Environmental and economic evaluation of the high-pressured and cryogenic vessels for hydrogen storage on the sedan

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Abstract

This paper carried out the environmental and economic evaluation for the hydrogen storage technologies on the sedan with Type 3 and Type 4 high-pressured and cryogenic vessels based on life cycle analysis (LCA) method. It is found that Type 4 high-pressured vessel manufacture emits minimum greenhouse gas (GHG) with 5539 $kgCO_2$ eq, which is lower than Type 3 high-pressured vessel of 7219 $kgCO_2$ eq and cryogenic vessel of 135 000 $kgCO_2$ eq in their whole life cycle. The economic analysis shows that Type 4 high-pressure vessel has the lowest cost of 10.4 US$/$kgH_2$ and the minimum energy consumption of 5.2 kWh/kgH_2, which is lower than Type 3 high-pressure vessel and cryogenic vessel. With this result, Type 4 high-pressure vessel is a promising choice for hydrogen mobility on the sedan regarding its environmental impact and economic performance.

Keywords: Type 4 high-pressure vessel; Type 3 high-pressured vessel; life cycle analysis (LCA); Hydrogen storage technologies

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1 INTRODUCTION

The elevation of carbon dioxide level in the atmosphere has been shown to contribute to extreme climate and global warming. It is estimated that fossil fuel burning contributes 75% of greenhouse gas (GHG) and 66% of nitrogen oxide emissions [1, 2]. Hydrogen, which is regarded as clean energy, is a promising strategy to mitigate the problems due to its green naturality, higher energy density and renewability [3, 4]. Besides the application of hydrogen in house, portable power and many more applications, hydrogen is an attractive fuel option for transportation and electricity generation applications in cars [5, 6].

However, hydrogen has low ambient temperature density, resulting in a low energy per unit volume [7]. And the active characteristics of hydrogen cause serious embrittlement and explosion risks [8, 9]. Therefore, a storage method that has the potential for higher energy density is a key enabling technology for the advancement of hydrogen and fuel cell technologies in cars [10, 11].

A series of hydrogen storage technologies have been developed for the application of hydrogen in cars, including two basic technologies: physical-based [12, 13] and material-based technology [14, 15]. Compared with material-based hydrogen storage technology, physical-based hydrogen storage technology (e.g. high-pressured or cryogenic technology) is a mature storage technology [11]. Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressured vessel [16]. Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8 °C. Thus, different vessels are manufactured with different materials and structures in order to reach their storage requirements. For example, Type 3 high-pressured vessel is manufactured with alumni alloy liner, and Type 4 high-pressured vessel has carbon fiber liner [17, 18]. And the cryogenic vessel is made with the insulation part to keep the temperature. Obviously, different materials and structures would have different environmental impacts and economic performance. Agostini *et al.* [19] assessed the environmental impacts and the costs of an auxiliary power unit (APU) for a light duty vehicle and compared it with high-pressured vessel. Recently, a life cycle assessment (LCA) of a fuel cell electric vehicle (FCEV) was carried out and focused on the manufacturing process of the

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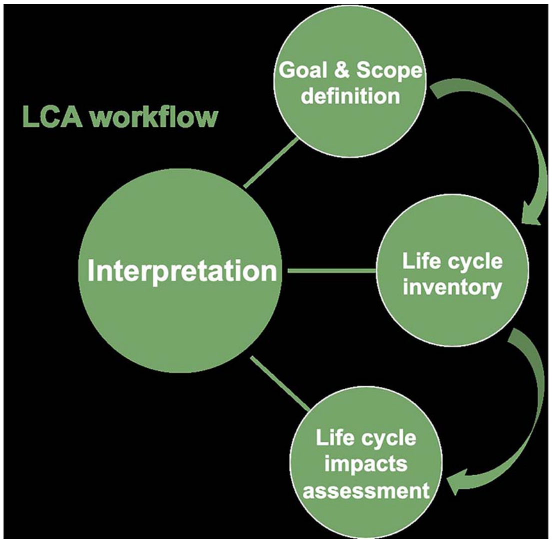

Figure 1. *Workflow of the LCA*

hydrogen storage tank and carbon fibers needed for its production [20]. It is found that the tank was important for climate change, ionizing radiation and fossil depletion, but less relevant for toxic-related environmental indicators. However, it is still desired for a systematic evaluation of its environmental and economic performance for different hydrogen storage, which would provide guidelines for hydrogen storage technology design and drive hydrogen application on the sedan.

