It is not the same green: A comparative LCA study of green hydrogen supply network pathways

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ABSTRACT

Green hydrogen (H_2), a promising clean energy source garnering increasing attention worldwide, can be derived through various pathways, resulting in differing levels of greenhouse gas emissions. Notably, Green H_2 production can utilize different methods, such as integrating standard photovoltaic panels, thermal photovoltaic, or concentrated photovoltaic thermal collectors with electrolyzers. Furthermore, it can be conditioned to different states or carriers, including liquefied H_2, compressed H_2, ammonia, and methanol, and stored and transported using various methods. This paper employs the Life Cycle Assessment methodology to compare 18 different green hydrogen pathways and provide recommendations for greening the hydrogen supply chain. The findings indicate that the production pathway utilizing concentrated photovoltaic thermal panels for electricity generation and hydrogen compression in the conditioning and transportation stages exhibits the lowest environmental impact, emitting only 2.67 kg of CO_2 per kg of H_2.

1. Introduction

Hydrogen (H_2) is a key element in pursuing cleaner and greener energy solutions. As a clean fuel, it emits primarily water vapor when combusted or used in fuel cells, rendering it an appealing alternative to fossil fuels. Global hydrogen demand reached 95 Million tonnes in 2022, almost 3% more than in 2021, and is expected to reach more than 150 Million tonnes in 2030 [1]. According to the H_2 Council, H_2 is projected to contribute greatly to the transportation sector, industrial sector, and power generation by satisfying around 150, 110, and 140 Million tonnes per Annam, respectively [2]. Hence, harnessing hydrogen's potential is vital for transitioning to a sustainable and environmentally responsible energy system. Additionally, utilizing hydrogen carriers is essential for efficiently storing and transporting hydrogen, which is crucial for advancing clean energy solutions, reducing carbon dioxide (CO_2) emissions, and meeting the global demand of different carriers such as ammonia.

To date, H_2 is still mainly produced from natural gas and coal, resulting in high CO_2 emissions. As an alternative, green H_2 is produced using renewable energy sources like wind, solar, or hydropower through a process called electrolysis. The hydrogen generated through this process is considered "green" because the energy used is clean and sustainable, resulting in a zero-carbon emission fuel.

However, realizing the full benefits of green hydrogen requires a thorough understanding of its life cycle, encompassing production, conditioning, transportation, storage, and reconditioning. This is done through carrying Life Cycle Assessment (LCA) of the hydrogen supply network (HSN) pathways.

Several LCA studies on green hydrogen energy have been reported in the literature so far which are summarized in Table 1. Weidner et al. [3], Osorio-Tejada et al. [4], Li et al. [5], Zhu et al. [6], Tayarani and Ramji [7], Chisalita et al. [8], Ozawa et al. [9], Wulf and Kaltschmitt [10] and Ozawa et al. [11] conducted LCA for both green and gray HSC. While [12–17], and [18] focused on carrying LCA for green HSC solely. Nevertheless, all studies considered producing green hydrogen from coupling standard photovoltaic (PV) panels, wind turbines, or hydropower with an electrolyzer. They all fall short in investigating the environmental impact of different technologies and pathways this paper addresses. Additionally, they did not consider different hydrogen forms or carriers in their LCA.

This paper makes the following main contributions:

1. Analyzing the environmental impacts of producing green hydrogen using PV panels, photovoltaic thermal (PV-T) collectors, or concentrated photovoltaic thermal (CPV-T) collectors with electrolyzers reveals significant variations in efficiency. CPV-T collectors, with built-in concentrators and trackers, achieve the highest efficiency, further enhanced by hot water circulation. PV-T collectors also benefit from hot water circulation, making

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them more efficient than standalone PV panels. This increased efficiency improves the electrolyzer's performance.

2. Comparing the environmental impacts of 18 green HSN pathways to determine the pathway with the lowest global warming potential (GWP).

2. Literature review

This paper presents a summary of related work. It first discusses research that focused mainly on carrying out LCAs for green and gray HSC. Then, it discusses the LCAs conducted solely for green HSC. Finally, it highlights the novelty of this work in relation to the existing literature. Table 1 displays the detailed description of the scope, HSN stages considered in each research and its gap.

2.1. LCA for green and gray hydrogen supply chain

Sayer et al. [19], Weidner et al. [3], Osorio-Tejada et al. [4], Li et al. [5], Zhu et al. [6], Tayarani and Ramji [7], Chisalita et al. [8], Ozawa et al. [9], Wulf and Zapp [18] and Ozawa et al. [11] conducted LCA for gray and green HSC. They considered producing green hydrogen by coupling standard PV panels, wind turbines, or hydropower with an electrolyzer. The HSC configuration considered in these LCA studies had similar production and conditioning stages. Nevertheless, Osorio-Tejada et al. [4], Li et al. [5], Zhu et al. [6] and Chisalita et al. [8] extended the scope of HSC configuration to include storage and transportation stages. On the other hand, the reconditioning stage was considered in [9], and [11].

Furthermore, Weidner et al. [3] and Tayarani and Ramji [7] considered only compressing hydrogen in their LCA. In addition to compressing hydrogen, Sayer et al. [19] considered liquefying it. While [4,8] conditioned hydrogen to ammonia only. In addition to conditioning hydrogen to ammonia, Zhu et al. [6] considered conditioning hydrogen to methanol. On the other hand, Li et al. [5] considered compressing or liquefying hydrogen, or conditioning it to methanol.

In terms of reported LCA results, Sayer et al. [19], Weidner et al. [3] and Tayarani and Ramji [7] highlighted that green hydrogen produced from PV panels would have a lower environmental impact than other conventional pathways. On the other hand, Li et al. [5] reported that green hydrogen produced from hydropower and conditioned to methanol is the most environmentally friendly pathway compared to the other considered pathways which are green hydrogen produced from PV panels or wind turbines or conventional methods. Additionally, Ozawa et al. [11] pointed out that producing hydrogen from wind turbines and then liquefying it results in lower emissions than producing hydrogen from PV panels and conditioning it to one of the liquid organic hydrogen carriers (LOHC). Also, Wulf and Zapp [18] reported similar results in terms of producing hydrogen from wind turbines; however, compressing hydrogen is the most environmentally friendly option compared to conditioning it to one of the LOHC. Zhu et al. [6] and Chisalita et al. [8] highlighted that the solar PV-based ammonia pathway has the lowest emissions and that emissions are significantly reduced compared to conventional methods.

2.2. LCA for green hydrogen supply chain

Khan et al. [12], Noh et al. [13], Díaz-Motta et al. [20], Kim et al. [21], Kanz et al. [14], Kolb et al. [15], Akhtar et al. [16], Wulf and Kaltschmitt [10] and Wulf et al. [17] carried out LCA for green HSC. Noh et al. [13], Díaz-Motta et al. [20], Akhtar et al. [16], Wulf and Kaltschmitt [10] and Wulf et al. [17] considered producing green hydrogen from coupling wind turbines with electrolyzers. In addition to producing green hydrogen using wind turbines, Khan et al. [12], Kim et al. [21], Kolb et al. [15] and Kanz et al. [14] discussed producing green hydrogen from PV panels.

Khan et al. [12] and Kanz et al. [14] considered only compressing hydrogen in their LCA study. However, Kolb et al. [15] included liquefying hydrogen in addition to compressing it. On the other hand, Noh et al. [13] and Akhtar et al. [16] considered compressing or liquefying hydrogen, or conditioning it to ammonia or LOHC in their LCA study. While [21] discussed liquefying hydrogen, or conditioning it to methanol or formic acid. Lastly, Díaz-Motta et al. [20] conditioned hydrogen to ammonia only.

Noh et al. [13] reported that conditioning hydrogen to ammonia is the most attractive pathway compared to other pathways in terms of environmental performance. While [16] LCA results showed that compressing hydrogen and transporting it via pipelines has the lowest GWP, while the LOHC has the highest emissions. Similarly, Wulf et al. [17] LCA results highlighted that compressing hydrogen and transporting it via pipelines has the least GWP. Lastly, the LCA results of Wulf and Zapp [18] pointed out that the liquefied hydrogen pathway produces fewer emissions than the LOHC pathway. Also, the LCA results of Kim et al. [21] showed that liquefying hydrogen produces less emissions than conditioning hydrogen to formic acid.

