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ORIGINAL ARTICLE

Economics and Sustainability of Introducing Clean Hydrogen from Australia in the Republic of Korea

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Abstract

Hydrogen is one of the alternative energy sources given its clean combustion without carbon emissions and high gravimetric energy density. However, it is required for the hydrogen to be generated by cleaner pathways rather than the conventional gas reforming pathway which emits significant carbon. Currently, it is considered that water electrolysis using renewable energy is the ultimate cleaner pathway of hydrogen production. Unfortunately, given that renewable energy capacity has a large deviation by the global region and may not meet some regional demands, the international trading of renewable energy-based clean hydrogen will be inevitable. In line with the trend, a case study of introducing clean hydrogen from Australia in Korea is conducted with economic and environmental impact analyses to indicate its economics and sustainability. In the pathway of hydrogen introduction, water electrolysis with renewable energy mix, and ammonia are considered as the hydrogen production way, and hydrogen carrier, respectively.

Keywords Hydrogen · Renewable energy · Ammonia · Unit cost · Greenhouse gas

Introduction

The era of global boiling follows the era of global warming, recording the hottest month in 2023. Furthermore, given that the rise in global temperature is definitely due to greenhouse gas (GHG) emissions, even the hotter months await us if the GHG emissions keep increasing. Thus, to mitigate the global boiling by reducing GHG emissions, various technical efforts have been made for industrial sectors especially the energy sector which is the majority of the global emissions. The main strategies for the energy sector include near-term technologies such as combining carbon capture into conventional plants, and long-term technologies such as electrification of plants, and alternating energy sources with new and renewable energies. As one of the representative new energies, hydrogen (H_2) has been spotlighted given its high gravimetric energy density and clean combustion without carbon emissions. Even though the H_2 does not emit GHG during combustion, its current production processes such as steam methane reforming (SMR) emit significant amounts of carbon dioxide making its life-cycle highly carbon-positive. Thus, cleaner production processes are required for H_2 to become a future sustainable energy source and one of the possible processes for cleaner production of H_2 suggested so far is water electrolysis with renewable electricity which produces green H_2. Here, the most important thing for green H_2 to be stably produced is the stable and sufficient supply of renewable electricity. However, the capacity of renewable energy is significantly varied by global region, so several countries can produce more H_2 than their domestic demands while other countries cannot meet their domestic demands by their own production. Thus, it is clearly considered that the international trade of green H_2 will be necessary in the future for H_2 to become a major energy source worldwide and various possible projects have been announced so far, mainly in several major countries including Korea, Japan, Australia, to name a few, as presented in Table 1.

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Table 1 Announced projects for international trade of H_2

Main proponents	Importer	Exporter	Project title	H_2 type	H_2 carrier	Amount (tonH_2/y)	Target year	Refs.
Chiyoda	Japan	Brunei	SPERA	Blue	LOHC	–	2040	[1]
CSIRO, JSE, J-Power, Sumitomo	Japan	Australia	HESC	Blue	LH_2	225,000	2030	[2]
SABIC, Mitsui O.S.K. Lines	Japan	Saudi Arabia	–	Blue	NH_3	2,000,000	2030	[3]
Total Eren	Asia and Europe	Chile	H_2 Magallanes	Green	NH_3	800,000	2027	[4]
Total Eren, Provaris Energy	Asia (Singapore)	Australia	HyEnergy	Green	NH_3	200,000	–	[5]
Fortescue Future Industries	–	Australia	Bell Bay Hydrogen	Green	NH_3	44,000	2030	[6]
Origin Energy	Asia (Japan)	Australia	Green H_2	Green	LH_2	36,500	2030	[7]
Sumitomo	Japan	Australia	–	Green	–	–	–	[8]
Sumitomo, Colbun S. A	Japan	Chile	–	Green	NH_3	–	–	[9]
Hydrogen Utility, Royal Vopak	Korea, Japan	Australia	H_2-Hub Gladstone	Green	NH_3	300,000	–	[10]
Provaris Energy	Asia (Japan)	Australia	Tiwi H_2	Green	CGH_2	90,000	2028	[11]
Provaris Energy, Norwegian Hydrogen	Europe	Norway	–	Green	CGH_2	40,000	2027	[12]
Hyphen Energy	Germany	Namibia	–	Green	NH_3	353,000	2030	[13]
Iberdrola, Trammo	Northern Europe (Germany, Netherlands, France)	Southern Europe	–	Green	NH_3	18,000	2026	[14]
Korea Zinc, Ark Energy	Korea	Australia	–	Green	NH_3	100,000	2030	[15]
Analyzed by Net Zero Technology Center	Germany	Scotland	–	Green	CGH_2	1,000,000	2030	[16]

Fig. 1 Announced national targets related to the production amount of H_2 in the Republic of Korea

Among the various projects presented in Table 1, Australia, Japan, and the Republic of Korea are the majorities preparing international trade of green H_2 for compensating the imbalance of their capacity and demand. Currently, the Korean Ministry of Trade announced a report for the H_2 economy in 2021 containing detailed targets related to the production amount of H_2 in the future as presented in the Fig. 1 [17]. According to the report, the Republic of Korea is planning to produce domestic clean H_2 of more than 1 million tons annually by 2030 and 5 million tons by 2050 and import overseas clean H_2 of about 2 million tons annually by 2030 and 23 million tons by 2050.

At the same time, numerous large-scale renewable energy generation sites are under construction and even already powered on in Australia to utilize abundant renewable energy sources which are sufficient to fulfill domestic demands and export yield energy as well. Renewable energy capacities of each state and territory are presented in Fig. 2a and it is clear that most of the large-scale generation sites are in Eastern Australia including Queensland, New South Wales, and Victoria accounting for more than 80% of the total capacity of Australia [18]. Among the various projects for the generation of renewable energy in Eastern Australia, three representatives including Sun Metals solar farm, Macintyre wind farm, and Collinsville wind farm are considered in this study as presented in Fig. 2b [19–21]. Here, a H_2 hub named 'SunHQ' is under construction at the site near the Sun Metals solar farm in Townsville so this hub is considered for the production of green H_2 with renewable energy [22].

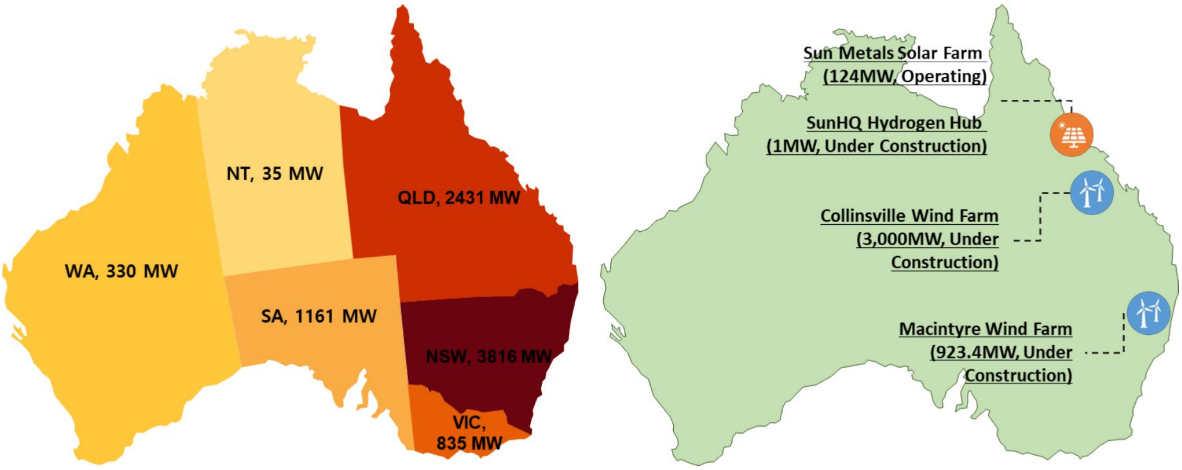

Fig. 2 Australia Nation's renewable energy **a** industry powered on in 2022 and **b** some representative projects in Eastern states

In line with the trends, the economics and sustainability of the green H_2 supply pathway between Australia and Korea are analyzed in this study, with unit cost and GHG emission of supplied H_2 by currently suggested representative pathways. As Fig. 3 presents, the scope of consideration for the pathways includes renewable electricity generation with both solar photovoltaic (PV) and wind power, water electrolysis H_2 production, H_2 transmission from production site to exporting port, synthesis of ammonia (NH_3) which is considered to as a H_2 carrier, NH_3 storage in both exporting and importing port, NH_3 ship transportation, reformation of NH_3 to H_2 with cracking, and the final storage of H_2 in Korea.

