hydrogen tank by truck	Liquid hydrogen tank	Liquid hydrogen
4	Central factory: NGSR	Hydride cylinder by truck	Hydride cylinder	Hydride
5	Central factory: coal gasification	Hydrogen gas cylinder by truck	Hydrogen gas cylinder	Hydrogen gas
6	Central factory: coal gasification	Hydrogen gas by pipeline	Hydrogen gas tank	Hydrogen gas
7	Central factory: coal gasification	Liquid hydrogen tank by truck	Liquid hydrogen tank	Liquid hydrogen
8	Central factory: coal gasification	Hydride cylinder by truck	Hydride cylinder	Hydride
9	Refueling stations: water electrolysis (industrial electricity)		Hydrogen gas tank	Hydrogen gas
10	Refueling stations: water electrolysis (valley electricity)		Hydrogen gas tank	Hydrogen gas
11	Central factory: methanol synthesis via natural gas	Methanol tank by truck	Methanol tank	Methanol reforming onboard

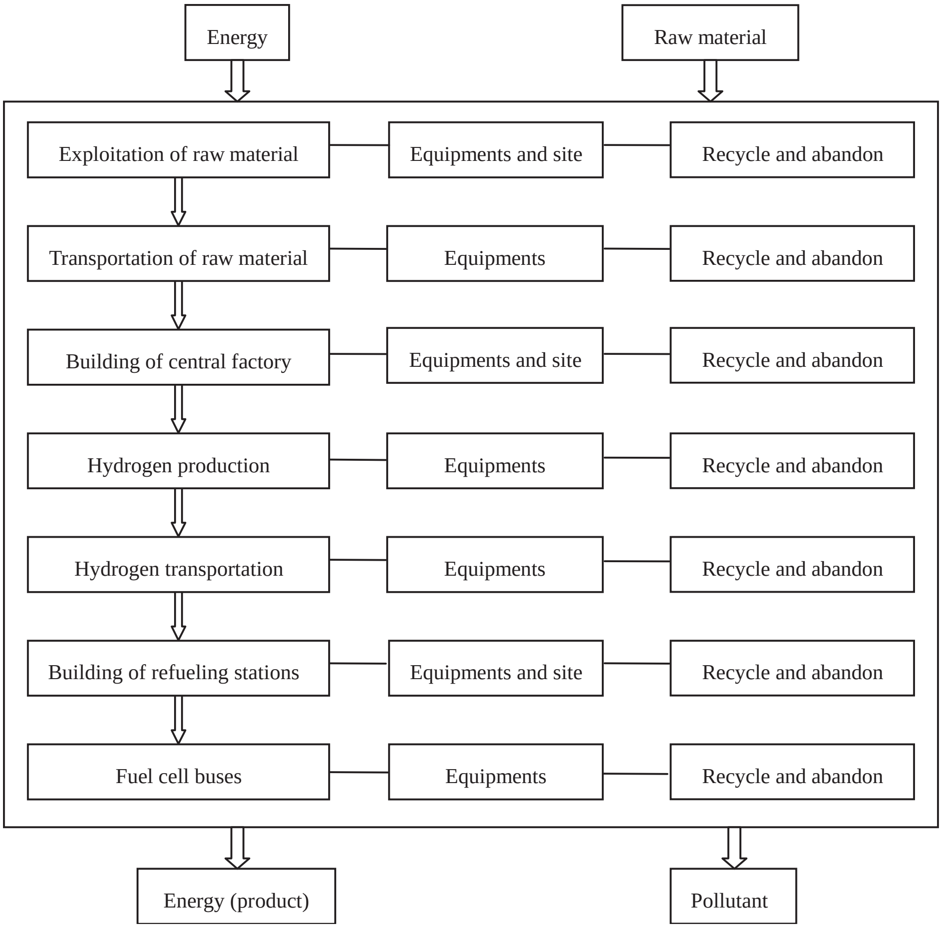

Fig. 3. System boundaries for Plans 1–8.