To the best of knowledge, this paper is the first to (1) analyze the environmental impact of producing hydrogen from coupling different PV technologies (i.e., PV-T and CPV-T collectors) with electrolyzer and (2) compare the environmental impact of 18 green HSN pathways to determine the best pathways that achieve the lowest GWP.

3. Methodology

This paper uses LCA methodology to evaluate the environmental impact of 18 green HSN pathways. The LCA study consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. Each phase is explained below in detail.

3.1. Goal and scope definition

The goal of the LCA is to assess the environmental impacts of each HSN pathways over its life cycle. This LCA focuses only on measuring the GWP's impact on the environment. GWP is measured in kg of carbon dioxide equivalent (hereafter, denoted by $kgCO_{2equ}$).

The proposed HSN includes different hydrogen production methods, conditioning, transportation means, storage types, and reconditioning processes, which creates 18 pathways that need to be environmentally investigated to determine which has the highest and lowest CO_2 emissions. Figs. 1 and 2 depict the complete proposed HSN five stages and its six pathways. The LCA scope covers the cradle to the grave of the HSN pathways. In other words, the LCA considers each process's construction, production, operation and maintenance, and end-of-life stages in the HSN. In addition, it includes the material, energy, and emissions flow from and to each process. This paper explains the scope of each HSN stage in the context of the LCA study below.

3.1.1. Hydrogen production stage

Green hydrogen is produced from an electrolysis process that uses treated industrial-produced (IP) water or treated sewage effluent (TSE) water as a feedstock. The feedstock is deionized through a water-deionizing process. The electrolysis process is coupled with renewable energy in the form of PV panels, PV-T collectors, and CPV-T collectors, for the energy source. This paper assumes half of the water demand of the electrolysis is met from treated IP water, and the other half is met from TSE water. Thus, green hydrogen can be produced in three ways: electrolysis coupled with PV panels, PV-T collectors, or CPV-T collectors, as shown in Fig. 3. It also highlights the energy, material, and emissions flow from the production stage's construction, production, operation and maintenance, and end-of-life.
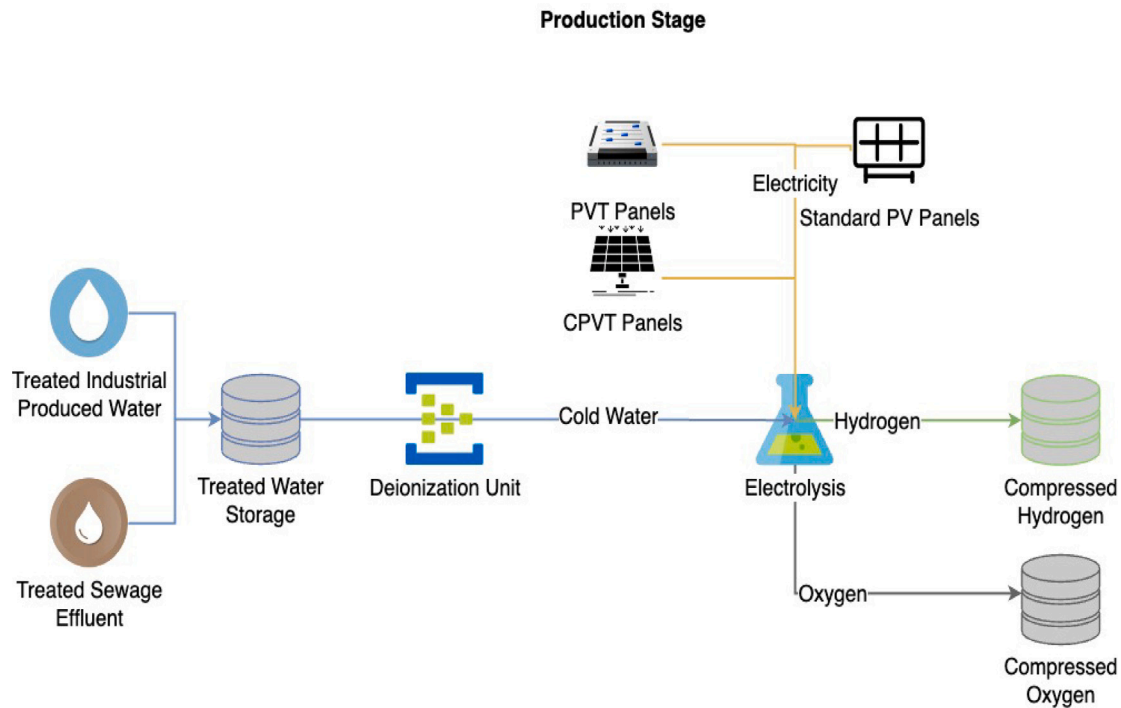
Production Stage

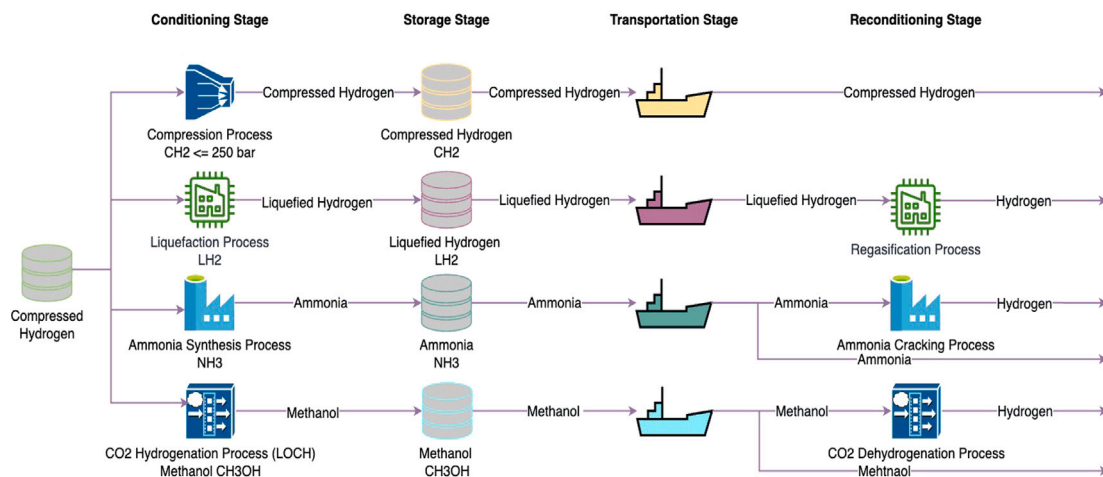**Fig. 1.** The proposed green HSC configuration and pathways — Part 1.

Fig. 2. The proposed green HSC configuration and pathways — Part 2.

3.1.2. Conditioning, storage, transportation, and reconditioning stages

After hydrogen is produced, it goes through four stages in the HSN sequentially: conditioning, storage, overseas transportation, and reconditioning stages. In each stage, the hydrogen can go through six possible pathways: CH_2 pathway, LH_2 – H_2 pathway, NH_3 – H_2 pathway, CH_3OH – H_2 pathway, NH_3 pathway, and CH_3OH pathway.

The CH_2 pathway includes compressing hydrogen to 70 bar via a compression process, storing it in compressed hydrogen storage, and transporting it overseas to consumers as compressed hydrogen in a compressed hydrogen container as indicated in Fig. 4.

The LH_2 – H_2 pathway includes liquefying hydrogen to −253 C via a liquefaction process, storing it in liquid hydrogen storage, transporting it overseas to consumers as liquefied hydrogen in a liquid hydrogen tanker, and then regasifying it to hydrogen at the consumer side in a regasification process as indicated in Fig. 5.

The NH_3 – H_2 pathway includes synthesizing hydrogen to ammonia via the Haber Bosch process, storing it in ammonia storage, transporting

it overseas to consumers as ammonia in an ammonia tanker, and then cracking it to hydrogen at the consumer side using the ammonia cracking process as indicated in Fig. 6.

The NH_3 pathway is similar to the NH_3 – H_2 pathway, with the difference that ammonia is not cracked to hydrogen; instead, it is delivered to consumers as a final product. It has the same structure as in Fig. 6; however, without the ammonia cracking process (i.e., reconditioning stage).