Methods

Before estimating the expenditures and emissions from the whole supply chain of green H_2 trade pathways, a detailed scope with supposed technologies for each process and real conditions of project sites are required to be structured. Thus, the structured scope of the whole project pathway is demonstrated in Fig. 4. Two representative cases are considered with a base scenario for the first case and a more optimistic scenario for another case. First, the capacity of renewable electricity mixed with solar PV and wind energy is assumed to be 600 MW and different percentages of each renewable energy are considered for the two cases. Also, the Macintyre wind farm which is about 1500 km away from the H_2 production hub is considered for case 1, while another wind farm named Collinsville about 200 km far from the hub is considered for case 2. For the water electrolysis base production of green H_2, there are three representatives of the electrolyzer type including alkaline electrolyzer, proton-exchange membrane (PEM) electrolyzer, and solid-oxide electrolyzer [23]. Among the types, the PEM electrolyzer is considered in this study, given that it currently reached a commercialization level, operates at a comparatively higher pressure and current density resulting in high efficiency and purity, and also can be smoothly linked to renewable energy due to its short start-up time [23]. Of the renewable power produced at a total scale of 600 MW, 500 MW is assumed to be used to produce green H_2 and the rest energy to other required processes in Australia including

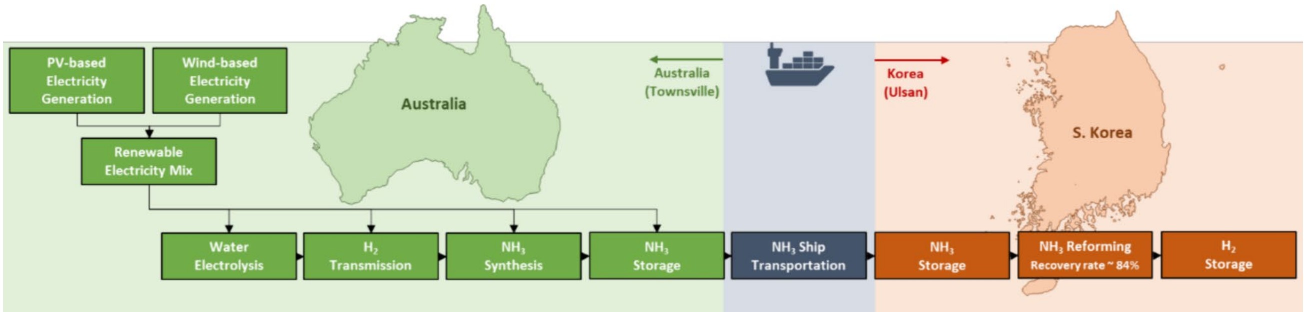

Fig. 3 Overall schematic diagram of the considered pathway for supplying green H_2 from Australia to Korea

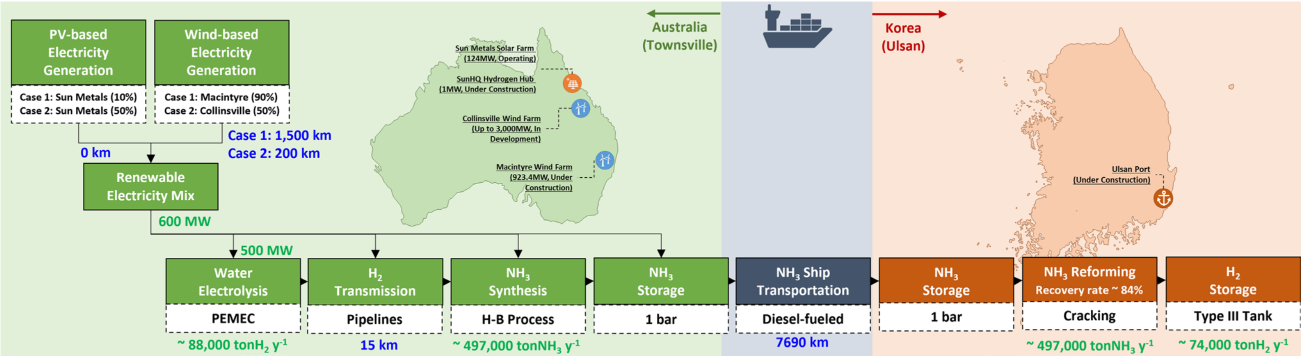

Fig. 4 Detailed scope for each process and conditions of the considered project in this study

H_2 transmission, NH_3 synthesis, and storage. Thus, green H_2 is produced about 88,000 tons annually in Australia, so the corresponding NH_3 production is about 497,000 tons annually. The produced H_2 at the production site is required to be transmitted to the exporting port in Australia, and the existing Townsville port is considered in this study. For the transmission, the H_2 pipeline is considered to be used due to the large amount (88,000 tonH$_2$ y^{-1}) and short distance (15 km) between the site and port. Before the transportation of H_2 from Townsville in Australia to the port of Korea, it is commonly required for H_2 to be conditioned into the form of liquid-state carriers such as liquid H_2 (LH_2), liquid organic H_2 carrier (LOHC), and NH_3, given that the gaseous H_2 itself has a significantly low volumetric energy density making its transportation economically uncompetitive and unstable [24]. As Table 1 presents, most of the current projects are considering NH_3 as a feasible H_2 carrier for their supply pathways, and it is due to its appropriate H_2 contents (~ 17 wt%), and ease of storage compared to the other types of carrier, so NH_3 is considered to as the H_2 carrier in this study as well. Here, numerous researches have been conducted to develop a new technique for synthesizing NH_3 rather than the conventional Haber–Bosch (H–B) process which emits significant amounts of GHG, however, there is no industrial-scale alternative yet [25], so the currently possible H-B process is considered, remaining the possibility of emission reduction through alternation of this process in the future. The synthesized NH_3 will be stored near the Townsville port followed by transportation to Korea with a conventional vessel which is fueled by marine diesel. Thus, additional emission reduction may be expected in this transportation process by considering other eco-friendly vessels such as LNG-fueled, H_2-powered, and to name a few. The existing Ulsan port is considered the port in Korea for importing overseas H_2, given that a green H_2 logistics hub is under construction in Ulsan port intended to be completed by 2030 and it will feature facilities for green NH_3 import and NH_3 cracking as well [26]. After the transportation, some of the imported green NH_3 will be stored and others will be reformed back to H_2 by cracking at the facility featured in the port. Through the considered NH_3 cracking process with a recovery rate of 84%, some amount of the supplied NH_3 will be lost, and eventually, about 74,000 tons of H_2 will be supplied in the final. Finally, the supplied green H_2 will be stored in an H_2 storage tank for further distribution to end-users in Korea.

Economic Analysis

Basically, economic analysis is commonly conducted by estimation of total expenditure (TOTEX) which is the sum of capital expenditure (CAPEX) and operating expenditure (OPEX). The CAPEX of a process includes all the expenditures associated with construction and modifications of required plants for the process, while the OPEX of a process includes all the expenditures associated with consumption of required raw materials, electricity, labor, maintenance, and to name a few. The exact cost of required equipment can be directly provided by a current price quote from a vendor or obtained cost data can be used with several adjustments for considering the effects of capacity and time with the following Eqs. (1) and (2), respectively.

Table 2 Capital and operating costs associated with a solar farm

Descriptions/unit	Value	
	Case 1	Case 2
PV module capital/\$ kW^{-1}	1300 [29]	140 [30]
PV module O&M/\$ kW^{-1} y^{-1} [29]	5	5
PV converter (inverter) capital/\$ kW^{-1} [29]	40	40
PV converter O&M/\$ kW^{-1} y^{-1} [29]	10	10

O&M operating and maintenance costs

Table 3 Specifications of the considered Plug Power's PEM electrolyzer cell

Descriptions/unit	Value
Stack life/y	10
Electricity consumption/kWh kgH_2^{-1}	49.9
Water consumption/gal kgH_2^{-1}	2.7
Stack cost/\$ kW^{-1+}	~354 (curve fitting)

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \tag{1}$$

$$C_2 = C_1 \cdot \left(\frac{I_2}{I_1}\right) \tag{2}$$

where A, C, I, and n refer to equipment cost attribute, purchased cost, cost index, and cost exponent, respectively. Subscripts a and b refer to equipment with the required attribute and base attribute, respectively, and 1 and 2 refer to the base time when the cost is known and the time when the cost is desired, respectively.

To analyze the annual expenses of the process together with annually expensed OPEX, the initially expensed costs of required equipment can be annualized by multiplication of capital recovery factor (CRF) which can be calculated by Eq. (3) considering the lifetime of the equipment and discount rate. In this study, the discount rate of 4.5% is assumed for the estimation of all the required processes, and different lifetimes are considered for the respective process.

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where i refers to discount rate (%) and N can refer to lifetime/project year/economic analysis period/the number of annuities received.

With the basic logic for the estimation of economics, expenditure from each process can be individually calculated. First, for the electricity generation with solar energy at the Sun Metals solar farm, energy generated by each PV panel can be calculated with the following Eq. (4) using the panel area, yield, and global horizontal irradiation value of the desired production site, and performance ratio.

$$E = A \times r \times H \times \mathrm{PR} \tag{4}$$

where E, A, r, H, and PR refer to energy generated by a panel (kWh y^{-1}), total solar panel area (m^2), solar panel yield, global horizontal irradiation (kWh m^{-2} y^{-1}), and performance ratio. Here, a 10 m^2 size panel with 19.8% yield and 10% loss is considered, and the global horizontal irradiation of Townsville in Australia is found to be about 2120 kWh $m^{-2}y^{-1}$ [27].