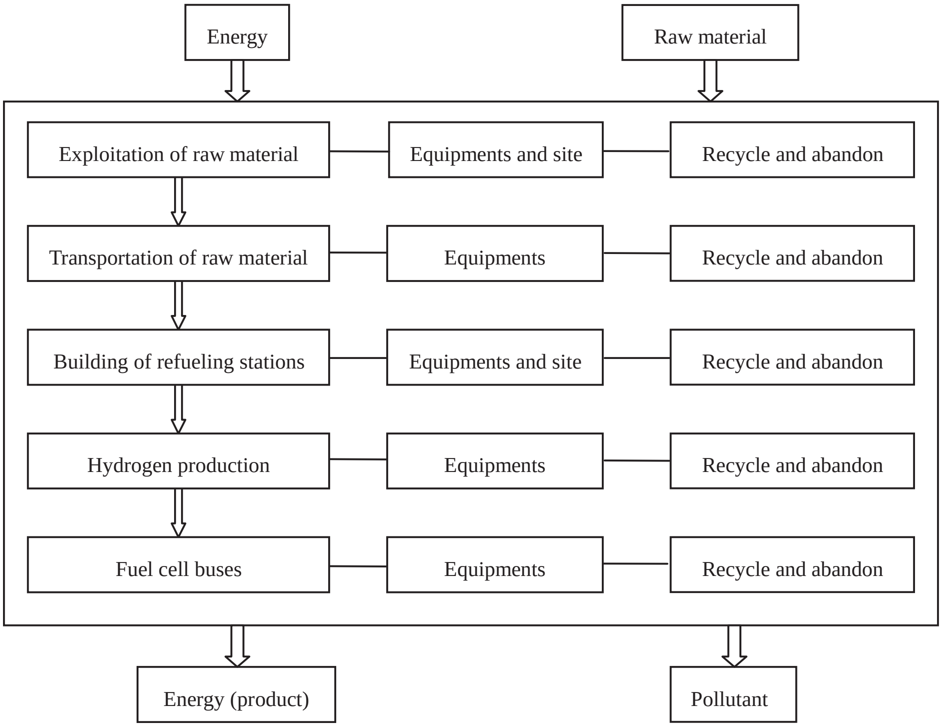

Fig. 4. System boundaries for Plans 9–10.

The scale of upstream subsystems are determined by downstream subsystems, so the collection of data should take the order from downstream subsystem to upstream subsystem, as shown in the following part.

(1) *The utilization subsystem*: The fuel cell vehicles can be classified as fuel cell cars, fuel cell buses, and so on. In view of the limit of cost and hydrogen storage capacity onboard, fuel cell buses are more advantageous than fuel cell cars. It is believed that only fuel cell buses can be commercialized in the market of China in the near future, so the fuel cell buses are chosen as the utilization subsystem of the plans [17].

From the growth rate [5] and the current amount of buses in Beijing [18], and the supposition that 10% of new buses are fuel cell buses [7], it is concluded that the number of fuel cell buses in Beijing will be 500 in 2008.

(2) *The refueling subsystem*: One fuel cell bus consumes 120 Nm^3H_2/day, and the storage capacity onboard of one fuel cell bus is 496 Nm^3H_2 [17]. From the supposition that there are four hydrogen refueling stations in Beijing and the period of one station consuming all hydrogen is 4 days, it is calculated that the storage capacity of one station is $60,000\ Nm^3H_2$.

(3) *The transportation subsystem*: One fuel cell bus consumes 120 Nm^3H_2/day, and the number of fuel cell buses is 500, then the transportation capacity is $60,000\ Nm^3H_2$ (except the leakage of hydrogen). It is supposed that the central factory is located in the outskirts of Beijing and 50 km far from the hydrogen refueling stations for Plans 1–8 and 11.

(4) *The production subsystem*: From the transportation capacity stated above and the leakage of hydrogen, the production capacity of hydrogen in every plan can be calculated. The advanced technologies in China will be adopted in all processes of hydrogen production (for Plan 11, methanol is produced in this subsystem).

3.5. LCA of energy

(1) *Energy consumption inventory*: In order to assess the energy performances of the plans, the paper must get the energy consumption inventory first.