The CH_3OH – H_2 pathway includes hydrogenating hydrogen to methanol via the CO_2 hydrogenation process, storing it in the methanol storage, transporting it overseas to consumers as methanol in a methanol tanker, and then dehydrogenating it to hydrogen at the consumer side in the CO_2 dehydrogenation process as indicated in Fig. 7.

The CH_3OH pathway is similar to CH_3OH – H_2 with the difference that methanol is not dehydrogenated to hydrogen; instead, it
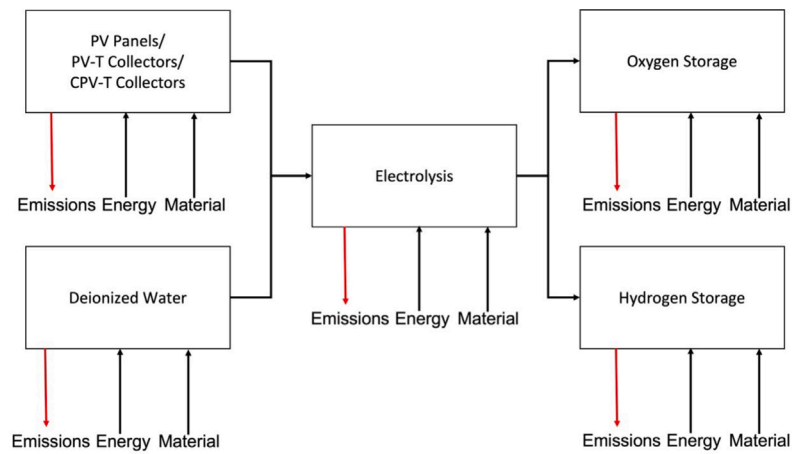
Fig. 3. The hydrogen production stage.
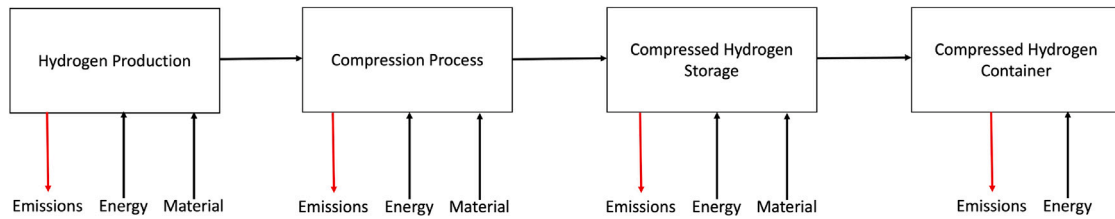
Fig. 4. The compressed hydrogen pathway.
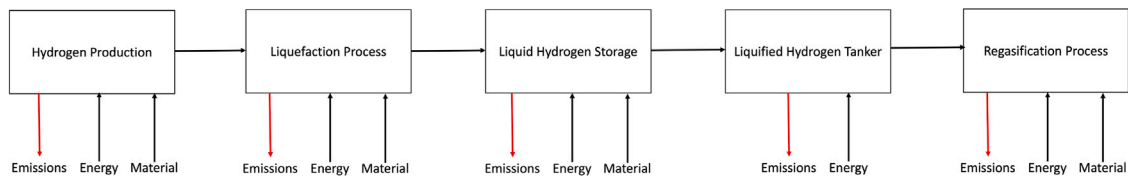
Fig. 5. The liquefied hydrogen pathway.
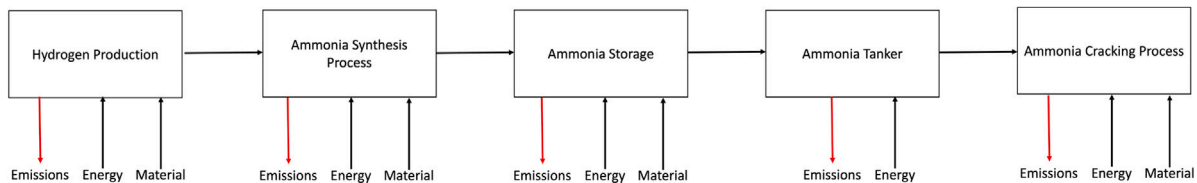
Fig. 6. The ammonia–hydrogen pathway.

is delivered to consumers as a final product. It has the same structure as in Fig. 7; however, without the CO_2 dehydrogenation process (i.e., reconditioning stage).

Renewable energy (i.e., standard PV panels, PV-T collectors, and CPV-T collectors) supplies the required energy to all processes in the HSN, except the reconditioning process, which is carried out on the consumer side.

The functional unit of this LCA is the quantity of CO_2, in kg, emitted during the life cycle of all processes in the HSN when one kg of hydrogen is produced (i.e., $kgCO_2/kgH_2$).

Fig. 7. The methanol–hydrogen pathway.

3.2. Life cycle inventory

The detailed LCI of all processes is included in the supplementary material. However, this paper describes the LCI of each process in each stage in the sections below.

3.2.1. Hydrogen production stage

• **Water Feedstock**

Water feedstock is an essential input for green hydrogen production. The LCA considers two primary sources of water feedstock for the electrolysis process: TES water and IP water. The LCI is included in Appendix (1) of the supplementary material.

• **Water Deionizing Process**

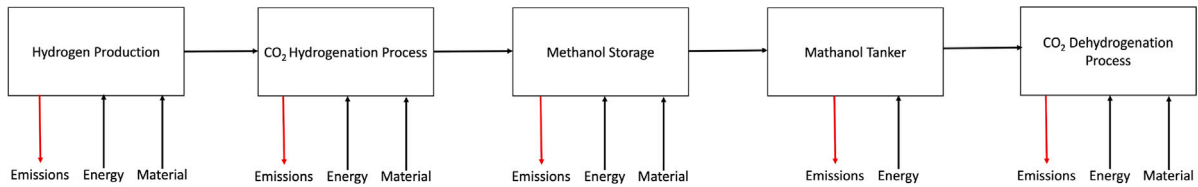The water deionizing process is crucial as it deionizes the water before its consumption by electrolysis. This process ensures that the cleanest form of hydrogen is produced. This paper adopts the electro-deionization coupled with the reverse osmosis process. It is one of the most common commercially available techniques to deionize water. This paper uses the available LCI on GaBi software for this process. The energy required to deionize one kg of water is 1.1 kWh.

• **Renewable Energy**

This paper assumes that HSN employs renewable energy in the form of standard PV panels, PV-T collectors, and CPV-T collectors to supply the required energy to all the processes in the hydrogen production stage. For the standard PV panels, this paper uses the available LCI in GaBi software. The PV panel's efficiency is 18%, and they are mono-crystalline silicon panels.

For PV-T collectors, the LCI is not widely available in the literature. Thus, this paper estimates the LCI of the PV-T collectors by multiplying the LCI of the standard PV panels and solar thermal collectors with a ratio. The ratio is calculated by dividing the PV-T collectors efficiency by the PV panels efficiency. The PV-T collector's efficiency could reach 60%, as reported in the literature. So, the calculated ratio is 3.33. The LCI is included in Appendix (3) of the supplementary material.

Similarly, this paper estimates the LCI of the CPV-T collectors in the same manner since their LCI has yet to be discussed in the literature. However, in addition to including the LCI of the standard PV panels and solar thermal collectors, this paper includes the LCI of concentrated mirrors. The CPV-T collector's efficiency could reach 80%, as reported in the literature. So, the calculated ratio is 4.44. The LCI is included in Appendix (4) of the supplementary material.

• **Hydrogen Electrolysis**

The hydrogen electrolysis process is the core process in the green hydrogen production stage. Hydrogen electrolysis requires two essential inputs: water feedstock and energy source. The HSN adopts the alkaline electrolyzer to produce hydrogen. It is one of the most widely and commercially available processes. The process requires 10 kg of deionized water and 50 kWh of energy as inputs to produce one kg of hydrogen and eight kg of oxygen. This paper uses the available LCI on GaBi software for this process.

• **Storage**

The HSC includes three storages to temporarily store oxygen, hydrogen, and treated water before the following process. The LCI of the hydrogen and oxygen storage, and treated water storage are included in Appendix (5) and Appendix (2) of the supplementary material, respectively.