For the electricity generation with wind energy at the both Macintyre and Collinsville wind farms, power generated by each turbine can be calculated with the following Eqs. (5)–(6) using the air density, wind speed, blade size, efficiency, and possible losses from various parts.

$$P_{\mathrm{Turbine}} = 0.5 \cdot \rho_{\mathrm{air}} \cdot v_{\mathrm{Wind}}^3 \cdot (\pi l_{\mathrm{Blade}}^2) \cdot \mu \tag{5}$$

$$\mu = (1 - k_{\mathrm{m}}) \cdot (1 - k_{\mathrm{e}}) \cdot (1 - k_{\mathrm{t}}) \cdot (1 - k_{\mathrm{w}}) \cdot C_{\mathrm{P}} \tag{6}$$

where P_{Turbine} (VA) refers to the real output power of a wind turbine considering the total efficiency, ρ_{air}, v_{Wind}, l_{Blade} are air density (1.225 kg m^{-3}), wind speed (m s^{-1}), and blade length of the turbine (81.5 m), respectively. Here the wind speed of the considered wind farms is found to be about 9.5 m s^{-1} [28]. μ is the efficiency of the turbine which can be calculated by Eq. (6) with losses. k_{m}, k_{e}, k_{t}, k_{w}, C_{P} are mechanical losses of blades and gearbox (0.3%), electrical losses of the turbine (0%), time out of order (3%), wake losses (10%), and turbine efficiency (40%), respectively.

Here, the electrical losses of the turbine are assumed to be 0% in this equation and losses occurred from the long-distance transmission of electricity are separately estimated for consideration by Eq. (7) with specific resistance of copper cable (16.8 nΩ·m), distance, current (A), and cross-sectional area of considered cable (800 mm^2). Associated capital and operating costs required for the solar farm are organized in Table 2 and correlation equations for estimating costs related to wind farms are presented in Eqs. (8)–(13).

$$\mathrm{Loss(MW)} = \mathrm{Current}^2 \cdot R_{\mathrm{Cu}} \cdot \frac{L_{\mathrm{Cable}}}{A_{\mathrm{Cable}}} \tag{7}$$

Ref. [31]

$$C_{\mathrm{Turbine}}(\$\mathrm{EA}^{-1}) = 191 \cdot 10^3 \cdot P_{\mathrm{Turbine}} \tag{8}$$

Ref. [32]

Table 4 Specifications of the Haber–Bosch NH_3 synthesis and NH_3 cracking processes

Descriptions/unit	Synthesis [37]	Cracking [37, 38]
Base plant investment cost/M\$	36	477
Base plant capacity/tonNH_3 d^{-1}	250	2,880
Electricity usage/kWh kgH_2^{-1}	3.74	1.5
Heat usage/kWh kgH_2^{-1}	0	9.7
Cost exponent/–	0.67	0.67

Table 5 Specifications of the conventional diesel-fueled ship [39]

Descriptions/unit	Value
Ship investment cost/M$	80
Max loading/tonNH_3	50,400
Average speed/knots	17.38
Fuel cost/$ ton^{-1}	395
Fuel consumption/ton d^{-1}	39
Operating cost/$ d^{-1}	5550
Distance/km	7690

Table 6 Specifications of the storage system for NH_3 and H_2

Descriptions/unit	H_2 [40]	NH_3 [41]
Tank capacity/ton	1	56,700
Tank investment/M$	0.7	97
Electricity use/kWh kgH_2^{-1}	3.7	0.02
OPEX/ % of CAPEX	2	2
Storing percentage/% of total	20	20
Storing period/ days	30	30

$$C_{\text{Support}}(\$\text{EA}^{-1}) = 1.373 \cdot 10^{-3} \cdot P_{\text{Turbine}} \cdot \left(1 + 0.8 \cdot 10^{-6} \cdot \left(h_{\text{hub}} \cdot l_{\text{Blade}}^{2} - 10^{5}\right)\right) \tag{9}$$

Ref. [33]

$$C_{\text{Transformer (LV-MV)}}\left(\$\text{EA}^{-1}\right) = -170{,}000 + 145{,}000 \cdot \left(V_{\text{Cable}} \cdot I_{\text{Cable}}\right)^{0.4473} \tag{10}$$

Ref. [33]

$$C_{\text{Transformer (MV-HV)}}\left(\$\text{EA}^{-1}\right) = -47{,}397 \cdot \left(V_{\text{Cable}} \cdot I_{\text{Cable}}\right)^{0.7513} \tag{11}$$

Ref. [32]

$$C_{\text{Cable,66kV}}\left(\$\text{km}^{-1}\right) = 96{,}700 + 87{,}912 \cdot e^{234.35 \cdot I_{\text{Cable}} \cdot 10^{-5}} \tag{12}$$

Ref. [32]

$$C_{\text{Substation}}\left(\$\text{EA}^{-1}\right) = 0.98 \cdot 55{,}500 \cdot P_{\text{Wind}} \tag{13}$$

where Current, R_{Cu}, L_{Cable}, and A_{Cable} refer to the current of the considered cable (A), the resistance of copper (Ω•m), length (m), and cross-sectional area (mm^2) of the considered cable, respectively. h_{hub}, V_{Cable}, I_{Cable}, P_{Wind} refer to the height of a wind turbine (m), cable voltage level (MV), cable ampacity (A), and installed wind power capacity (MVA), respectively.

With the calculated energy generated by each panel or wind turbine and investigated expenditures for construction and operation of equipment for the farm, the levelized cost of electricity (LCOE) generated by the considered electricity generation farm can be calculated with a related Eq. (14).

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{14}$$

where I_t, M_t, F_t, E_t refer to investment expenditures, operations and maintenance expenditures, fuel expenditures, and electrical energy generated in a considered year t, respectively. r refers to the discount rate, and n is the expected lifetime of the system or power station.

For the production of green H_2 by water electrolysis, PEM electrolyzer cell is considered in this study as aforementioned, and specifications of the electrolyzer are based on the product of Plug Power (EX-4250D) and organized in Table 3 [34]. In addition, the cost data according to the system scale are obtained from the International Renewable Energy Agency (IRENA) report and utilized in curve fitting for identifying a correlation equation between cost and scale of the system presented in Eq. (15) [35].

$$C_{\text{Stack}}\left(\$\ \text{kW}^{-1}\right) = 1081.35025 \cdot \text{Scale}_{\text{Stack}}(\text{MW})^{-0.17465} \tag{15}$$

Given that the distance between SunHQ H_2 hub and Townsville port is about 15 km, transmission of the produced H_2 from the production site to the exporting port is required. Thus, the H_2 transmission by pipelines is considered and related costs can be estimated using following equations from (Eq 16) to (Eq 22) which are reconfigured with proper unit operation based on provided relational expressions for estimating appropriate diameter of pipelines, required material costs, required labor costs, and to name a few, in a previous study [36].

$$D_{\text{Pipe}} = \left[\left(\left(\frac{r_{H_2}}{21{,}024}\right)^{0.9091} \cdot d_{\text{Pipe}}^{0.5} \cdot 4.524\right)^{0.415}\right] \cdot 0.025 \tag{16}$$

$$M_{\text{Pipe}} = 1869 \cdot \left(\frac{D_{\text{Pipe}}}{0.025}\right)^{2} \tag{17}$$

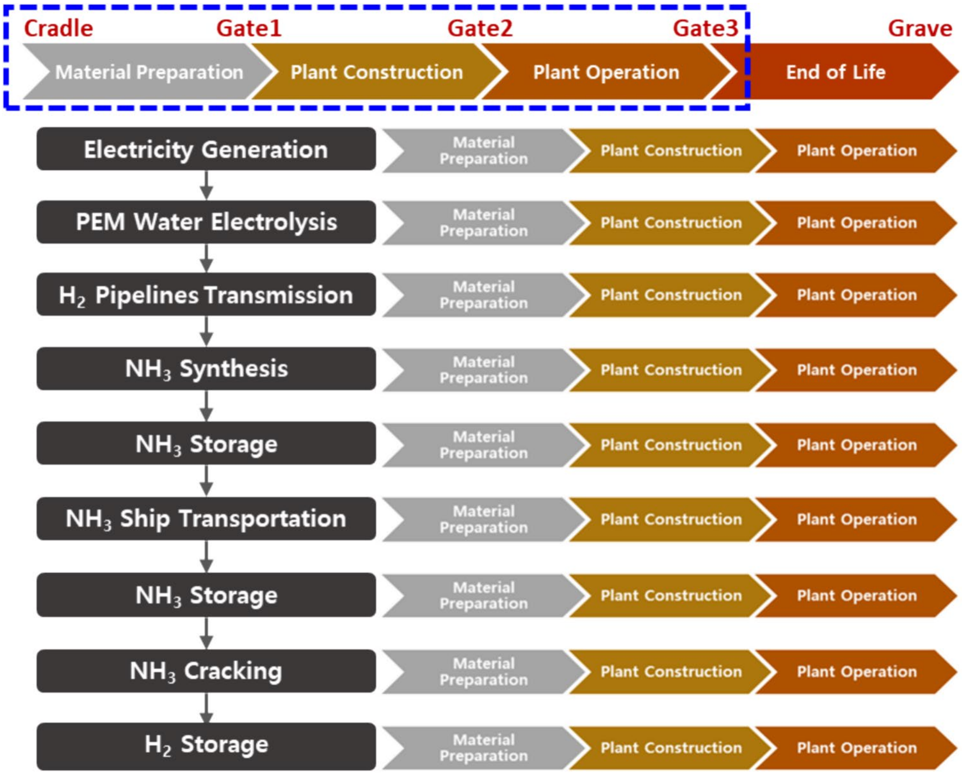

Fig. 5 Description of the boundary condition considered for environmental impact analysis in this study