In this work, a detailed environmental and economic evaluation is carried out for two physical-based hydrogen storage technologies (e.g. high-pressured or cryogenic technology) based on LCA. Due to their technological maturity, Type 3 and Type 4 high-pressured and cryogenic vessels are typically investigated in terms of GHG emissions, economic performance and energy consumption. This work would provide a comprehensive understanding of the hydrogen storage technology on the sedan and guide future research toward hydrogen utilization.

2 METHODOLOGY

In this work, the environmental and economic evaluations are carried out via LCA method. According to the definition of LCA by ISO 14045, this method is used to clarify the impacts on the environment as shown in Figure 1, which is divided into four parts: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact analysis and (4) interpretation [1].

Physical-based hydrogen storage technology, such as high-pressured and cryogenic technologies, is a more mature storage technology. In this work, high-pressured and cryogenic hydrogen storages are investigated. For the high-pressured hydrogen storage technology, different storage vessel is clarified based on their materials and structures. Type 3 high-pressured vessel (manufactured with metal or alloy and fiber) and Type 4 high-pressured vessel (manufactured with high density polyethylene, HDPE, and fiber) are invested as representative high-pressured hydrogen storage technology due to their used application. The cryogenic vessel has a familiar structure like the high-pressured vessel but has an insulation part to keep the temperature.

The above hydrogen vessel is investigated with the same capacity of 7.2 kg, which is calculated for energy equivalent with 45 L of no. 92 gasoline, considering the power conversion efficiency of the sedan. Specifically, no. 92 gasoline is gasoline with an octane number of 92 and an n-heptane number of 8. The density of no. 92 gasoline is 0.725 kg/L and the tank capacity of fuel for the sedan is ~45 L. So the mass of the sedan fully held will be ~32.6 kg. The fuel calorific value of no. 92 gasoline is 43.71 MJ/kg, and the average energy efficiency for sedan engines is 30%. The total energy that the sedan fuel tank fully holds will be ~427.8 MJ, which is equivalent to ~118.8 kW h. The energy transaction efficiency for the hydrogen fuel cell is 50%, and the calorific value of 1 kg hydrogen is 33 kW h electricity. Finally, the preset capacity for hydrogen is ~7.2 kg.

The environmental and economic performance in the manufacture and utilization of vessels are investigated. The inventory of hydrogen storage vessels is divided into materials consumption and energy consumption of the main components of the hydrogen storage vessel.

The LCA method is carried out via the Simapro 9.3 software. Moreover, the CML-IA database ver.2016 is chosen as the assessment method which was developed by the Center of Environmental Science of Leiden University.

3 RESULTS AND DISCUSSIONS

3.1 Materials consumption

The hydrogen storage tanks used for high-pressured gaseous hydrogen storage can be roughly divided into four types: Type 1: metallic pressure vessel, Type 2: metallic liner hoop wrapped with carbon fiber reinforced thermoplastic (CFRP), Type 3: metallic liner fully wrapped with CFRP and Type 4: polymer liner fully wrapped with CFRP (Figure 2a). The Type 3 and Type 4 hydrogen storage tank that consists of a polymer liner could greatly reduce the weight of the vessel, which has been applied in the hydrogen mobility on the sedan. As shown in Figure 2(b), the cryogenic vessel has an inner vessel that is an aluminum-lined, carbon fiber-wrapped pressure vessel similar to those typically used for storage of compressed gasses. This vessel is surrounded by a vacuum space filled with numerous sheets of highly reflective metalized plastic (minimizing heat transfer into vessel), and an outer metallic jacket.

Type 3 high-pressured vessel is manufactured with 6061 aluminum alloy, T700 carbon fiber and epoxy resin [23, 24]. The materials and energy consumption are listed in Table 1. In its cycle life, Type 3 high-pressured vessel consumed 26 kg of 6061 alu-