3.2.2. Conditioning stage

Table 2 shows the feedstock required to produce one kg of hydrogen from each conditioning process, the energy required for each conditioning process (i.e., hydrogen compression, hydrogen liquefaction, ammonia synthesis and CO_2 hydrogenation), and losses during the conditioning process. The LCI of the hydrogen compression process, hydrogen liquefaction process, and CO_2 hydrogenation process are included in Appendix (10), Appendix (11), and Appendix (12) of the supplementary material, respectively. The LCI of the ammonia synthesis process is obtained from GaBi software.

3.2.3. Storage stage

Hydrogen is stored temporarily after its conditioning before to overseas transportation. The compressed hydrogen, liquefied hydrogen, ammonia and methanol are stored in a special type of storage that can store them temporarily. This paper assumes 0.18% losses of liquefied hydrogen [15], 0.062% losses of ammonia [35], and 0.005% losses of methanol during their storage [34]. The LCI of the compressed hydrogen storage, liquefied hydrogen storage, ammonia storage, and methanol storage is included in Appendix (13), Appendix (14), Appendix (15) and Appendix (16) of the supplementary material, respectively.

3.2.4. Transportation stage

The LCI considers only the transportation stage, excluding vessel production, the vessel's end-of-life treatment, and the fuel supply chain.

• **Containers**

The compressed hydrogen is transported overseas via a compressed hydrogen container [13]. The container uses heavy fuel oil as fuel for transportation. This paper uses the available LCI on GaBi software for the compressed hydrogen container. The LCI is based on the container's fuel consumption. To calculate the specific fuel consumption, this paper first calculates the fuel consumption using the below equation:

Fuel Consumption (kg_{fuel}/km)

$$= \frac{-5 \times 10^{-9} \times \text{Dead Weight}^2 + 0.0016 \times \text{Dead Weight} + 9.8129}{\text{Capacity Utilization} \times \text{Distance}}$$

The equation is derived from [36]. This paper assumes the capacity utilization is 48%, the traveled speed is 37 km/hr, and the dead weight of the container is 43,000 tonnes. Then, this paper calculates the specific fuel consumption to find the associated GHG emissions using the below equation which is derived from [36]:

$$\text{Specific Fuel Consumption} (kg_{fuel}/kg_{cargo}) = \frac{\text{Fuel Consumption}}{\text{Dead Weight} \times 1000}$$

Table 1
A summary of life cycle assessment studies from the literature.

Author	Scope	H₂ Prod	Cond.	Storage	Trans.	Recond.	Gap
Sayer et al. [19]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Compressed H$_2$ or Liquefied H$_2$	X	✓	X	They did not consider storage, or reconditioning stages in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Weidner et al. [3]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Compressed H$_2$	X	X	X	* They did not consider storage, transportation, or reconditioning stages in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Osorio-Tejada et al. [4]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Ammonia	✓	✓	X	* They did not consider the reconditioning stage. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Li et al. [5]	LCA for green and gray HSC.	PV panels, wind turbines, or hydropower + electrolyzers	Compressed H$_2$, Liquefied H$_2$ or Methanol	✓	✓	X	* They did not consider the reconditioning stage in the HSC. * They considered only standard PV panels.
Zhu et al. [6]	LCA for green and gray HSC.	PV panels + electrolyzers	Ammonia or Methanol	✓	✓	X	* They did not consider the reconditioning stage in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Tayarani and Ramji [7]	LCA for green and gray HSC.	PV panels + electrolyzers	Compressed H$_2$	X	✓	X	* They did not consider storage and distribution in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Chisalita et al. [8]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Ammonia	✓	✓	X	* They did not consider the reconditioning stage. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Ozawa et al. [9]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Liquefied H$_2$, LOHC, or Ammonia	✓	✓	✓	* They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Ozawa et al. [11]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Liquefied H$_2$, or LOHC	✓	✓	✓	* They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Wulf and Kaltschmitt [10]	LCA for green and gray HSC.	PV panels or wind turbines + electrolyzer	Compressed H$_2$ or LOHC	X	✓	✓	* They did not consider the storage stage in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Khan et al. [12]	LCA for green HSC.	Wind turbines or PV panels + electrolyzer	Compressed H$_2$	X	X	X	* They did not consider storage, transportation, or reconditioning stages in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Noh et al. [13]	LCA for green HSC.	Wind turbines + electrolyzer	Compressed H$_2$, Liquefied H$_2$, Ammonia, or LOHC	X	✓	✓	* They did not consider the storage stage in the HSC. * They did not consider PV panels.
Díaz-Motta et al. [20]	LCA for green HSC.	Wind turbines + electrolyzer	Ammonia	✓	X	X	* They did not consider the transportation or reconditioning stages in the HSC. * They did not consider PV panels. * They did not consider other hydrogen forms or carriers.
Kim et al. [21]	LCA for green HSC.	PV panels or wind turbines + electrolyzer	Liquefied H$_2$, Methanol or Formic Acid	X	✓	✓	* They did not consider the storage stage in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Kolb et al. [15]	LCA for green HSC.	PV panels or wind turbines + electrolyzer	Compressed H$_2$, or Liquefied H$_2$	✓	✓	✓	* They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Kanz et al. [14]	LCA for green HSC.	PV panels or wind turbines + electrolyzer	Compressed H$_2$	X	✓	✓	* They did not consider the storage stage in the HSC. * They considered only standard PV panels. * They did not consider other hydrogen forms or carriers.
Akhtar et al. [16]	LCA for green HSC.	Wind turbines + electrolyzer	Compressed H$_2$, Liquefied H$_2$, Ammonia, or LOHC	X	✓	X	* They did not consider the storage or the reconditioning stage in the HSC. * They did not consider PV panels.
Wulf et al. [17]	LCA for green HSC.	Wind turbines + electrolyzer	Compressed H$_2$, or LOHC	✓	✓	X	* They did not consider the reconditioning stage. * They did not consider PV panels. * They did not consider other hydrogen forms or carriers.
Wulf and Zapp [18]	LCA for green HSC.	Wind turbines + electrolyzer	Liquefied H$_2$, or LOHC	X	✓	✓	* They did not consider the storage stage in the HSC. * They did not consider PV panels. * They did not consider other hydrogen forms or carriers.

Table 2
Energy consumption and losses for different conditioning stages.

Conditioning process	Feedstock	Output product	Energy (kWh/kgH_2)	Losses (%)	Reference
Hydrogen compression (70 bar)	1 kg H_2	1 kg compressed H_2	0.57	0.50	Ghandehariun and Kumar [22], Hong et al. [23], Knop [24], Weiszflog and Abbas [25] and Kaiser et al. [26]
Hydrogen liquefaction (−253 C)	1 kg H_2	1 kg liquefied H_2	10	1	Weiszflog and Abbas [25], Kolb et al. [15], Elgowainy et al. [27], Stolzenburg and Mubbala [28] and Kaiser et al. [26]
Ammonia synthesis	4.68 kg N_2; 1 kg H_2	1 kg NH_3	11.2	0.025	GaBi software
CO_2 hydrogenation	7.25 kg CO_2; 1 kg H_2	1 kg CH_3OH	10.9	0.005	Cordero-Lanzac et al. [29], Rigamonti and Brivio [30], Soler et al. [31], Demirel [32], Lee et al. [33], Kaiser et al. [26] and Al-Breiki and Bicer [34]

• **Tankers**

The liquefied hydrogen is transported overseas via a liquid hydrogen tanker [16,21,37]. The tanker uses heavy fuel oil as fuel for transportation. This paper uses the available LCI on GaBi software for the liquefied natural gas tanker. The LCI is based on the tanker's fuel consumption. The below fuel consumption equation represents the fuel consumption of the liquefied natural gas tanker, which this paper uses to calculate the fuel consumption of the liquefied hydrogen tanker. However, this paper considers the density of the liquefied hydrogen by calculating the density ratio of liquefied natural gas to liquefied hydrogen as per [15]. The ratio is 1/6.

$$\text{Fuel Consumption } (kg_{fuel}/km) = \frac{0.0001 \times \text{Dead Weight} + 11.058}{\text{Capacity Utilization} \times \text{Distance}} \times \frac{1}{6}$$

The equation is derived from [36]. This paper assumes the capacity utilization is 48%, the traveled speed is 37 km/hr, and the dead weight of the container is 60,000 tonnes. Then, this paper calculates the specific fuel consumption to find the associated greenhouse gas emissions using the below equation which is derived from [36]:

$$\text{Specific Fuel Consumption } (kg_{fuel}/kg_{cargo}) = \frac{\text{Fuel Consumption}}{\text{Dead Weight} \times 1000}$$

In addition to that, this paper considers the liquefied hydrogen losses that occur over the transportation days. Thus, it assumes 0.2% liquefied hydrogen losses in a day [15]. This paper calculates the total and specific losses using the below equations which are derived from [36]:

Liquefied Hydrogen Losses (tonnes/day) = 0.002 × Dead Weight

Total Liquefied Hydrogen Losses (tonnes)

= Liquefied Hydrogen Losses × day

Specific Liquefied Hydrogen Losses (tonnes)

$$= \frac{\text{Total Liquefied Hydrogen Losses}}{\text{Dead Weight}}$$

Transportation days can be calculated by dividing the traveled distance by the traveled speed. This paper uses the specific liquefied hydrogen loss value in the LCI outputs.