$$L_{\mathrm{Pipe}} = \left(\left(343 \cdot D_{\mathrm{Pipe}} \cdot 39.37\right)^2 + 2074 \cdot \left(D_{\mathrm{Pipe}} \cdot 39.37\right) + 170{,}013\right) \cdot \left(d_{\mathrm{Pipe}} \cdot 1.609\right) + 185{,}000) \tag{18}$$

$$E_{\mathrm{Comp}} = 820 \cdot r_{\mathrm{H}_2} \tag{19}$$

$$C_{\mathrm{Comp}} = 1{,}455{,}000 \cdot r_{\mathrm{H}_2} \tag{20}$$

$$C_{\mathrm{Pipe}} = \left(\mathrm{IR} + M_{\mathrm{Pipe}}\right) \cdot d_{\mathrm{Pipe}} \cdot \mathrm{CRF} + C_{\mathrm{Comp}} \tag{21}$$

$$O_{\mathrm{Pipe}} = L_{\mathrm{Pipe}} \cdot \mathrm{CRF} + C_{\mathrm{Pipe}} \cdot 5\% + E_{\mathrm{Comp}} \tag{22}$$

where D, M, L, E, and IR refer to the diameter of pipelines, material cost for manufacturing pipelines, labor cost required for construction of pipelines, electricity cost for powering pipelines by compressors, and installation and right-of-way costs for pipelines, respectively. d_{Pipe}, C_{Pipe}, and O_{Pipe} refer to the distance of required pipeline construction in kilometers, CAPEX, and OPEX of the constructed pipelines, respectively. Here, the IR, and lifetime of pipelines are assumed to be 600,000 \$ km^{-1} and 50 years, respectively, in this study.

Next, the produced and transmitted green H_2 requires a conditioning process for it to be stored and transported in the form of an H_2 carrier and a reconditioning process for the carrier to discharge the stored H_2 as well. Because the NH_3 is considered to be the H_2 carrier in this study, analysis of Haber–Bosch NH_3 synthesis and cracking of NH_3 are conducted and associated specifications of the processes are organized in Table 4. To estimate the variable OPEX associated with electricity usage, since NH_3 synthesis takes place in Australia, the estimated Australian renewable energy-based electricity price was applied, while an assumed Korean electricity price of 0.06 \$ kWh^{-1} was applied to NH_3 cracking given that it takes place in Korea. For case 2 considered in this study, the required heat energy for cracking of NH_3 is neglected given the possibility of heat integration with other processes, assuming the optimistic scenario.

After the conditioning of H_2, the synthesized green NH_3 will be transported by ship from Australia to Korea. The conventional marine diesel-fueled ship is considered for the ship transportation process in this study and required specifications for the analysis are organized in Table 5. As the table presents, the ship with a max loading capacity of 50,400 tons of NH_3, average speed of about 17 knots, and daily fuel consumption of 39 tons is considered for 7690 km of green NH_3 transportation from Australia to Korea in this study.

Before the transportation of NH_3 in Australia and both the imported green NH_3 and H_2 after the reconditioning of

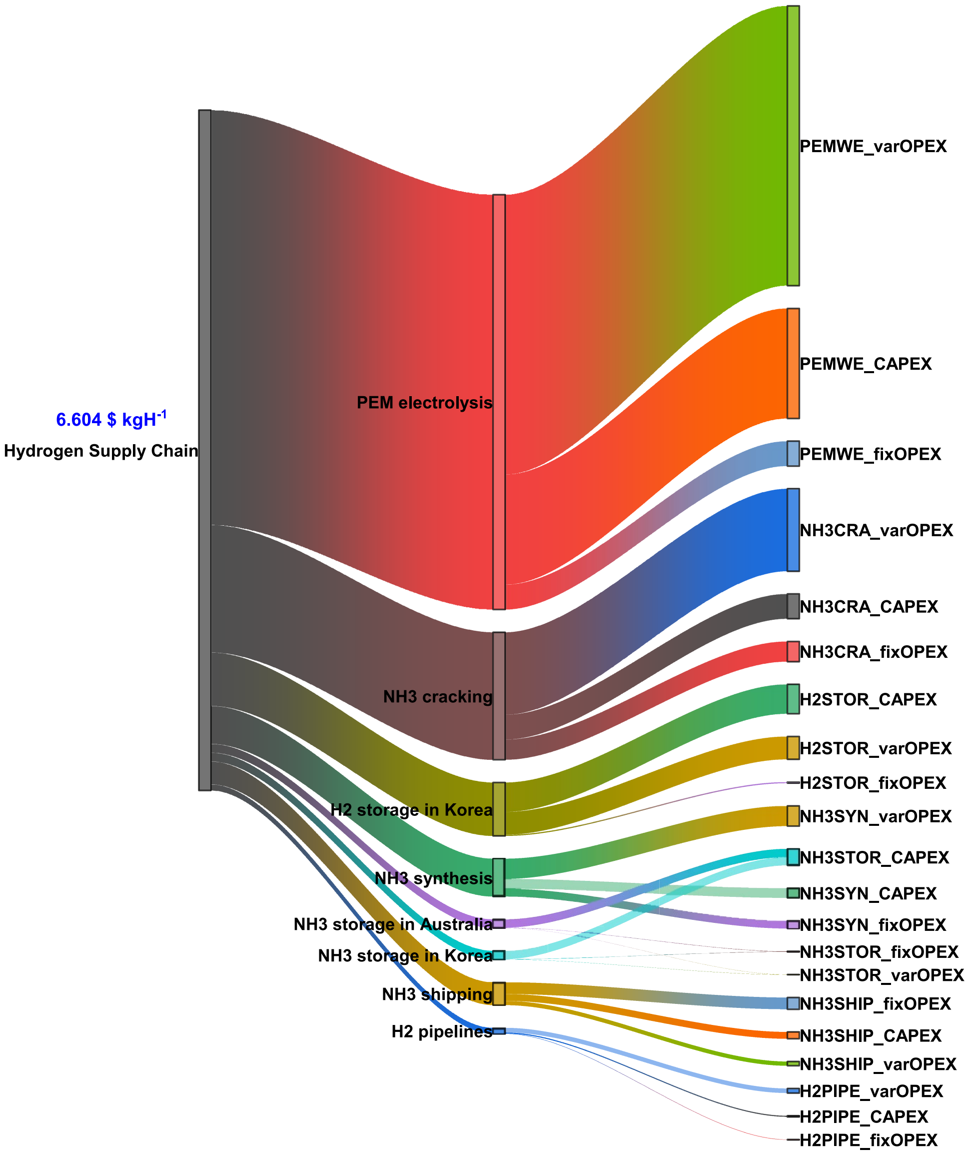

Fig. 6 Unit H_2 cost expensed for introducing green H_2 from Australia to Korea by considered pathway with case 1

transported green NH_3 in Korea will require some storage system at the port. For the H_2 storage, though there are five types of tank according to the used components and structures, type III tank which is overwrapped by metal liner composite is considered for the storage process in this study, given that the tank can endure some high-pressure up to 700 bars and has a much more efficient capacity than commonly used type I tank, that is, a smaller and lighter tank can be used to store the same amount than the type I [40]. Even though the type III tank is the priciest of all the types so far due to the use of carbon fiber, a number of studies predict that its price could be lowered [40]. The specifications associated with storage tank for NH_3 and H_2 are organized in Table 6.

Sustainability Analysis

To identify the sustainability of the considered pathway for green H_2 introduction from Australia in Korea, environmental impact analysis is conducted by estimating GHG emission amount with the 'GREET' model developed by the Argonne National Laboratory. Basically, there are various kinds of GHGs including the representative carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), but only the three representatives are considered to as GHGs for the environmental impact analysis in this study. Global warming potential (GWP) is an index to measure how much infrared thermal radiation a GHG absorbs over a given time after it has been emitted to the