According to the data of material consumption, recycle process, production process and ending process (compression or liquefaction of hydrogen) and related energy consumption factors in every subsystem, the energy consumption in every subsystem can be gotten. Then the total energy consumption in every plan can be calculated (see Table 4).

(2) *Impact assessment*: Generally, the total energy efficiency (η_0) is the criterion for evaluating the energy performance of a plan. Its definition is

$$\eta_0 = W_{\text{effective}}/W_{\text{total}}. \quad (1)$$

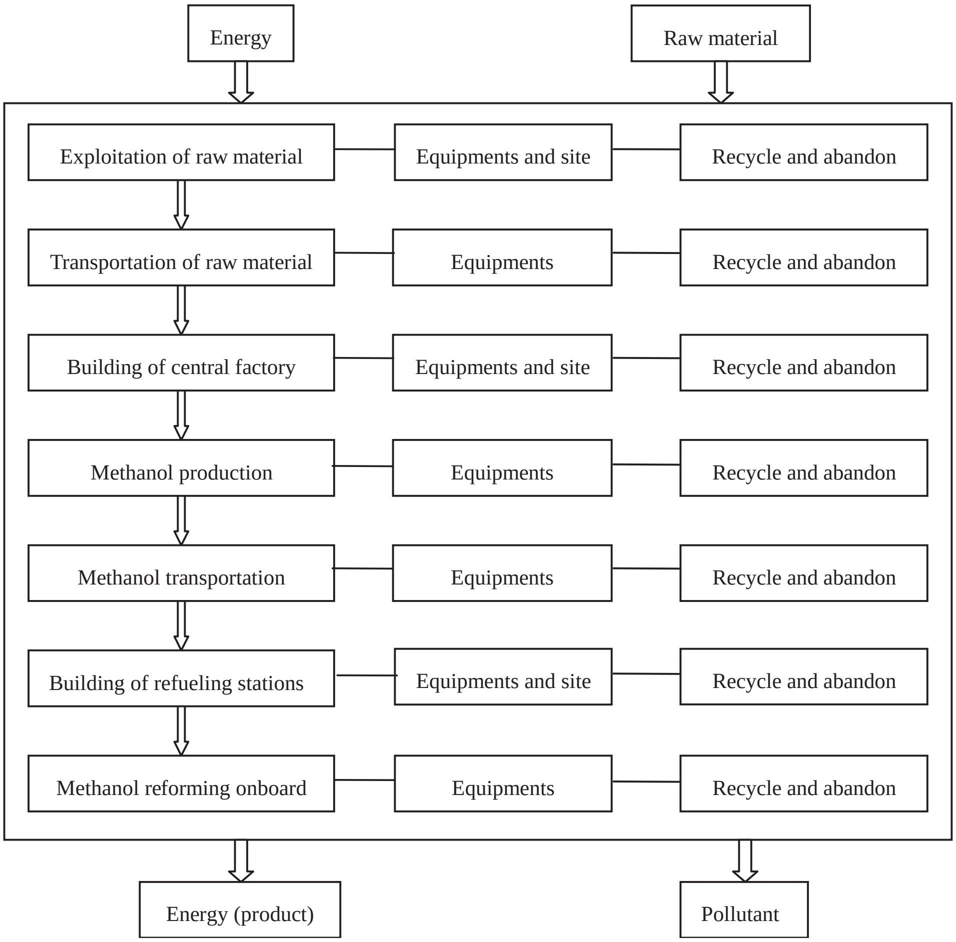

Fig. 5. System boundaries for Plan 11.

Table 4
The energy consumption inventory (MJ/kg H_2)

Plan no.	1	2	3	4	5	6	7	8	9	10	11
Production	173.55	165.58	212.49	164.02	154.80	150.58	193.87	145.94	674.62	674.63	264.29
Transportation	5.08	2.25	0.76	1.78	5.08	2.25	0.76	1.78	0.00	0.00	0.51
Refueling	0.60	2.92	0.47	51.22	0.60	2.92	0.47	51.22	2.92	2.92	0.01
Utilization	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93
Total	185.17	176.68	219.66	222.95	166.41	161.68	201.03	204.87	683.47	683.48	270.74

In Eq. (1), $W_{\mathrm{effective}}$ is the effective energy output when 1 kg H_2 is fueled to the fuel cell bus, and W_{total} is the total energy consumption to supply 1 kg H_2.