Similarly, ammonia and methanol are transported in the same way as the liquefied hydrogen. For transporting ammonia, this paper considers the ammonia's density by calculating the density ratio of liquefied natural gas to ammonia as per [15]. The ratio is 1.33. In addition, this paper assumes 0.04% of ammonia losses in a day [33]. For transporting methanol, this paper considers the methanol's density by calculating the density ratio of liquefied natural gas to methanol as per [26]. The ratio is 1.76. In addition, this paper assumes 0.005% of methanol losses in a day [34]. This paper uses the same equations to calculate the losses, total losses, and specific losses as in liquefied hydrogen.

3.2.5. Reconditioning stage

Table 3 shows the feedstock produced from reconditioning one kg of hydrogen from each reconditioning process, the energy required for each reconditioning process (i.e., hydrogen regasification, ammonia cracking, and CO_2 dehydrogenation), and losses during the reconditioning process. The reconditioning process occurs after the overseas transportation. The LCI of the hydrogen regasification process, ammonia cracking process, CO_2 dehydrogenation process are included in Appendix (17), Appendix (18), and Appendix (19) of the supplementary material, respectively.

3.3. Life cycle impact assessment

This paper uses the CML 2001 – Jan 2016 method where GWP for a 100-year time horizon characterizes the GHG emissions values in units of $CO_{2\text{-equivalent}}$. To this end, Table 4 shows the GWP-100 years results obtained from GaBi software for 18 green HSN pathways.

4. Life cycle interpretation

This paper assesses the GWP of 18 green HSN pathways and identifies the best pathway in terms of environmental performance. The pathways that deliver hydrogen as an end product i.e., which are the first four pathways indicated in Table 4 are compared with each other. While the last two pathways in Table 4 are compared with each other. This is to ensure that the results of the pathways of the same scope are compared to each other. This is highlighted in the sections below.

4.1. Renewable energy impact

The LCA results show that coupling CPV-T collectors with the electrolysis process produces the lowest GWP compared to other collectors (i.e., PV panels and PV-T collectors) for all pathways, as shown in Figs. 8 and 9, respectively. Indeed, the higher efficiency of the CPV-T collectors (i.e., 80%) allows them to produce more hydrogen quantities than the standard PV panels (i.e., efficiency of 18%) and PV-T collectors (i.e., efficiency of 60%) for the same period. Thus, this reduces the GWP per kg of hydrogen for CPV-T collectors compared to other collectors.

The LCA results highlight that the GWP decreases by 23.97%, 20.20%, 16.56%, and 9.60% for the CH_2, $LH_2 - H_2$, $NH_3 - H_2$, and $CH_3OH - H_2$ pathways, respectively, when PV-T collectors are employed instead of standard PV panels. In addition, the GWP decreases by 26.4%, 22.2%, 18.2%, and 10.5% for the CH_2, $LH_2 - H_2$, $NH_3 - H_2$, and $CH_3OH - H_2$ pathways, respectively, when CPV-T collectors are employed instead of standard PV panels as highlighted in Fig. 8.

Similarly, the same observation can be highlighted for the NH_3 and CH_3OH pathways, which are related to delivering ammonia or methanol as an end product. The GWP decreases by 20% and 19.61% for NH_3, and CH_3OH pathways, respectively, when PV-T collectors are employed instead of standard PV panels. Additionally, the GWP decreases by 22.2% and 20.6% for NH_3, and CH_3OH pathways, respectively, when CPV-T collectors are employed instead of standard PV panels as highlighted in Fig. 9.
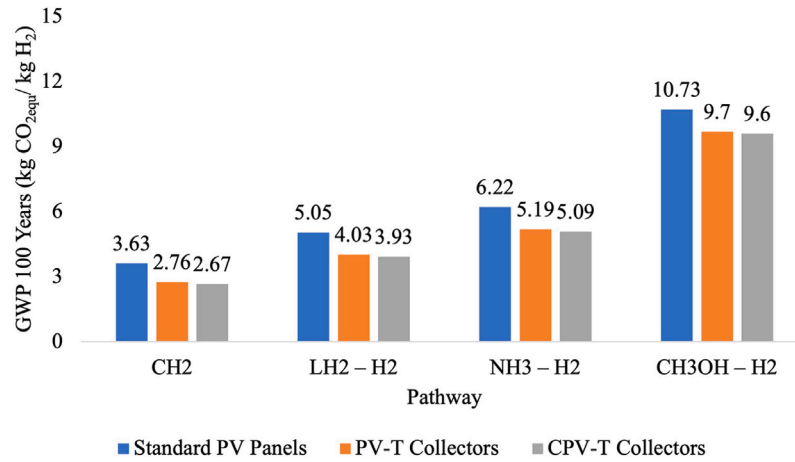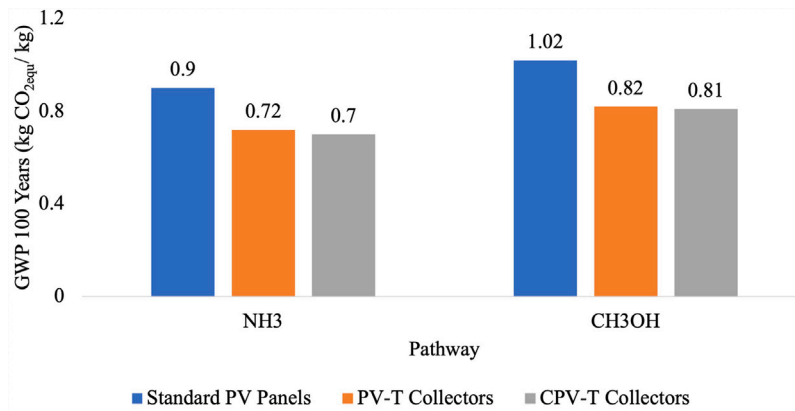
Fig. 8. The GWP of the green hydrogen pathways.

Fig. 9. The GWP of the green ammonia and methanol pathways.

Table 3
Energy consumption and losses for reconditioning stages.

Reconditioning process	Feedstock	Output product	Energy (kWh/kgH$_2$)	Losses (%)	Reference
Hydrogen regasification	1 kg liquefied H$_2$	1 kg H$_2$	2.53	0.5%	Weiszflog and Abbas [25], Stolzenburg and Mubbala [28], Hong et al. [23] and Kolb et al. [15]
Ammonia cracking	5.68 kg NH$_3$	1 kg H$_2$	1.93	1.38%	Stolzenburg and Mubbala [28], Hong et al. [23] and Dilshani et al. [38]
CO$_2$ dehydrogenation	5.18 CH$_3$OH	1 kg H$_2$	10.37	2.47%	Kaiser et al. [26], Patonia and Poudineh [35] and Voelker et al. [39]

Table 4
The GWP results obtained from the LCA study for all pathways in kgCO$_2$/kg.

Pathway	Standard PV panels	PV-T collectors	CPV-T collectors
CH$_2$	3.63	2.76	2.67
LH$_2$–H$_2$	5.05	4.03	3.93
NH$_3$–H$_2$	6.22	5.19	5.09
CH$_3$OH–H$_2$	10.73	9.70	9.60
NH$_3$	0.90	0.72	0.70
CH$_3$OH	1.02	0.82	0.81

4.2. The environmental impact of Green HSN pathways

The results of this section focus on analyzing the GWP when electrolysis is coupled with CPV-T collectors, as the same conclusion can be drawn for the standard PV panels and PV-T collectors.