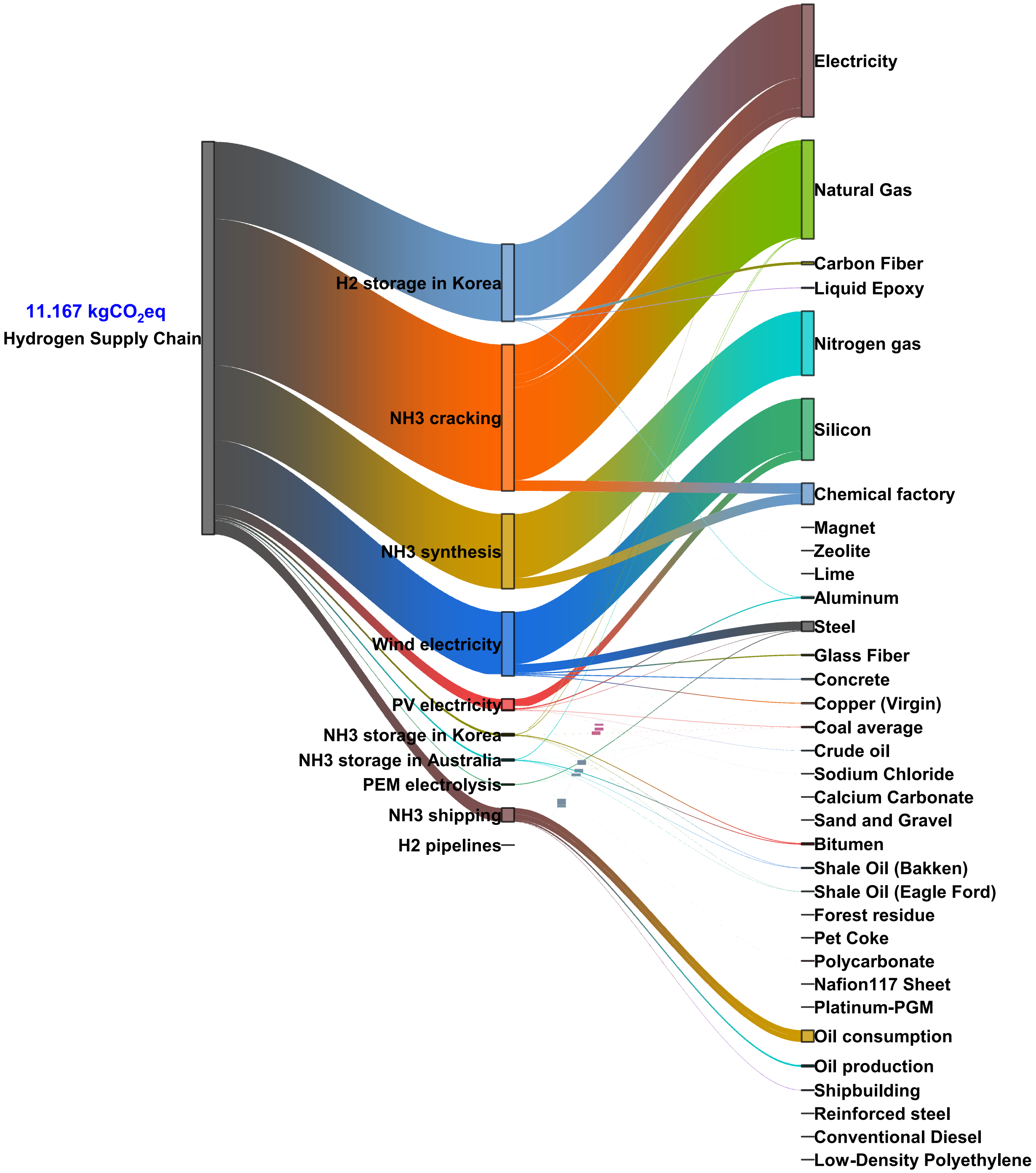

Fig. 7 GHG emissions for introducing green H_2 from Australia to Korea by considered pathway with case 1

atmosphere. It can be measured according to the strength of gas absorption, the rate of gas removal from the atmosphere, and the considered time frame. Among the several standards, a GWP over 100 years (GWP-100) of each is considered to be 1, 28, and 265 for CO_2, CH_4, and N_2O, respectively, following the IPCC Fifth Assessment Report in 2014 (AR5) [42]. The functional unit is considered to be the GHG emission amount to supply 1 kg of H_2. For the boundary condition of analysis, 'cradle-to-gate', which can consider the stages from material preparation to plant operation except for the end-of-life stage, is considered for each process of the pathway from electricity generation in Australia to the final storage in Korea as Fig. 5 describes. Amounts of all the required resources for each process of

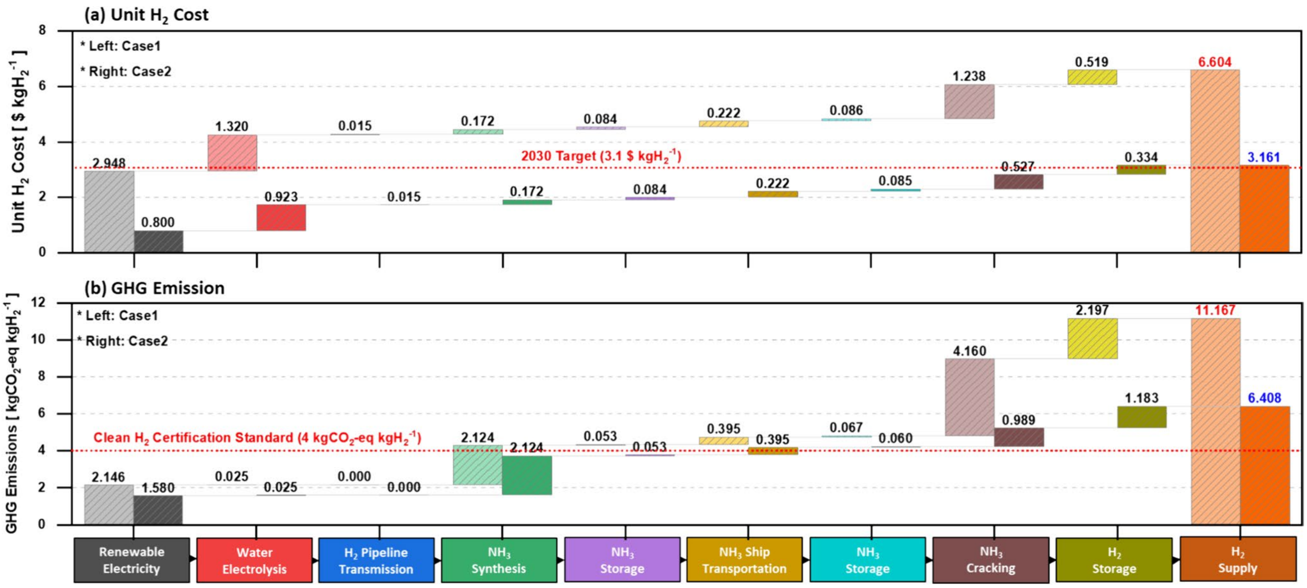

Fig. 8 Comparative results of **a** unit H_2 cost and **b** GHG emission from green H_2 supply pathway with case 1 and case 2

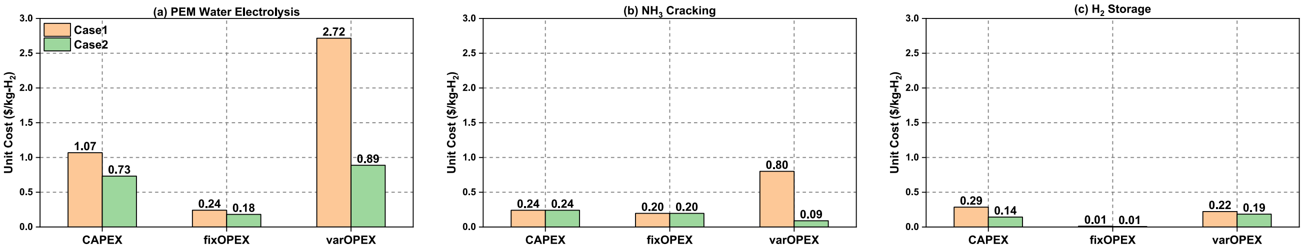

Fig. 9 Detailed results of estimated unit H_2 costs from cost-intensive processes. **a** PEM water electrolysis, **b** NH_3 cracking, and **c** H_2 storage account for the highest percentages of the total cost of green H_2 supply pathway

the overall pathway are based on numerous studies that have been published and all the used values are organized in supplementary information. The supply routes of each resource could be applied by using both default pathways and GREET and user-defined pathways as well.

Results and Discussion

From the analyses on costs expensed and GHGs emitted by introducing green H_2 from Australia to Korea, unit cost and sustainability of the introduced green H_2 can be identified. The analyses are conducted on the two cases of pathway to indicate not only how much the costs and emissions are inevitable with conservatively considering all the required technologies, but also how much they can be reduced by considering optimistically improved technologies for several processes. First, results of unit H_2 cost and GHG emission from the pathway with case 1 are presented in Figs. 6 and 7, respectively, with the form of a Sankey diagram for indicating the hot spots of each. In the case of unit H_2 cost, the total is about 6.6 \$ kgH_2^{-1} and the majority of the total depends on PEM electrolysis H_2 production with renewable energy generation which is presented as a variable OPEX of the electrolysis process. Here, among the total expenditure to generate renewable electricity, CAPEXs expensed for the related facilities are the majority. In addition to the H_2 production, NH_3 cracking and H_2 storage processes account for large percentages of the total as well, especially the heat and electricity required for the NH_3 cracking which is presented as a variable OPEX of the cracking process. In the case of GHG emission, the total is about 11.2 $kgCO_2$-eq kgH_2^{-1} and the majority of the total depends on NH_3 cracking for regeneration of H_2 due to its highly required heat and electricity and the use of conventional grid in Korea. Thus, some feasible alternatives such as heat integration for mitigation of heat usage and utilization of possible renewable energy sources in Korea for reducing the emission from