Because the energy efficiency of fuel cell bus is 40% [19] in the paper and LHV of H_2 is 120 MJ/kg [9],

$$W_{\mathrm{effective}} = 120\ \mathrm{MJ} \times 40\% = 48\ \mathrm{MJ}. \quad (2)$$

Then, the total energy efficiency of every plan can be gotten (see Fig. 6).

From Table 4 and Fig. 6, the major conclusions are:

(a) The total energy efficiency of Plan 6 is the highest (30%), and the total energy efficiencies of Plans 9 and 10 are the lowest (7%). As a whole, the total energy efficiencies of all plans are not high (7–30%).
(b) The rank of four methods of producing hydrogen in energy performance is (from best to worst): coal

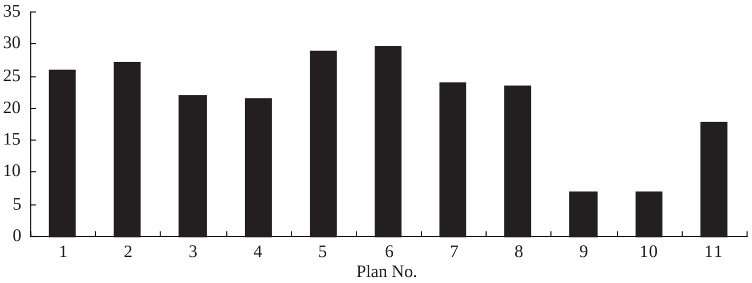

Fig. 6. The total energy efficiency η_0 (%).

Table 5
Sensitivity analysis of energy performances (change of η_0, %)

Plan no.	1	2	3	4	5	6	7	8	9	10	11
A	+17.29	+18.27	+14.58	+13.85	+14.69	+15.18	+12.18	+11.53	+19.58	+19.58	+18.20
B	+5.70	+5.99	+4.88	+4.66							
C									+220.14	+220.13	

gasification, NGSR, methanol reforming onboard, and water electrolysis.

(c) The rank of four methods of storing and transporting hydrogen in energy performance is (from best to worst): hydrogen gas by pipeline, hydrogen gas by cylinder, liquid hydrogen, and hydride. The energy performance of storing and transporting hydrogen as liquid hydrogen or hydride is not good because there is much energy consumption in the processes of liquefaction of hydrogen and releasing and activation of hydride.

(3) *Improvement assessment*:

(a) Control analysis: From inventory analysis and impact assessment, it is concluded that: the energy consumption of storing and transporting hydrogen in form of liquid hydrogen and hydride is enormous, so the two methods are not practicable unless the energy consumption of liquefying hydrogen and activating hydride can be reduced considerably.

(b) Sensitivity analysis: In order to find the key parameters that impact results greatly, the paper will analyze change of original results corresponding to the change of a parameter when other parameters keep constant.

The following three parameters are changed in sensitivity analysis: A. The efficiency of production subsystem increases 20% in every plan. B. Avoided operation (excess steam generated by NGSR is exported to another facility [20]) is taken in Plans 1–4. C. Water is electrolyzed with the electricity from renewable energy in Plans 9 and 10.

The results of sensitivity analysis are listed in Table 5 and the major conclusions are:

- The efficiency of production subsystem impacts the total energy efficiency greatly because the energy consumption of production subsystem occupies most of the total energy consumption, which shows improving the technologies of production subsystem is the main direction to reduce the total energy consumption.
- Avoided operation can improve the total energy efficiencies of Plans 1–4 about 5%.
- Electrolyzing water with the electricity from renewable energy can improve the total energy efficiencies of Plans 9 and 10 twice.

3.6. LCA of environment

(1) *Pollutant emission inventory*: In order to assess the environmental performances of the 11 plans, the paper must get the pollutant emission inventory first.

According to the data of material consumption, energy consumption, recycle process, production process and ending process (compression or liquefaction of hydrogen) and relative pollutant emission factors in every subsystem [21], the pollutant emissions in every subsystem can be gotten. Then the total emissions of pollutant in every plan can be calculated (see Table 6).