• **Hydrogen as End-Product Pathways**

The LCA results indicate that the CH$_2$ pathway has the lowest GWP, which is 2.67 kgCO$_{2equ}$/kgH$_2$, compared to other pathways, lower by 47.2%, 90.6%, and 259.6% for LH$_2$ – H$_2$, NH$_3$ – H$_2$, and CH$_3$OH – H$_2$ pathways, respectively. The reason is mainly related to the fact that the compression process does not require much energy to compress hydrogen (i.e., 0.57 kWh/kgCH$_2$), and no reconversion process occurs in this pathway compared to other pathways. Most of the emissions in this pathway are coming from the production stage (i.e., 2.50 kgCO$_{2equ}$/kgH$_2$).

On the other hand, the CH$_3$OH – H$_2$ pathway has the highest GWP which is 9.60 kgCO$_{2equ}$/kgH$_2$, compared to other pathways, higher by 259.29%, 144.27%, 88.51% for CH$_2$, LH$_2$ – H$_2$, and NH$_3$ – H$_2$ pathways, respectively.

The highest GWP is mainly, because, (i) the CO$_2$ dehydrogenation process is an endothermic process that requires much heat to

dehydrogenate methanol to hydrogen; this requires burning natural gas to supply the required heat, which emits CO_2, and (ii) the CO_2 hydrogenation process includes capturing CO_2 to be used as a feedstock in the hydrogenation process. The capturing process emits CO_2.

Looking at other pathways, the $LH_2 - H_2$ pathway has a higher GWP (i.e., 47.2%) than the CH_2 pathway because (i) the liquefaction process is a more energy-intensive process than the compression process, which consumes a considerable amount of energy (i.e., 10 kWh/kgLH$_2$), and (ii) this pathway includes a reconversion process of the liquefied hydrogen through the regasification process, which consumes around 0.047 kWh/kgH$_2$. The $NH_3 - H_2$ pathway has a higher GWP by 90.59% and 29.5% than CH_2 and $LH_2 - H_2$ pathways, respectively. As a result of (i) the ammonia synthesis process is more energy-intensive (i.e., 11.2 kWh/kgH$_2$) than the liquefaction process and the compression process, and (ii) the ammonia cracking process is more energy-intensive (i.e., 1.93 kWh/kgH$_2$) than the hydrogen regasification process.

• **Ammonia and Methanol as End-Product Pathways**

The LCA results conclude that the NH_3 pathway always has the lowest GWP, 0.70 kgCO$_{2equ}$/kgNH$_3$, compared to all pathways considered in the LCA study, though ammonia synthesis is energy-intensive. The reason for the lowest GWP is that this pathway has no reconversion process in the HSN since ammonia is delivered to consumers as an end product, so no energy is needed for the reconversion process. Notably, the GWP of the reconversion process (i.e., ammonia cracking) represents 21.9% of the total GWP. In addition, this pathway is concerned with producing one kilogram of ammonia. Thus, the GWP value represents the GWP of producing one kilogram of ammonia (i.e., equivalent to 0.176 kg of H_2). In contrast, other pathways are concerned with producing one kilogram of hydrogen. Thus, higher GWP values are expected for other pathways except for CH_3OH and NH_3 pathways.

For a fair comparison, this paper compares the NH_3 pathway with the CH_3OH pathway. The GWP of the CH_3OH pathway is 13.33%, 13.89%, and 15.7% more than the GWP of the NH_3 pathway when the CPV-T collectors, PV-T collectors, and PV panels are employed respectively. The main reasons behind the high GWP are: (i) more hydrogen (i.e., 0.193 kgH$_2$/kgCH$_3$OH vs. 0.176 kgH$_2$/kgNH$_3$) is required from electrolysis to produce one kilogram of methanol compared to ammonia. This leads to consuming more deionized water. Hence, more energy is supplied from CPV-T collectors to the electrolysis and water deionizing process, and (ii) the CO_2 hydrogenation process includes capturing CO_2 to be used as a feedstock in the hydrogenation process. The capturing process emits CO_2. As a result, the CO_2 hydrogenation process emits 19.8% more CO_2 (i.e., 0.32 kgCO$_{2equ}$/kg CH$_3$OH) than the ammonia synthesis (i.e., 0.26 kgCO$_{2equ}$/kgNH$_3$).

4.3. The environmental impact of Green HSN stages

The results of this section focus on analyzing the GWP when electrolysis is coupled with CPV-T collectors, as the same conclusion can be drawn for the standard PV panels and PV-T collectors.

• **Hydrogen as End-Product Pathways**

Fig. 10 highlights the GWP of each stage (i.e., production, conditioning, storage, transportation, and reconditioning) in the HSN of each pathway. The figure shows that all pathways emit the same amount of CO_2 for the production stage, which is 2.5 kgCO$_{2equ}$/kgH$_2$ since one kg of hydrogen is produced from the electrolysis process when the CPV-T collectors are employed. If the PV-T collectors are employed, the GWP is 2.60 kgCO$_{2equ}$/kgH$_2$, 4% more than the CPV-T collectors. If the PV panels are employed, the GWP is 3.47 kgCO$_{2equ}$/kgH$_2$, 38.8% more than the CPV-T collectors. In the CPV-T collectors case, the production stage represents 93.6%, 63.7%, and 49.1% of the total GWP for the CH_2, $LH_2 - H_2$, and $NH_3 - H_2$ pathways, respectively. This stage consumes the most electricity; hence, it has the most emissions compared

to other processes in other stages of these pathways. However, in the $CH_3OH - H_2$ pathway, the production stage represents 26.1% of the total GWP.

For the conditioning stage, the compression process in the CH_2 pathway emits the least CO_2 (i.e., 0.14 kgCO$_{2equ}$/kgH$_2$) since the compression process does not consume much energy (i.e., 0.57 kWh/kgCH$_2$) compared to other conditioning processes in other pathways. Thus, the compression process represents only 5.4% of the total GWP. While the conditioning stage in the $LH_2 - H_2$ and $NH_3 - H_2$ pathways contribute to 29.6% (i.e., 1.17 kgCO$_{2equ}$/kgH$_2$) and 28.6% (i.e., 1.46 kgCO$_{2equ}$/kgH$_2$) of the total GWP, respectively. They have a higher GWP than the CH_2 pathway as the conditioning process in these pathways consumes more electricity (i.e., 11.2 kWh/kgH$_2$ for ammonia synthesis and 10 kWh/kgLH$_2$ for hydrogen liquefaction) than the compression process in the CH_2 pathway; hence, they have more emissions. On the other hand, the CO_2 hydrogenation process in the $CH_3OH - H_2$ pathway emits the most CO_2 (i.e., 1.66 kgCO$_{2equ}$/kgH$_2$) compared to other conditioning processes in other pathways as this process consumes 10.9 kWh/kgH$_2$. In addition, it includes capturing CO_2 to use as a feedstock for the process. However, the GWP of this CO_2 hydrogenation process contributes only 17.3% of the total GWP in the $CH_3OH - H_2$ pathway.