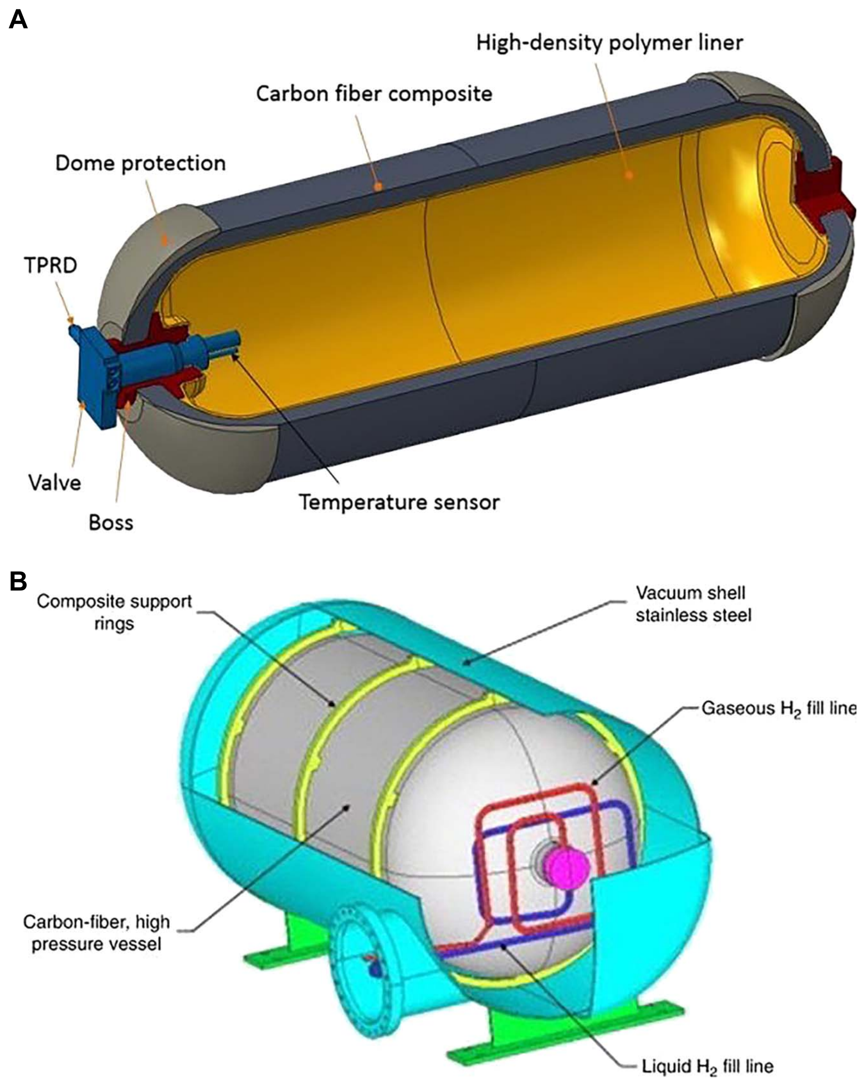

Figure 2. *(a) Type 4 high-pressured vessel [21]; (b) cryogenic vessel [22].*

Table 1. *Materials and energy consumption for Type 3 high-pressured vessel*

Items	Unit	Value
6061 aluminum alloy	kg	26
T700 carbon fiber	kg	96
Epoxy resin	kg	64
Electricity	kW h	374

Table 2. *Materials and energy consumption for Type 4 high-pressured vessel*

Items	Unit	Value
HDPE	kg	7.5
T700 carbon fiber	kg	76
Epoxy resin	kg	26
Electricity	kW h	238

minum alloy, 96 kg of T700 carbon fiber and 64 kg of epoxy resin. And the electricity is consumed with 374 Kwh for its manufacture and operation.

Type 4 high-pressured vessel has a similar structure as Type 3 high-pressured vessel, whose inner lining part is made of HDPE in a rotomolding process, and a polymer layer is made of T700 carbon fiber and epoxy resin [20]. Table 2 shows the materials and energy consumption. 7.5 kg of HDPE, 76 kg of T700 carbon fiber and 26 kg of epoxy resin are used for Type 4 high-pressured vessel. Compared with Type 3 high-pressured vessel, less electricity (238 Kwh) is consumed for HDPE in a rotomolding process and T700 carbon fiber construction.

The cryogenic hydrogen storage vessel structure is based on Type 3 high-pressured vessel, which is composed of aluminum alloy lining, carbon fiber polymer container and insulation shell to maintain a constant temperature [22]. The insulation is made of stainless steel and metalized PET reflective layer to form a protective shell and a reflective layer to achieve thermal insulation.

Table 3. *Materials and energy consumption for Type 4 high-pressured vessel*

Items	Unit	Value
6061 aluminum alloy	kg	9.5
T700 carbon fiber	kg	35
Epoxy resin	kg	23
Stainless steel	kg	51
Copper tube	kg	2
Computer	kg	0.2
Heat exchanger	kg	2.6
Metalized PET	kg	0.05
Electricity	kW h	158

Furthermore, a system is equipped to control the temperature and keep the hydrogen in a liquid attitude with the computer, tubes and heat exchanger. The materials and energy consumption are listed in Table 3. It is clear that more materials are consumed for the cryogenic hydrogen storage vessel, such as copper tube, heat exchanger, metalized PET etc.