(2) *Impact assessment*: According to the pollutant emission inventory, the effect-oriented models established by the Center of Environmental Science (CML) of Leiden University are used to evaluate the environmental performances of the 11 plans [22].

Table 6
The pollutant emission inventory (kg/kg H_2)

Plan no.		1	2	3	4	5	6	7	8	9	10	11
Waste gas	SO_2	0.062	0.053	0.160	0.182	0.114	0.116	0.216	0.236	0.616	0.616	0.083
	CO_2	16.659	15.761	26.573	28.222	23.605	23.748	33.846	35.283	59.532	59.537	21.244
	NO_x	0.059	0.048	0.103	0.114	0.076	0.071	0.121	0.132	0.316	0.316	0.074
	CO	0.022	0.020	0.019	0.023	0.016	0.014	0.013	0.017	0.020	0.020	0.021
	CH_4	0.072	0.072	0.074	0.072	0.000	0.000	0.000	0.000	0.000	0.000	0.110
	Dust	0.224	0.188	0.623	0.706	0.427	0.434	0.838	0.914	2.475	2.475	0.275
Waste water		1011	822	2950	3350	1994	2014	3989	4359	11882	11883	1277
Solid waste		4783	3884	13994	15880	9454	9546	18930	20672	56340	56343	6011

Effect-oriented models characterize the environmental effects of all kinds of pollutants as 18 classified environmental effects and 10 of them can be calculated already (global warming, human toxicity, photochemical oxidation, acidification, eutrophication, ozone layer depletion, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, and abiotic depletion). The calculation includes three steps:

(a) Characterization: One classified environmental effect corresponds to some kinds of pollutants. Choose a specific pollutant as the reference pollutant and definite its characterization factor as 1. And then give the characterization factors of other pollutants by comparing their contribution to the classified environmental effect with that of the reference pollutant.
(b) Normalization: Multiply the emission of every pollutant by its characterization factor for one classified environmental effect and add the product together, then multiply the sum by a specific normalization coefficient (reciprocal value of the annual emission of the reference pollutant in a specific area), finally the standard index of the classified environmental effect can be gotten. Repeat the above steps, the standard indexes of other classified environmental effects can also be gotten.
(c) Weighting: Give a weight to every classified environmental effect and convert the standard indexes of all classified effects into a total index of environmental effect of a plan by weighting method.

In the paper, there are five classified environmental effects (global warming, human toxicity, photochemical oxidation, acidification, eutrophication) corresponding to the six kinds of waste gas in the pollutant emission inventory (see Table 6). The emissions of waste water and solid waste are considered individually because they cannot be converted into classified environmental effects without the specific inventory of ingredients.

The paper can get the standard indexes of these classified environmental effects of every plan by the above steps (see Fig. 7; reference pollutants, normalization coefficients and characterization factors see Table 7 [22]). The third step is skipped because there is still not a recognized method of weighting in the world.

From Table 6 and Fig. 7, the major conclusions are:

(a) The standard indexes of classified environmental effects and the emissions of waste water and solid waste of Plan 2 (NGSR + pipeline) are minimum, so Plan 2 is the best plan in environmental performance.
(b) The standard indexes of classified environmental effects and the emissions of waste water and solid waste of Plans 9 and 10 (water electrolysis in the refueling stations) are maximum, so Plans 9 and 10 are the worst plans in environmental performance. In conventional opinion, the environmental performance of water electrolysis should be the best, but the paper gets the contrary conclusion because the angle of conventional opinion and that of the paper are different. The conventional opinion only reviews the process of water electrolysis, but the paper reviews all the life cycle including the production of electricity used in electrolysis. Although the pollutant emissions of the process of water electrolysis is nearly zero, the pollutant emissions of the process from primary energy sources to electricity is enormous because coal is the dominating primary energy source for electricity in China. In view of the whole life cycle, the environmental performance of water electrolysis is not as good as expected because it only transfers the pollutant emissions from the process of water electrolysis to the process of electricity production.
(c) The rank of four methods of producing hydrogen in environmental performance is (from best to worst): NGSR, methanol reforming onboard, coal gasification, and water electrolysis.
(d) The rank of four methods of storing and transporting hydrogen in environmental performance is (from best to worst): hydrogen gas by pipeline, hydrogen gas by cylinder, liquid hydrogen, and hydride. In concept of life cycle assessment, the more energy a plan consumes, the more pollutant emissions it brings.