For the storage stage, storing methanol in the $CH_3OH - H_2$ pathway emits the least CO_2 emissions (i.e., 0.0023 kgCO$_{2equ}$/kgH$_2$) as not much energy (i.e., 0.012 kWh/kgCH$_3$OH) is required to store the methanol compared to other carriers. This is because methanol can be stored as a liquid at ambient temperature and pressure, typically not requiring refrigeration. In addition, methanol has the lowest boil-off (i.e., 0.005%) and low boiling points. The methanol storage contributes to 0.02% of the total GWP. Nevertheless, storing liquefied hydrogen in the $LH_2 - H_2$ pathway emits the highest CO_2 emissions (i.e., 0.026 kgCO$_{2equ}$/kgH$_2$) as a significant quantity of energy (i.e., 0.042 kWh/kgLH$_2$) is needed to store liquefied hydrogen compared to other carriers. This is because liquefied hydrogen must be cooled to a very low temperature (-253 °C) to maintain its liquid state, which requires significant energy. In addition, liquefied hydrogen has the highest boil-off (i.e., 0.18%). The liquid hydrogen storage contributes to 0.7% of the total GWP. For the other two pathways, storing ammonia in the $NH_3 - H_2$ pathway emits more CO_2 emissions (i.e., 0.015 kgCO$_{2equ}$/kgH$_2$) than storing methanol as more energy (i.e., 0.014 kWh/kgNH$_3$) is needed. This is because ammonia has a higher boiling point (-33 °C) than methanol (+64.7 °C) and requires refrigeration to maintain its liquid state at ambient temperature and pressure. The energy required to maintain the low temperature of liquid ammonia is significant, especially for large-scale storage systems. However, storing ammonia emits less CO_2 emissions than storing compressed hydrogen since compressing hydrogen requires special equipment to handle the high pressures, which requires a significant amount of energy. It is noteworthy to mention that the boil-off of ammonia is 0.062%. Ammonia storage contributes to 0.3% of the total GWP. Storing compressed hydrogen in the CH_2 pathway emits slightly less emissions (i.e., 0.025 kgCO$_{2equ}$/kgH$_2$) than storing liquefied hydrogen. Compressed hydrogen can be stored at a much higher temperature and pressure without requiring the same level of cooling as liquefied hydrogen. While compressing hydrogen still requires energy (i.e., 0.03 kWh/kgCH$_2$), it is generally less energy-intensive than liquefying hydrogen. The compressed hydrogen storage contributes to 0.9% of the total GWP.

For the reconditioning stage, the CH_2 pathway does not include a reconditioning process as compressed hydrogen is delivered to end consumers. So, the regasification process in the $LH_2 - H_2$ pathway emits the least CO_2 (i.e., 0.23 kgCO$_{2equ}$/kgH$_2$) as it consumes only 0.047 kWh/kgH$_2$ compared to other conditioning processes in other pathways. The regasification process contributes to only 5.4% of the total GWP. While, the ammonia cracking in the $NH_3 - H_2$ pathway has a higher GWP than the regasification process in the $LH_2 - H_2$ pathway as it consumes more electricity (i.e., 1.93 kWh/kgH$_2$); hence
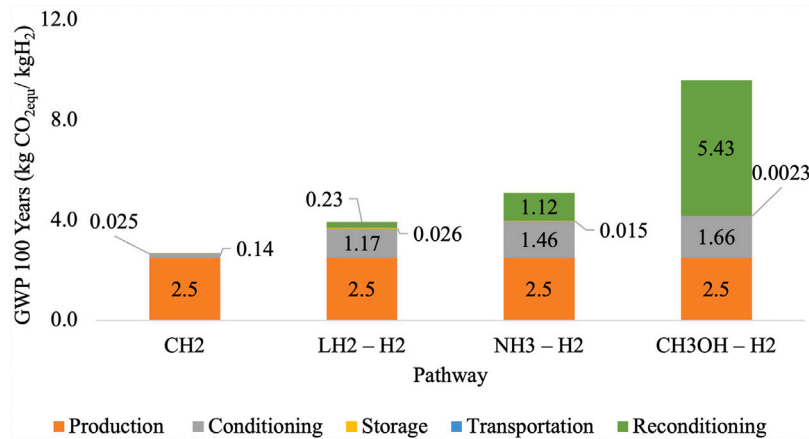
Fig. 10. The GWP of each stage in the HSN of each pathway that delivers hydrogen as an end product.

emitting more emissions (i.e., 1.12 $kgCO_{2equ}/kgH_2$). The ammonia cracking process contributes to 29.7% of the total GWP. However, the CO_2 dehydrogenation process in the $CH_3OH - H_2$ pathway emits the most CO_2 (i.e., 5.43 $kgCO_{2equ}/kgH_2$) compared to other reconditioning processes in other pathways, as it is an endothermic process that requires the most heat and electricity (i.e., 0.37 kWh/kgH_2 and 10 kWh/kgH_2 of thermal energy) to dehydrogenate methanol to hydrogen; hence, this requires burning natural gas which emits CO_2. It produces the most emissions. The CO_2 dehydrogenation process contributes to 56.6% of the total GWP.

- **Ammonia and Methanol as End-Product Pathways**

Fig. 11 highlights the GWP of each stage (i.e., production, conditioning, storage, and transportation) in the HSN of ammonia and methanol pathway. The figure shows that for the production stage, the CH_3OH pathway emits 9.1% (i.e., 0.48 $kgCO_{2equ}/kgCH_3OH$) more than the NH_3 pathway (0.44 $kgCO_{2equ}/kgNH_3$), when the CPV-T collectors are employed. If the PV-T collectors are employed, the GWP of the CH_3OH pathway is 0.54 $kgCO_{2equ}/kgCH_3OH$, 12.5% more than the CPV-T collectors. The GWP of the NH_3 pathway is 0.49 $kgCO_{2equ}/kgNH_3$, 11.4% more than the CPV-T collectors. Comparing the two pathways together when PV-T collectors are employed, the CH_3OH emits 9.3% more than the NH_3 pathway. If PV panels are employed, the GWP of the CH_3OH is 0.74 $kgCO_{2equ}/kgCH_3OH$, 54.2% more than the CPV-T collectors. The GWP of the NH_3 pathway is 0.68 $kgCO_{2equ}/kgNH_3$, 54.5% more than the CPV-T collectors. Comparing the two pathways when PV panels are employed, the CH_3OH emits 8.8% more than the NH_3 pathway. The production stage and conditioning stage of the CH_3OH pathway has always a higher GWP than the NH_3 pathway for the same reasons explained earlier in Section 4.2.

4.4. Overseas transportation

This paper provides a further analysis of transportation to gain insights into the GWP. This paper assumes that the capacity of the container/ tanker is 160,000 m^3 and the end product (i.e., hydrogen, ammonia, or methanol) is transported from Qatar to Japan. Hence, the traveled distance is around 8000 km, and the speed is 37 km/hr. This paper calculates the quantities of the end product transported in the container/ tanker in one trip by considering the density of the transported end product and the volume of the container/tanker. Table 5 highlights the transported quantities of each pathway along with the GWP. This paper considers the boil-off of 0.2%, 0.04%, and 0.005% when transporting liquefied hydrogen, ammonia, and methanol, respectively.

Fig. 12 highlights the GWP of the transportation stage of each pathway, considering the assumptions mentioned above. This paper

notices that transporting hydrogen in a compressed state in containers has the lowest GWP (i.e., 0.4×10^6 $kgCO_{2equ}/kgH_2$) compared to other carriers. The reason is that compressed hydrogen has the lowest density (i.e., 38 kg/ m^3); thus, transporting it consumes the least fuel and has the least emissions. On the other hand, transporting hydrogen in methanol form in tankers has the highest GWP (5.8×10^6 $kgCO_{2equ}/kgH_2$). The reason is that methanol has the highest density (i.e., 793 kg/m^3); thus, transporting it consumes the most fuel and thus has the most emissions. One would expect that liquefied hydrogen would have the highest emissions due to the high boil-off (i.e., 0.2%) compared to other products. In between, transporting liquefied hydrogen in tankers emits 0.00175 $kgCO_{2equ}/kgH_2$, which is higher than transporting compressed hydrogen since it has a higher density than compressed hydrogen. However, it has lower emissions than transporting ammonia as the liquefied hydrogen has a lower density than ammonia. Comparing the other states with the compressed state, the emissions increase by 75%, 87%, and 93% for $LH_2 - H_2$, $NH_3 - H_2$, and $CH_3OH - H_2$ pathways, respectively. This paper concludes that as the density of the product increases, more quantities can be transported overseas. However, more fuel is consumed during the voyage, which results in more emissions.

5. Discussion of results

In the present paper, the GWP of all the green H_2 pathways has been assessed via LCA. The comparison of this paper's results with prior studies offers new insights about pathways that have never been investigated so far, namely $NH_3 - H_2$ and $CH_3OH - H_2$. Besides, some differences emerged on the remaining pathways that are worth further discussion. Table 6 summarizes the results obtained in the present paper with the ones reported in the literature from prior similar studies.