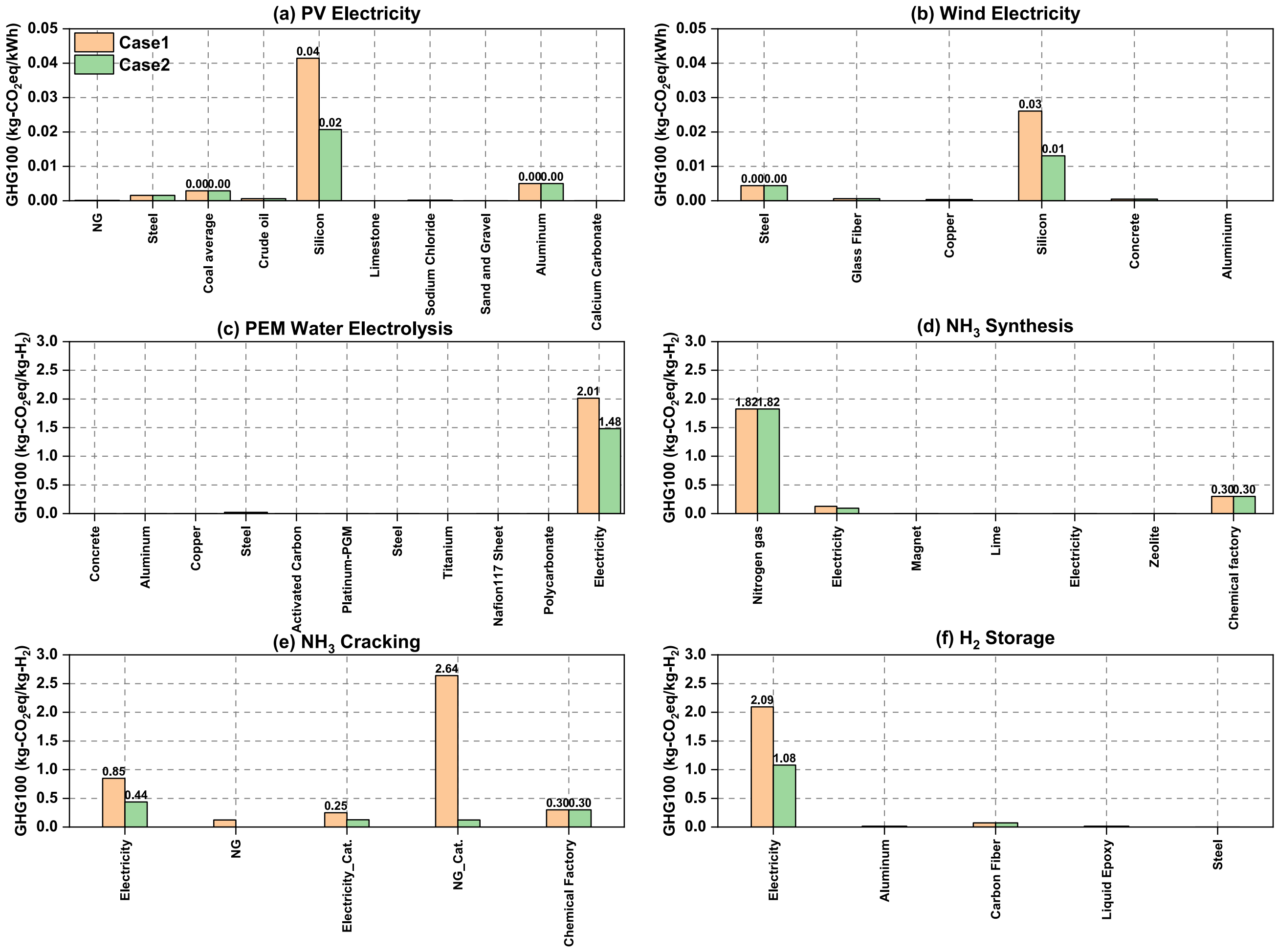

Fig. 10 Detailed results of estimated GHG emissions from emission-intensive processes. (**a**) and (**b**) indicate the emissions from renewable energy generation on the same scale given that electricity accounts for the most parts of each process. Other subgraphs from (**c**) to (**f**) indicate the emissions from the major processes from H_2 production to H_2 storage on the same scale and the processes in Australia (electrolysis and NH_3 synthesis) include emissions from using renewable electricity as well

electricity consumption may be considered. In addition to the NH_3 cracking process, H_2 storage, wind electricity generation, and NH_3 synthesis also generate large amounts of GHGs more than 2 $kgCO_2$-eq kgH_2^{-1} from each of them. Electricity required to store H_2 in Korea is the main cause that the H_2 storage process becomes one of the emission-intensive processes and nitrogen from air separation unit (ASU) and silicon are the main cause of NH_3 synthesis and wind electricity generation, respectively. Thus, the total unit cost and GHG emission from green H_2 supply might be significantly reduced if some kinds of improvement and alternatives for the current technologies are used in the aforementioned majorities.

Here, though the emission from wind electricity is much higher than the emission from solar PV electricity, the result is that the used electricity amount of wind-based is much higher than solar-based, that is, the comparison between those two kinds of process needs to be conducted with the same unit amount of electricity for both. From the analysis with the same unit amount, the solar PV and wind electricity emit 0.052 and 0.032 $kgCO_2$-eq kWh^{-1}, respectively. Thus, for solar PV energy to be competitive compared to wind energy, it is required for its process to reduce the use of the main cause of its emission, and the main cause is found to be the use of silicon for manufacturing panels.

As abovementioned, the total unit H_2 cost and emissions from the supply pathway can be reduced by possible reduction of material uses, utilization of new technologies, and conditions of the pathway. Thus, with several assumptions mentioned in the methodology section, case 2 is also considered to be analyzed in this study for comparison with case 1. To recap assumptions for case 2, first, the ratio of used renewable energy is the same for both wind and solar-based energy, while those are 90% and 10% for case 1. Second, given that the loss occurred from the transmission of wind energy from Macintyre farm which is 1500 km far apart from the H_2 hub is very high, the Collinsville farm which is 200 km from the hub is considered for case 2. Third, CAPEXs of wind turbines, solar PV modules, and PEM electrolyzer systems, H_2 storage tanks are assumed to be lower than case 1, and grid electricity price in Korea is considered to be 50 \$ MWh^{-1} while it is 60 for case 1. Fourth, the heat energy required to crack NH_3 into H_2 is neglected considering the possibility of heat integration for the process. Fifth, the usage of emission-intensive materials such as platinum for manufacturing PEM electrolyzer cells, and silicon for wind turbines and solar panels are considered to be half of the consumption considered in case 1. Last, the percentage of wind energy used for electricity in Korea is assumed to be increased from 4% to 30% decreasing the percentage of coal-based energy generation from 40% to 14%.

The results of the analysis on case 2 can be found in Fig. 8 compared with the results of case 1. As Fig. 8 presents, the cost of generating renewable electricity, producing H_2 by electrolysis, and cracking of NH_3 can be significantly reduced by assuming different shares of solar and wind energy, the optimal CAPEXs of renewable farms and electrolyzer cells, and energy consumption. Here, the price reduction of renewable energy consequently reduces the cost of energy consumption required throughout the entire process in Australia. With the considerable reduction in several major processes, the total unit H_2 cost of the supplied green H_2 can be reduced to 3.161 \$ kgH_2^{-1} which is lower than half of the cost of green H_2 supplied with case 1. Not only the cost reduction but also the GHG emission reduction can be realized by considering case 2 for the pathway. The lower usage of several emission-intensive materials, increased percentage of wind energy for electricity used in Korea, and heat energy integration could reduce emissions from several processes such as renewable electricity