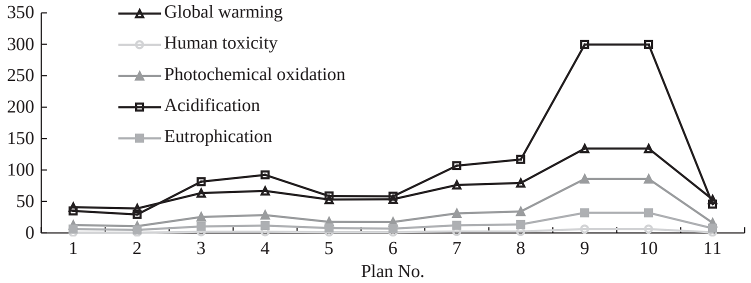

Fig. 7. The standard indexes of classified environmental effects (1E-14 year/kg H_2).

Table 7
Reference pollutants, normalization coefficients and characterization factors of classified environmental effects

Classified environmental effect	Reference pollutant	Normalization coefficient (1E-14 year/kg)	Pollutant	Characterization factor
Global warming	CO_2	2.25	CO_2	1.000
			CH_4	21.000
Human toxicity	1,4-DB	2.01	SO_2	1.200
			NO_x	0.780
			CO	0.012
			Dust	0.820
Photochemical oxidation	C_2H_2	2200.00	SO_2	0.048
			NO_x	0.028
			CO	0.027
			CH_4	0.006
Acidification	SO_2	334.00	SO_2	1.200
			NO_x	0.500
Eutrophication	PO_4^{3-}	774.00	NO_x	0.130

(3) *Improvement assessment*:

(a) Control analysis: From inventory analysis and impact assessment, it is concluded that: CO_2 is the main pollution source of global warming, and SO_2 is the main pollution source of acidification and photochemical oxidation, and the effects of global warming, acidification, and photochemical oxidation are more serious than the effects of eutrophication and human toxicity, so CO_2 and SO_2 are the main pollutants necessary to be dealt with first.

(b) Sensitivity analysis: The following three parameters are changed in sensitivity analysis: A. The efficiency of production subsystem increases 20% in every plan. B. Avoided operation is taken in Plans 1–4. C. Water is electrolyzed with the electricity from renewable energy in Plans 9 and 10.

The results of sensitivity analysis are listed in Table 8 and the major conclusions are:

- The environmental performances of Plans 9 and 10 are more sensitive to the efficiency of production subsystem than those of other plans.
- Avoided operation can improve the environmental performances of Plans 1–4, especially those of Plans 1 and 2.
- Electrolyzing water with electricity from renewable energy can improve the environmental performances of Plans 9 and 10 about 60%.

3.7. LCA of economy

(1) *Cost inventory*: According to the data of raw material, equipments, infrastructure, energy consumption, labor cost, depreciation, etc. in every subsystem, the material cost, capital cost and O&M cost, that is the cost of the subsystem, can be estimated. From the cost of every subsystem (except the utilization subsystem), the hydrogen cost of every plan can be gotten (see Table 10). Fig. 8 reflects the proportion of every subsystem in the hydrogen cost of every plan. The correlative assumptions of economy are listed in Table 9.