Cetinkaya et al. [40] reported that the GWP of producing hydrogen from electrolysis coupled with PV panels is 2.41 $kgCO_{2equ}/kgH_2$; however, its scope considered the production stage only. Considering the same scope, this LCA value is 3.03 $kgCO_{2equ}/kgH_2$. The percentage difference between the two values is 22.8%.

For the $LH_2 - H_2$ pathway, Frank et al. [41] reported a GWP between 5.10 and 5.28 $kgCO_{2equ}/kgH_2$, which is almost in line with this LCA value (5.05 $kgCO_{2equ}/kgH_2$) when standard PV panels are employed. Their scope is almost the same, with minor differences. The percentage difference between the two values is between 0.99% and 4.45%.

For the NH_3 pathway, Yousefi Rizi and Shin [42] reported a GWP of 1.15 $kgCO_{2equ}/kgH_2$, while [32,34] estimated a GWP value of 1.03 $kgCO_{2equ}/kgH_2$ and 1.1 $kgCO_{2equ}/kgH_2$, respectively. This LCA estimated a GWP significantly lower (0.90 $kgCO_{2equ}/kgH_2$) when standard
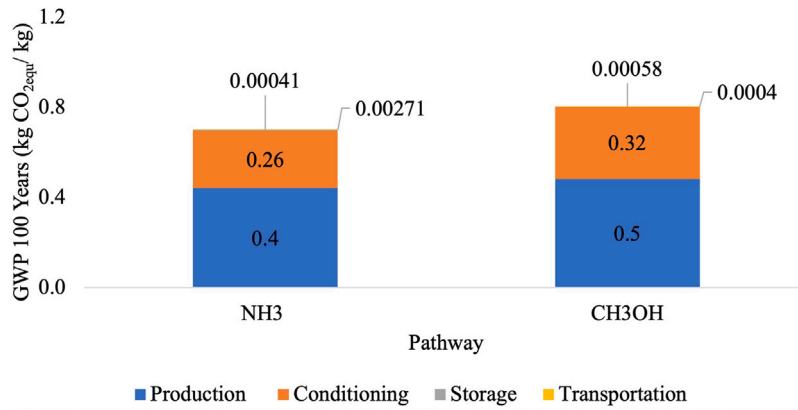
Fig. 11. The GWP of each stage in the green HSN of each pathway that delivers ammonia or methanol as an end product.
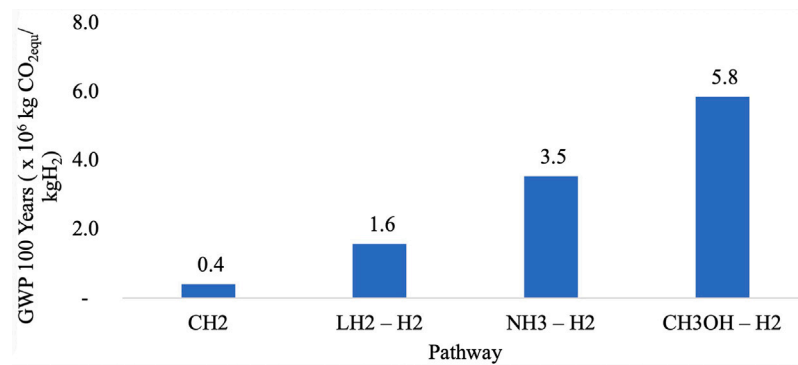

Fig. 12. The GWP of the transportation stage of each pathway.

Table 5
The transported quantities of each pathway and the GWP.

Pathway	CH_2	LH_2–H_2	NH_3–H_2	CH_3OH–H_2
End product	CH_2	H_2	H_2	H_2
Transported product	CH_2	LH_2	NH_3	CH_3OH
Density (kg/m³)	38	71	683	792
Quantity (kg)	6,080,000	11,360,000	109,216,000	126,720,000
Quantity to be transported (kg)	18,249,300	1,573,880	3,543,200	5,849,700
GWP 100 years (kg CO_{2equ}/kgH_2)	**400,300**	**1,573,880**	**3,543,200**	**5,849,700**

Table 6
A comparison between GWP values obtained in the present paper and the values reported in literature from prior studies.

Pathway	Present paper	Prior studies	Percentage of difference	Reference
CH_2	3.03	2.41	22.8%	Cetinkaya et al. [40]
LH_2–H_2	5.05	0.99%–4.45%	5.1; 5.28	Frank et al. [41]
NH_3–H_2	6.22	N.A	N.A	N.A
CH_3OH–H_2	10.73	N.A	N.A	N.A
NH_3	0.90	1.15; 1.03; 1.1	20%–24.4%	Yousefi Rizi and Shin [42], Demirel [32] and Al-Breiki and Bicer [34]
CH_3OH	1.02	0.53–1.56	41.6%–63.2%	Sarp et al. [43]

PV panels are employed. Their scope is almost the same, with minor differences. The percentage difference is between 20% and 24.4%.

For the CH_3OH pathway, Sarp et al. [43] reported that the GWP of almost the same scope as this LCA, except for transportation stages, is between 0.53 and 1.555 kgCO_{2equ}/kgH_2. This LCA value for the CH_3OH pathway is 1.02 kgCO_{2equ}/kgH_2. The percentage difference between the two values is 41.6% and 63.2%. Regardless of the percentage difference, this LCA value lies between the reported values of 0.53 and 1.555 kgCO_{2equ}/kgH_2.

6. Conclusion

This paper conducts an LCA study to compare 18 different green HSN pathways. It makes two main research contributions, (i) analyzing

the environmental impacts of producing green hydrogen from coupling PV panels, PV-T collectors, or CPV-T collectors with electrolyzers, and (ii) comparing the environmental impacts of 18 green hydrogen pathways, encompassing of core five stages, to determine the pathway with the lowest GWP.

The LCA results show that coupling CPV-T collectors with the electrolysis process produces the lowest GWP compared to PV panels and PV-T collectors, for all pathways. The CPV-T collectors achieve GWP reduction ranging from 10.5% and 26.4%, and from 1.04% and 3.37% compared to the standard PV panels and PV-T collectors, respectively, depending on the pathway.

More specifically, the LCA results indicate that when hydrogen is delivered as an end product to the user, the CH_2 pathway has the

lowest environmental impact at 2.67 kgH_2, compared to pathways that deliver hydrogen as an end product. This pathway involves producing hydrogen by coupling CPV-T collectors with an electrolyzer and compressing it. Furthermore, when ammonia is delivered as an end product to the user, the NH_3 pathway has the least environmental impact, measuring just 0.70 $kgCO_{2equ}$/kg compared to the other 18 investigated pathways. This pathway involves producing hydrogen by coupling CPV-T collectors with an electrolyzer and conditioning it to ammonia.

Despite the emission reduction that CPV-T collectors have to offer compared to other collectors due to their high efficiency, their reliance on concentrated sunlight raises questions about land use and ecosystem disruption. Additionally, their costs are relatively still high, where the cost of one panel is estimated to be 600$ [44]. On the other hand, standard PV panels would cost around 110$. This could potentially limit the CPV-T collectors' widespread application.

The results of this LCA study advance the knowledge in the hydrogen energy domain by allowing policymakers, researchers, and industry stakeholders to make informed decisions to optimize processes and resources, reduce GHG emissions, and enhance sustainability across the different stages of the HSN.

Future research can be directed toward investigating the blue HSN pathways, enabling a more thorough comparison between green hydrogen and blue hydrogen HSN.

Nomenclature

Abbreviation

Ammonia	NH_3
Carbon Dioxide	CO_2
Concentrated Photovoltaic Thermal Collectors	CPV-T
Global Warming Potential	GWP
Hydrogen	H_2
Hydrogen Supply Chain	HSC
Hydrogen Supply Network	HSN
Industrial Produced	IP
Kilogram	kg
Kilogram of Carbon Dioxide Equivalent	$kgCO_{2equ}$
Life Cycle Assessment	LCA
Life Cycle Inventory	LCI
Life Cycle Impact Assessment	LCIA
Liquid Organic Hydrogen Carrier	LOHC
Methanol	CH_3OH
Photovoltaic	PV
Photovoltaic Thermal Collectors	PV-T
Treated Sewage Effluent	TSE

CRediT authorship contribution statement

Dana Alghool: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohamed Haouari:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Paolo Trucco:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

The data are available in the Supplementary Material.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.06.346.

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