3.2 Environmental evaluation

The environmental impact is acted in multiple ways based on different storage technologies, including materials and energy consumption. Because hydrogen could effectively reduce GHG emissions in the field of transportation by replacing traditional fossil fuels, we will focus on investigating their GHG emissions with different hydrogen storage vessels. Based on LCA, the environmental impact is divided into CO_2 emissions from the manufacture and CO_2 emissions from the storage process. Figure 3 and Table 4 show the total GHG emissions of different hydrogen storage technologies. Cryogenic hydrogen storage vessel emits a maximum CO_2 of 135 000 kg, followed Type 3 high-pressured vessel of 7219 kgCO_2 eq and Type 4 high-pressured vessel of 5539 kgCO_2 eq. For the cryogenic hydrogen storage vessel, CO_2 from the storage process emits 98% of total CO_2, because it needs for more energy to maintain its liquid phase at a lower temperature. For the high-pressured hydrogen storage, CO_2 emission from the storage process of Type 3 high-pressured vessel is about 13% of total CO_2 emissions, which is lower than that of Type 4 high-pressured vessel (16%). Thus, the CO_2 emissions of high-pressured hydrogen storage vessels from manufacture are critical in their environmental impact evaluation.

Then the CO_2 emissions from different materials of high-pressured hydrogen storage vessels are analyzed in Figure 4. The high-pressured vessels are mainly manufactured with aluminum alloy, polymer, and carbon fiber as listed in Tables 1 and 2. As shown in Figure 4, above 80% of CO_2 emissions is from the production process of carbon fiber. Furthermore, it is found that electricity emits a portion of CO_2 up to 6%, which is from power generation. Thus, renewable energy, such as wind energy, solar energy and nuclear energy, would significantly decrease its CO_2 emissions. Thus, Type 4 high-pressured vessel has a better performance than Type 3 high-pressured vessel regarding GHG emission [19].

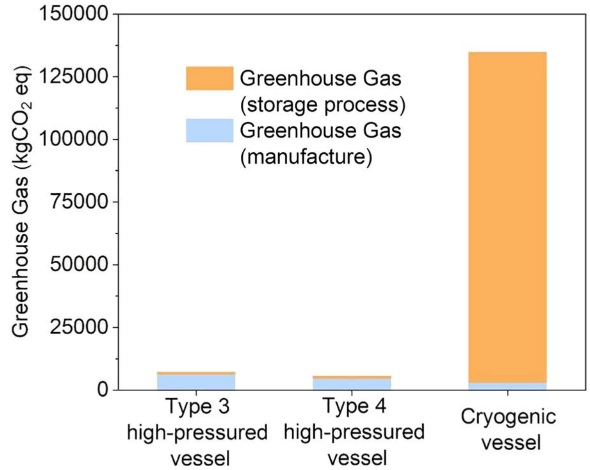

Figure 3. *Total GHG emissions of different hydrogen storage technologies.*

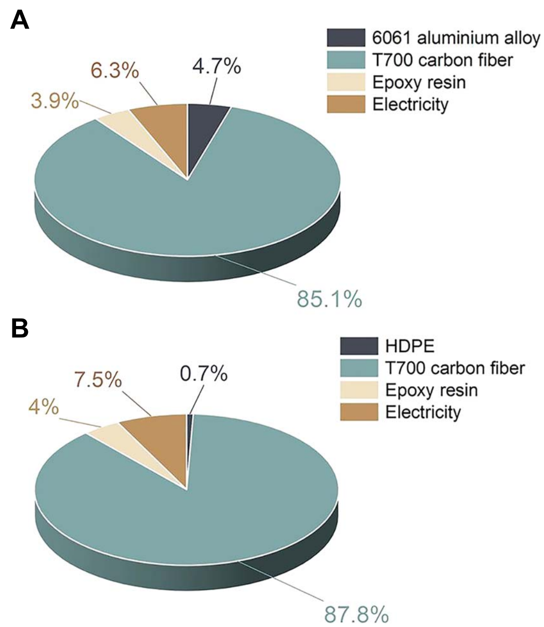

Figure 4. *GHG emission from manufacture of (a) Type 3 high-pressured vessel and (b) Type 4 high-pressured vessel.*

So, in terms of the environmental impact, the cryogenic hydrogen storage vessel emits maximum CO_2 with huge energy consumption for storage process. Compared with Type 3 high-pressured hydrogen storage vessel, Type 4 high-pressured hydrogen storage vessel would be a more practical technical choice in the future based on its overall lower GHG emission level.