Table 8
Sensitivity analysis for environmental performances (change of standard indexes of classified environmental effects, %)

Plan no.		1	2	3	4	5	6	7	8	9	10	11
G[a]	A	−12.27	−12.91	−8.12	−7.46	−9.93	−9.87	−7.09	−6.60	−15.65	−15.65	−4.01
	B	−15.24	−16.04	−10.09	−9.26							
	C									−65.72	−65.72	
H[a]	A	−2.40	−2.87	−0.95	−0.82	−2.14	−2.17	−1.22	−1.08	−15.52	−15.52	−2.86
	B	−45.78	−54.58	−18.17	−15.60							
	C									−65.17	−65.17	
P[a]	A	−4.81	−5.62	−2.41	−2.08	−3.65	−3.72	−2.24	−2.00	−15.20	−15.20	−5.60
	B	−31.19	−36.47	−15.62	−13.48							
	C									−63.83	−63.83	
A[a]	A	−3.57	−4.25	−1.56	−1.34	−2.13	−2.17	−1.22	−1.08	−15.34	−15.34	−4.07
	B	−39.40	−46.98	−17.19	−14.76							
	C									−64.45	−64.45	
E[a]	A	−4.42	−5.44	−2.58	−2.27	−1.74	−1.88	−1.12	−1.00	−14.98	−14.98	−5.02
	B	−24.02	−29.54	−14.01	−12.33							
	C									−62.93	−62.93	

[a] G, H, P, A, E represent global warming, human toxicity, photochemical oxidation, acidification, eutrophication individually.

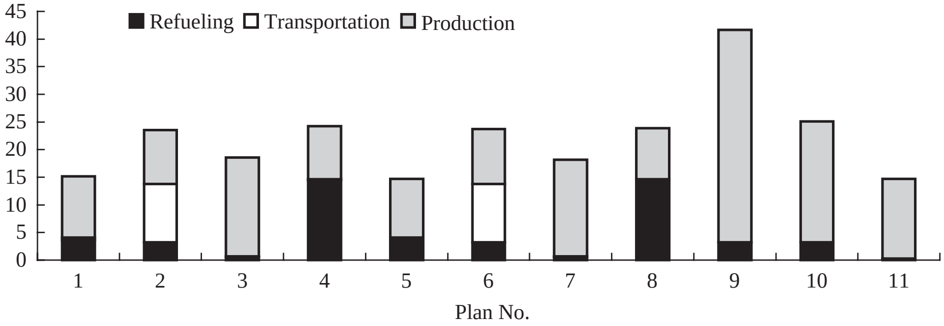

Fig. 8. The constitution of hydrogen cost (yuan RMB/kg H_2).

Table 9
Assumptions of economy

Item	Price (yuan RMB)
Industrial electricity (kW/h)	0.6
Valley electricity (kW/h)	0.3
Water (ton)	2.9
H_2SO_4 (ton)	600
Natural gas (Nm^3)	1.4
Coal (ton)	270
Diesel fuel (L)	2.8
Steel (ton)	2600
Cement (ton)	355
Labor (man/month)	1500

(2) *Impact assessment*: From Table 10 and Fig. 8, the major conclusions are:

(a) The hydrogen cost of Plan 11 is the lowest and material cost accounts for the major part. The hydrogen cost of Plan 9 is the highest and material cost (electricity used in electrolysis) accounts for the major part.

(b) The rank of four methods of producing hydrogen in economic performance is (from best to worst): methanol reforming onboard, coal gasification, NGSR, and water electrolysis.

(c) The rank of four methods of storing and transporting hydrogen in economic performance is (from best to worst): hydrogen gas by cylinder, liquid hydrogen,

Table 10
The hydrogen cost inventory (yuan RMB/kg H_2)

Plan no.	1	2	3	4	5	6	7	8	9	10	11
Material	6.45	6.45	6.60	6.41	1.28	1.28	1.31	1.28	34.67	17.88	9.85
Capital	6.43	15.83	4.20	9.32	8.29	17.69	6.10	11.17	5.94	6.36	2.28
O&M	2.30	1.27	7.76	8.49	5.16	4.75	10.78	11.42	1.04	0.82	2.55
Total	15.18	23.56	18.56	24.22	14.73	23.73	18.20	23.87	41.66	25.07	14.68

Table 11
Sensitivity analysis for economic performances (change of hydrogen cost, %)