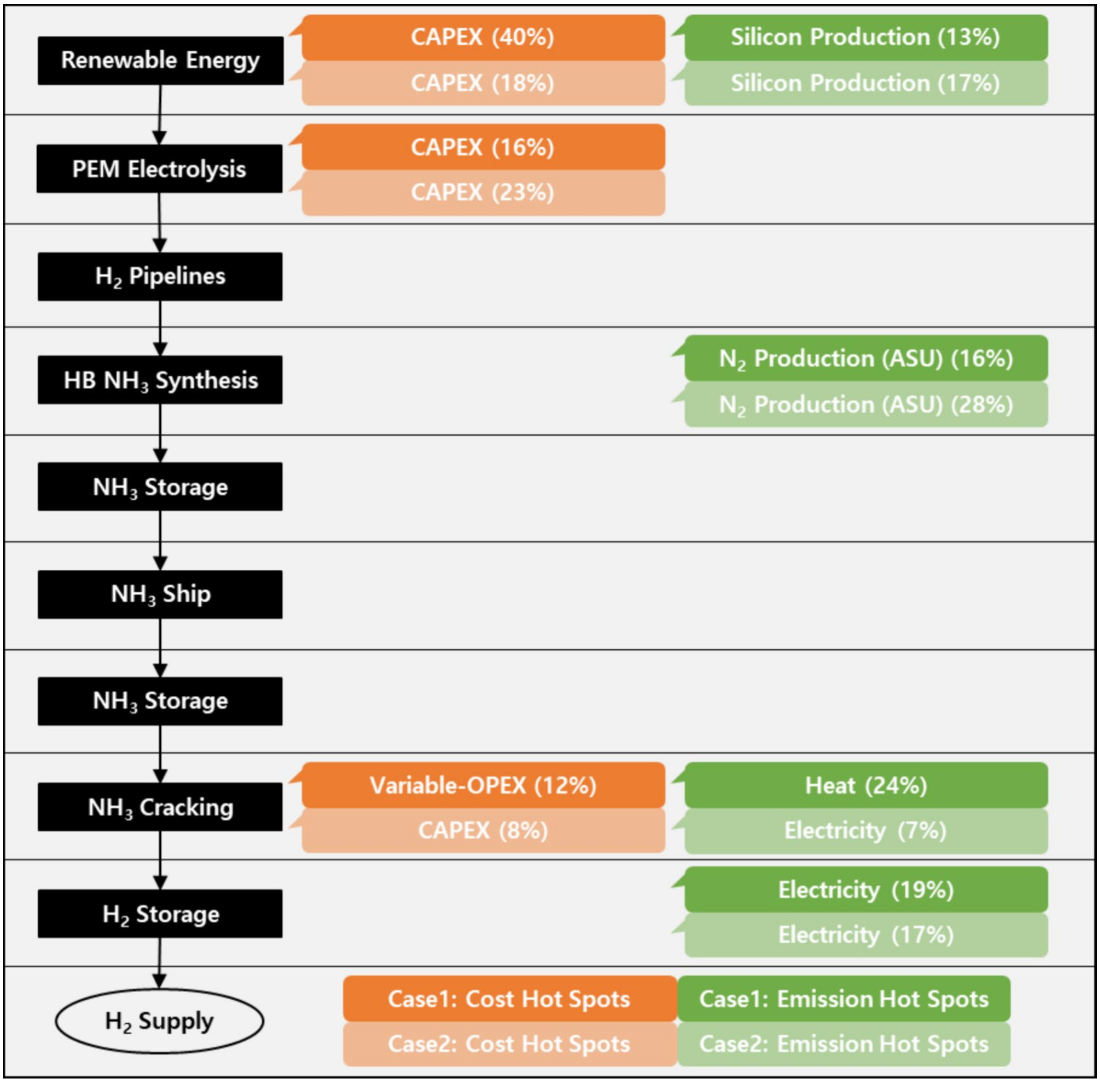

Fig. 11 Verified hot spots of cost and GHG emission in the analyzed green H_2 pathway

generation, NH_3 cracking, and H_2 storage. Considering case 2, the total GHG emission for supplying green H_2 can be reduced to 6.408 $kgCO_2$-eq kgH_2^{-1} while the emission is 11.167 $kgCO_2$-eq kgH_2^{-1} with case 1. Comparing the unit H_2 cost with the Korean national target cost of H_2 in 2030 and GHG emission with the clean H_2 certification standard in Korea [43, 44], both cost and emission of the pathway with case 1 are not yet in competitive ranges. Moreover, the GHG emission of the pathway cannot be competitive even considering case 2. Therefore, for the supplied H_2 to be certified as the clean H_2 in Korea, additional strategies would be necessary, such as improved technologies for renewable energy, alternative technology for synthesis of NH_3, use of more environmentally friendly vessels for transportation, an increasing percentage of renewable energy for electricity use in Korea, to name a few.

More detailed results of estimated costs and emissions from the major processes of the pathway with both cases are presented in Figs. 9 and 10. In the case of unit H_2 costs presented in Fig. 9, PEM water electrolysis with renewable energy accounts for the most percentage of the total cost mainly due to the variable OPEX which includes the renewable electricity price. Thus, several assumptions for possible cost reduction are considered including the cheaper CAPEXs, a closer wind farm, and different percentages of renewable energies, and the results of case 2 show significantly reduced variable OPEX which is approximately one-third of case 1. The variable OPEX of the NH_3 cracking process includes the cost for providing heat energy by NG indicating quite a high cost and emission as well, so an assumption that the heat integration for providing the required heat is considered for case 2, given the possibility of heat integration for the process. With the assumption, the considerable reduction of variable OPEX and emission from NG in the process can be found in Figs. 9b and 10e. As mentioned before, a significant reduction in several processes can be found due to the reduced use of resources like silicon and electricity, however, the emissions from providing electricity for all the presented processes, and nitrogen gas for NH_3 synthesis are still high making the supplied H_2 not feasible get certified as a clean H_2. Therefore, in addition to the efforts for the realization of technological assumptions in the case 2 scenario, the considerable emission reductions in electricity generation and air separation units are necessary for the green H_2 supplied by the suggested pathway to achieve at least the certification standard of clean H_2 in Korea.

Conclusions

Though green H_2 which is produced by water electrolysis coupled with renewable energy is currently considered to as a feasible alternative energy source, the capacity of its production heavily depends on the renewable energy capacity causing the regional deviation globally. Thus, the international trading of green H_2 is considered as the possible solution for mitigating the deviation and several projects have been announced and proceeding for realization of trading so far. This study aims to verify the economics and sustainability of one of the projects between Australia and Korea by covering the overall pathway of the project from green H_2 production in Australia to storage in Korea. The pathway is analyzed for two cases with the first case considering all the technologies conservatively and the second case considering several possible improved technologies and reduced resource usage.

The results from the analysis on case 1 indicate the total unit H_2 cost of 6.6 \$ kgH_2^{-1} and the GHG emission of 11.167 $kgCO_2$-eq kgH_2^{-1}. In the total unit H_2 cost of the supplied H_2, the majority is from the process of renewable energy-based PEM electrolysis H_2 production which accounts for about 65% of the total cost. Among the costs that emerged from renewable energy generation, CAPEXs for construction of the required facilities such as panels and turbines account for significant portions. In addition to the renewable energy generation and PEM electrolysis processes, NH_3 cracking and H_2 storage in Korea are majorities of the total cost as well due to their high energy consumption. In the GHG emission from the H_2 supply pathway, the majority of the total is NH_3 cracking due to its heat and electricity consumption and the associated use of natural gas and conventional grid in Korea. Similar to the cost-intensive processes, H_2 storage, wind energy generation, and NH_3 synthesis also account for a significant portion of the total more than 2 $kgCO_2$-eq kgH_2^{-1} from each process. The H_2 storage process emits significant GHGs due to its high consumption of electricity from the Korean grid, wind energy is due to the use of silicon, and NH_3 synthesis is due to the additional process to produce the required nitrogen by ASU.

The results from the analysis on case 2 indicate much lower unit H_2 cost and GHG emission, which are 3.161 \$ kgH_2^{-1} and 6.408 $kgCO_2$-eq kgH_2^{-1}, respectively. Significant reduction is mainly due to the reductions from the processes of renewable energy generation, NH_3 cracking, and H_2 storage. However, considering that the Korean national target cost of H_2 supply in 2030 is 3.1 \$ kgH_2^{-1} and the clean H_2 certification standard in Korea is 4 $kgCO_2$-eq kgH_2^{-1}, both estimated cost and emission from the pathway for supplying green H_2 with case 1 are not feasible yet and even with case 2 are uncertain to clearly achieve the national criteria. Therefore, additional strategies would be required especially in the electricity generation, electrolysis, NH_3 synthesis, cracking, and H_2 storage processes as are hot spots presented in Fig. 11. For the electricity generation, recycling silicon which is required to manufacture wind turbines and solar PV panel may generate the most considerable reduction in GHG emission from the process. For the PEM water electrolysis H_2 production, increasing plant size and reducing or replacing the required rare elements may generate the most reduction in cost expensed from the process. Last, for the H_2 storage in Korea, increasing the share of renewable energy for electricity will be the most necessary thing to reduce both cost and emission from the process. In addition to the strategies for the hot spots, others including the use of more environmentally friendly vessels for transportation of NH_3 and increasing the percentage of renewable energy for electricity use in Korea, to name a few, may be possible to be considered in the future for reduction in GHG emissions from the pathway.

In this study, most of the incidental processes including pipeline transmission, NH_3 synthesis, ship transportation, and storage are considered with conventional technologies like the HB process, conventional marine diesel-fueled vessels, use of conventional grid in Korea, and to name a few. Those conservative considerations might present realistic and stable guidelines for people to materialize the green H_2 introduction with the suggested pathway, however, several improved technologies like electrified HB, and NG-fueled vessels, that are quite possible to be considered may be analyzed in future work. Also, for the assessment of GHG emissions from each process of the pathway, most of the scope 1 and 2 emissions could be considered while most of the scope 3 emissions could not be considered except for the emissions from manufacturing the required equipment and facilities. Thus, a more comprehensive and expanded analysis of the environmental impact of the process will be required to present more realistic and reliable results in future work.

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Data availability We authors can provide the related calculation of the percentage results in this figure if requested.