3.3 Economic evaluation

Life cycle cost has an important impact on the final decision of technology choice, which includes the cost of manufacture, maintenance and operation. The main materials used in different vessels are listed in Table 5. It is clear that carbon fiber is expensive

Table 4. *GHG emissions details of different hydrogen storage technologies*

Types of vessels	GHGs (Production)/kgCO_2 eq	GHGs (storage work)/kgCO_2 eq	GHGs (total)/kgCO_2 eq
Type 3 high-pressured vessel	6280	939	7219
Type 4 high-pressured vessel	4600	939	5539
Cryogenic vessel	3060	131 741	135 000

Table 5. *Cost of materials for different vessels*

Material	6061 aluminum alloy	T700 carbon fiber	Epoxy resin	HDPE	Stainless steel	Electricity
Price/US$/kg or kW h	4.0	17.5	6.7	0.02	0.15	0.095

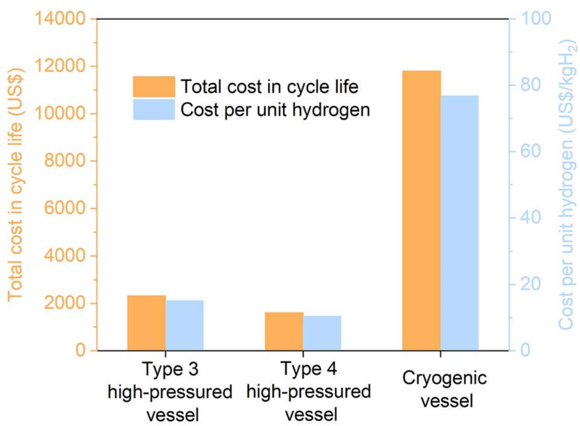

Figure 5. *Total cost and cost per unit hydrogen of different hydrogen storage vessels.*

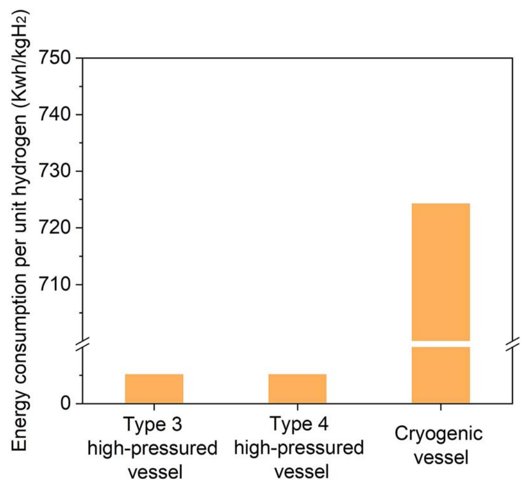

Figure 6. *Energy consumption per unit hydrogen of different hydrogen storage vessels.*

compared with metal, HDPE, and so on. Figure 5 depicts the total cost and cost per unit hydrogen of different hydrogen storage vessels. Type 4 high-pressure vessel has the lowest cost of 1602 US$ in their cycle life, followed by Type 3 high-pressure vessel of 2324 US$. Moreover, cryogenic hydrogen storage vessel has a maximum cost of 11 805 US$. Considering the cost per unit hydrogen, Type 4 high-pressure vessel has the lowest cost of 10.4 US$/kg$H_2$. Furthermore, Type 4 high-pressure vessel consumes less energy of 5.2 kWh/kgH_2 without extra energy to maintain storage conditions. However, cryogenic hydrogen storage vessel requires more energy of 724 kWh/kgH_2 to maintain operation conditions (Figure 6). Thus, Type4 high-pressure hydrogen storage vessel has the lowest monetary cost and energy consumption per unit of hydrogen, which has more potential application on the sedan in the future.

4 CONCLUSIONS

In this work, typical hydrogen storage technologies, including Type 3 and Type 4 high-pressured and cryogenic vessels, are investigated in terms of CO_2 emissions, economic performance and energy consumption based on LCA method. It has been determined that Type 4 high-pressure vessel manufacturing generates the fewest GHGs of 5539 kgCO_2 eq, compared to Type 3 high-pressure vessel of 7219 kgCO_2 eq, and cryogenic vessel of 135 000 kgCO_2 eq in their whole life cycles. According to the economic analysis, Type 4 high-pressure vessels are less expensive than Type 3 high-pressure vessels and cryogenic vessels with 10.4 US$/kg$H_2$ and minimum energy consumption of 5.2 kWh/kgH_2. Thus, Type 4 high-pressure vessel is a viable option for hydrogen transportation on this basis. This research would give a thorough understanding of the sedan's hydrogen storage system and serve as a roadmap for hydrogen utilization.

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