Plan no.	1	2	3	4	5	6	7	8	9	10	11
A	−7.59	−5.47	−5.93	−4.41	−1.45	−0.90	−1.20	−0.89	−13.43	−11.16	−11.61
B	−11.74	−8.47	−9.18	−6.83							
C	−16.52	−9.03	−1.24	−19.40	−15.89	−7.48	−1.26	−19.69	−4.26	−7.08	−0.02
D	+19.51	+14.07	+15.25	+11.34							+29.86
E					+1.94	+1.20	+1.61	+1.19			
F	+0.97	+1.03	+8.11	+6.74	+6.19	+3.87	+11.59	+9.30	+16.55	+13.93	+3.12

hydrogen gas by pipeline, and hydride. In conventional opinion, the higher energy density of a method is, the better its economic performance is. But in life cycle assessment, the conditions are not like that because the additional cost brought by the ending process (compression or liquefaction of hydrogen) must be considered. Moreover, the cost of pipeline is closely related with the specific situation and always very high [13].

(d) Plan 10 is more advantageous than Plan 9 in economic performance because valley electricity is much cheaper than industrial electricity, although this will cause more equipments of water electrolysis to be needed in Plan 10 than that in Plan 9 owing to shorter work-hour in Plan 10.

(3) *Improvement assessment*:

(a) Control analysis

From inventory analysis and impact assessment, the major conclusions are:

- For Plans 3, 4, 7, and 8, reducing the energy consumption of ending process (liquefying hydrogen gas or changing hydride into hydrogen) is the main direction to reduce the hydrogen cost.
- For Plans 2 and 6, reducing the cost of tubing is the main direction to reduce the hydrogen cost.

(b) Sensitivity analysis

The following six parameters are changed in sensitivity analysis: A. The efficiency of production subsystem increases 20% in every plan. B. Avoided operation is taken in Plans 1–4. C. Zero inventory is realized in the refueling stations in every plan. D. The price of natural gas changes from 1.4 yuan RMB/Nm^3 to 2.0 yuan RMB/Nm^3 in Plans 1–4 and 11. E. The price of coal changes from 270 to 330 yuan RMB/ton in Plans 5–8. F. The price of electricity increases 20% in every plan.

The results of sensitivity analysis are listed in Table 11 and the major conclusions are:

- The hydrogen cost of Plans 5–8 is less sensitive to the efficiency of production subsystem than that of other plans.
- Avoided operation can decrease the hydrogen cost of Plans 1–4 about 7–11%.
- Zero inventory of the refueling stations can greatly decrease the hydrogen cost of the plans in which hydrogen is stored as hydrogen gas or hydride.
- The impact of the price of natural gas on the hydrogen cost of Plans 1–4 and 11 is greater than that of the price of coal on the hydrogen cost of Plans 5–8.
- The hydrogen cost of Plans 9 and 10 is more sensitive to the price of electricity than that of other plans.

3.8. General conclusions

(1) *The best plan in energy performance*: Plan 6 (coal gasification + pipeline) is the best plan in energy performance and its total energy efficiency is 30%. Plan 5 (coal gasification + cylinder) is the next and its total energy efficiency is 29%.

(2) *The best plan in environmental performance*: Plan 2 (NGSR + pipeline) is the best plan in environmental performance and its standard indexes of classified environmental effects is (global warming, human toxicity, photochemical

oxidation, acidification, eutrophication) = (38.865, 0.512, 10.621, 29.106, 4.795). Plan 1 (NGSR + cylinder) is the next and its standard indexes of classified environmental effects is (global warming, human toxicity, photochemical oxidation, acidification, eutrophication) = (40.888, 0.611, 12.421, 34.699, 5.897).

(3) *The best plan in economic performance*: Plan 11 (methanol reforming onboard) is the best plan in economic performance and its hydrogen cost is 14.68 yuan RMB/kg H_2. Plan 5 (coal gasification + cylinder) is the next and its hydrogen cost is 14.73 yuan RMB/kg H_2.

(4) *The best plan*: In consideration of (1)–(3) totally, it is concluded that Plan 5 (coal gasification + cylinder) is the best plan from all the aspects of energy, environment and economy in Beijing Case Study.

4. Conclusion

The paper provides references for China to develop hydrogen energy and fuel cell vehicles. Moreover, the case study of Beijing gives an example for researchers to choose the best plan of hydrogen infrastructure for fuel cell vehicles in other conditions.

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