References

1. SPERA HydrogenTM Chiyoda's Hydrogen Supply Chain Business|CHIYODA Corporation n.d. https://www.chiyodacorp.com/en/service/spera-hydrogen/. Accessed 21 Dec 2023
2. Home—HESC n.d. https://www.hydrogenenergysupplychain.com/. Accessed 21 Dec 2023
3. Japan Receives First Low-Carbon Ammonia Cargo from Saudi Arabia—Hydrogen Central. n.d. https://hydrogen-central.com/japan-receives-first-low-carbon-ammonia-cargo-saudi-arabia/. Accessed 21 Dec 2023
4. Total Eren, 칠레에서 친환경 수소 프로젝트 시작 n.d. https://www.enerdata.co.kr/publications/daily-energy-news/h2-magallanes-new-total-eren-project.html. Accessed 21 Dec 2023
5. HyEnergy Project—HyResource n.d. https://research.csiro.au/hyresource/hyenergy-project/. Accessed 21 Dec 2023
6. Bell Bay Hydrogen Plant—Infrastructure Pipeline n.d. https://infrastructurepipeline.org/project/bell-bay-green-hydrogen-plant. Accessed 21 Dec 2023
7. Australia: Green Hydrogen Project Signs MOU With Port of Townsville. n.d. https://fuelcellsworks.com/news/australia-green-hydrogen-project-signs-mou-with-port-of-townsville/. Accessed 21 Dec 2023
8. Rio Tinto and Sumitomo Corporation to build hydrogen pilot plant for world's first trial lower-carbon alumina refining in Gladstone | Sumitomo Corporation n.d. https://www.sumitomocorp.com/en/jp/news/release/2023/group/16870. Accessed 21 Dec 2023
9. Memorandum concluded on green hydrogen and ammonia production in Chile | Sumitomo Corporation n.d. https://www.sumitomocorp.com/en/jp/news/topics/2023/group/20230203. Accessed 21 Dec 2023
10. H2U, Vopak to work on Gladstone green hydrogen and ammonia export project—Offshore Energy n.d. https://www.offshore-energy.biz/h2u-vopak-to-work-on-gladstone-green-hydrogen-and-ammonia-export-project/. Accessed 21 Dec 2023
11. Tiwi H2—HyResource n.d. https://research.csiro.au/hyresource/tiwi-h2/. Accessed 21 Dec 2023
12. Provaris and Norwegian Hydrogen launch 270MW green hydrogen project in Norway—Offshore Energy n.d. https://www.offshore-energy.biz/provaris-and-norwegian-hydrogen-launch-270mw-green-hydrogen-project-in-norway/. Accessed 21 Dec 2023
13. Namibia Signs $10 Billion Green Energy Deal With Germany's Hyphen n.d. https://www.voanews.com/a/namibia-signs-10-billion-green-energy-deal-with-germany-s-hyphen-/7118163.html. Accessed 21 Dec 2023
14. Iberdrola to build €750m green hydrogen plant in Southern Europe to supply ammonia to world-leading exporter | Hydrogen news and intelligence n.d. https://www.hydrogeninsight.com/production/iberdrola-to-build-750m-green-hydrogen-plant-in-southern-europe-to-supply-ammonia-to-world-leading-exporter/2-1-1464927. Accessed 21 Dec 2023
15. 고려아연 n.d. https://www.koreazinc.co.kr/?pageName=business/hydrogen_supply_uses&mainMenuId=kz-business&subMenuId=kz-biz-renewable-energy&menuId=kz-biz-hydrogen-supply. Accessed 21 Dec 2023
16. Scotland should capitalise on hydrogen pipeline exports to Europe—NZTC report | ICIS n.d. https://www.icis.com/explore/resources/news/2023/08/30/10920088/scotland-should-capitalise-on-hydrogen-pipeline-exports-to-europe-nztc-report/. Accessed 21 Dec 2023
17. Intralink, The Hydrogen Economy South Korea, Market Intelligence Report (2021). https://www.intralinkgroup.com/Syndication/media/Syndication/Reports/Korean-hydrogen-economy-market-intelligence-report-January-2021.pdf
18. Clean Energy Australia Report 2023 Clean Energy Australia Report 2023 Section Name 2 Accelerate Invest Explore n.d.
19. Collinsville Green Energy Hub | Ark Energy n.d. https://arkenergy.com.au/wind/collinsville-green-energy-hub/. Accessed 21 Dec 2023

20. MacIntyre Wind Farm | Ark Energy n.d. https://arkenergy.com.au/wind/macintyre-wind-farm/. Accessed 21 Dec 2023
21. Sun Metals Solar Farm | Ark Energy n.d. https://arkenergy.com.au/solar/sun-metals-solar-farm/. Accessed 21 Dec 2023
22. SunHQ Hydrogen Hub | Ark Energy n.d. https://arkenergy.com.au/hydrogen/hydrogen-project/. Accessed 21 Dec 2023
23. A. Kim, H. Kim, C. Choe, H. Lim, Feasibility of offshore wind turbines for linkage with onshore green hydrogen demands: a comparative economic analysis. Energy Convers. Manage. **277**, 116662 (2023). https://doi.org/10.1016/J.ENCONMAN.2023.116662
24. A. Kim, Y. Yoo, S. Kim, H. Lim, Comprehensive analysis of overall H_2 supply for different H_2 carriers from overseas production to inland distribution with respect to economic, environmental, and technological aspects. Renew. Energy **177**, 422–432 (2021). https://doi.org/10.1016/J.RENENE.2021.05.127
25. Deakin Bsc J. De-carbonising ammonia: alternatives to the Haber Bosch process? n.d.
26. 울산항만공사 국문홈페이지 > ESG경영 > (E) 지속가능한 친환경 항만 > 친환경에너지 물류허브 조성 > LNG, 수소 물류허브 구축 선도 n.d. https://www.upa.or.kr/contents.do?mId=0010150120040001000. Accessed 21 Dec 2023
27. Global Solar Atlas n.d. https://globalsolaratlas.info/map?c=-19.41803,147.137146,10&s=-19.255405,146.825409&m=site. Accessed 21 Dec 2023
28. Global Wind Atlas n.d. https://globalwindatlas.info/en. Accessed 21 Dec 2023
29. C. Ghenai, T. Salameh, A. Merabet, Technico-economic analysis of off grid solar PV/fuel cell energy system for residential community in desert region. Int. J. Hydrogen Energy **45**, 11460–11470 (2020). https://doi.org/10.1016/J.IJHYDENE.2018.05.110
30. M.K. Abbas, Q. Hassan, V.S. Tabar, S. Tohidi, M. Jaszczur, I.S. Abdulrahman et al., Techno-economic analysis for clean hydrogen production using solar energy under varied climate conditions. Int. J. Hydrogen Energy **48**, 2929–2948 (2023). https://doi.org/10.1016/J.IJHYDENE.2022.10.073
31. A. Elia, M. Taylor, B. Gallachóir, F. Rogan, Wind turbine cost reduction: a detailed bottom-up analysis of innovation drivers. Energy Policy **147**, 111912 (2020). https://doi.org/10.1016/J.ENPOL.2020.111912
32. U. Cali, N. Erdogan, S. Kucuksari, M. Argin, Techno-economic analysis of high potential offshore wind farm locations in Turkey. Energy Strat. Rev. **22**, 325–336 (2018). https://doi.org/10.1016/J.ESR.2018.10.007
33. R. Meere, J. Ruddy, P. McNamara, T. O'Donnell, Variable AC transmission frequencies for offshore wind farm interconnection. Renew. Energy **103**, 321–332 (2017). https://doi.org/10.1016/J.RENENE.2016.11.037
34. Plug EX-4250D Electrolyzer (English) n.d. https://resources.plugpower.com/electrolyzers/ex-4250d-f041122. Accessed 27 Dec 2023
35. IRENA, Green Hydrogen Cost Reduction Scaling Up Electrolysers to Meet the 1.5°C Climate Goal H_2O (2020). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf
36. N. Parker, *Using Natural Gas Transmission Pipeline Costs to Estimate Hydrogen Pipeline Costs* (University of California, USA, 2004)
37. F.I. Gallardo, A. MonfortiFerrario, M. Lamagna, E. Bocci, D. Astiaso Garcia, T.E. Baeza-Jeria, A techno-economic analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. Int. J. Hydrogen Energy **46**, 13709–13728 (2021). https://doi.org/10.1016/J.IJHYDENE.2020.07.050
38. Y. Ishimoto, M. Voldsund, P. Nekså, S. Roussanaly, D. Berstad, S.O. Gardarsdottir, Large-scale production and transport of hydrogen from Norway to Europe and Japan: value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. Int. J. Hydrogen Energy **45**, 32865–32883 (2020). https://doi.org/10.1016/J.IJHYDENE.2020.09.017
39. M. Niermann, S. Drünert, M. Kaltschmitt, K. Bonhoff, Liquid organic hydrogen carriers (LOHCs)—techno-economic analysis of LOHCs in a defined process chain. Energy Environ. Sci. **12**, 290–307 (2019). https://doi.org/10.1039/C8EE02700E
40. T. Amirthan, M.S.A. Perera, The role of storage systems in hydrogen economy: a review. J. Nat. Gas Sci. Eng. **108**, 104843 (2022). https://doi.org/10.1016/J.JNGSE.2022.104843
41. General inputs General n.d.
42. Global Warming Potential Values n.d.
43. Korean Government. Hydrogen economy activation roadmap. (2019). https://www.motie.go.kr/kor/article/ATCLf724eb567/210222/view#
44. South Korea plans to match US clean hydrogen standard—but won't include shipping of raw materials in its calculations | Hydrogen News and Intelligence n.d. https://www.hydrogeninsight.com/production/south-korea-plans-to-match-us-clean-hydrogen-standard-but-won-t-include-shipping-of-raw-materials-in-its-calculations/2-1-1436627. Accessed 5 Jan 2024