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Sustainability assessment of supply chains for green hydrogen production

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A B S T R A C T

The sustainability of supply chains for green hydrogen production is compared from a life cycle point of view: 1) offshore electrolysis with electricity from Dutch wind farms followed by pipeline transport of hydrogen to Rotterdam (Netherlands), 2) onshore electrolysis in Rotterdam with electricity from the same wind farms, 3) electrolysis with electricity from solar PV in Algeria followed by pipeline transport of hydrogen and 4) electrolysis and ammonia production with electricity from solar PV in Saudi Arabia followed by deep sea transport and ammonia cracking. The environmental sustainability is assessed with ReCiPe 2016 and Environmental Footprint 3.0. The Total Cumulative Exergy Loss (TCExL) method is used to calculate the exergetic sustainability. According to the endpoint scores, offshore electrolysis with wind energy is preferred, but the difference between the TCExL scores of both wind energy options is small. The preference order of the other supply chains is undecided. The offshore wind option is also preferred according to the midpoint indicators GWP/climate change, land use and water consumption/use. It is advised that the systems be investigated in more detail before drawing conclusions about the order of preference and that also attention be paid to the economic and social pillars of sustainability.

1. Introduction

The Netherlands is known for a high penetration of the use of natural gas in Dutch households and industry. However, the earthquakes caused by natural gas extraction, the limited availability of natural gas on the world market and the threat of climate change stimulated the search for alternative energy carriers such as hydrogen. The production of hydrogen from natural gas with capture and storage of the resulting carbon dioxide (blue hydrogen production) and hydrogen produced from renewable sources and energy carriers (green hydrogen production) have the attention of scientists, policy makers and companies [1–3].

About 0.8 million ton per year of hydrogen is produced in the Netherlands without capture and storage of CO_2, resulting in approximately 12.5 million ton of CO_2 emissions [4]. Several initiatives are being taken to make hydrogen production more sustainable. E.g., the H-vision project [5,6] aims at producing hydrogen for 90 % from residual gases originating from refineries in the Rotterdam port area and for 10 % from natural gas off the grid, followed by capturing and storing the resulting CO_2 in empty gas fields beneath the North Sea. The PosHYdon project [7] deals with offshore hydrogen production with electricity from wind energy. The import of hydrogen from abroad, e.g. that is produced with solar energy in North Africa followed by pipeline transport to Europe [8,9] is considered as well.

This research focuses on supply chains for green hydrogen production. The whole supply chain is considered from a life cycle perspective to prevent problem-shifting between the different phases of a life cycle and/or sustainability aspects [10]. In addition, the loss of work potential, also known as exergy or the 'quality of energy', is considered because exergy is needed for every process and activity to take place and because of the relationship between exergy and sustainability described by amongst others Dincer and Rosen [11]. Exergy that is lost is lost forever and the amount of exergy on earth can only be replenished by capturing exergy from solar and/or tidal energy [12].

In a previous study [13], the offshore and onshore electrolysis of water with electricity from Dutch wind farms and electrolysis with electricity from solar parks in Algeria followed by hydrogen transport via pipelines to the Netherlands was assessed by applying the ReCiPe 2016 and Total Cumulative Exergy Loss (TCExL) methods. In a follow-up study [14], ammonia production with solar energy in Saudi Arabia followed by deep-sea transport and ammonia cracking to hydrogen in the Netherlands (solar PV ammonia) was added as well as the use of the Environmental Footprint (EF) method recommended by the European Commission [15]. The research presented here is an updated version of

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the latter research, i.e. the model of the solar PV ammonia option has been improved and modified from a serial model in which the subsystems are sequentially connected to one another into a model in which the subsystems are connected in parallel. This parallel model has the same assessment results as the serial model but enables a more detailed investigation of the contributions of the subsystems to the overall scores of the green hydrogen supply chains. Another extension is the addition of the storage of hydrogen in liquid form in Rotterdam in the models of the three green hydrogen supply chains [13,14]. In this way, these three systems are better comparable with the solar PV ammonia option that already included storage of ammonia in liquid form in Rotterdam. The influence of the duration of the hydrogen or ammonia storage is investigated as well.

2. Sustainability assessment

The sustainability of the green hydrogen supply chains is assessed from a life cycle point of view (section 2.1) by applying two environmental methods, i.e. ReCiPe 2016 and Environmental Footprint 3.0 (section 2.2), and one exergetic assessment method, i.e. the Total Cumulative Exergy Loss (TCExL) method [16] (section 2.3).

2.1. Functional unit and system boundaries

The supply chain of 1 kg of gaseous hydrogen at 30 bar in Rotterdam, Netherlands, is assessed starting with the extraction of materials and the production of energy carriers from earth and includes the construction and decommissioning of all infrastructure, such as installations and equipment. The use of the hydrogen end product is not included, i.e., it is a cradle-to-gate assessment. The lifetime of the system components is set at or scaled to 25 years, except for long-distance infrastructure such as gas pipelines and electricity grids with a lifetime of 40–60 years [17,18].

2.2. Environmental life cycle assessment

The environmental sustainability is assessed with the help of the LCA software tool SimaPro release 9.6.0.1 [19] including the ecoinvent database 3 [20] which is used to model the background processes of the hydrogen supply chains. The Life Cycle Impact Assessment (LCIA) methods applied in this research are ReCiPe 2016 version 1.04 [21] and Environmental Footprint (EF) 3.0 [22]. The ReCiPe endpoint indicators damage to human health, ecosystem diversity and resource availability and its midpoint indicators global warming, land use and water consumption are calculated with ReCiPe's default perspective, i.e. Endpoint (H)/World (2010) H/A and Midpoint (H)/World (2010) H, resp. With regard to the EF method (version (adapted) V1.00/EF 3.0 normalization and weighting set), the total environmental impact of the supply chains and its midpoint indicators climate change, land use and water use are considered.

2.3. Exergetic life cycle assessment

The TCExL method consists of the following three components [12,16,23]: internal exergy loss, abatement exergy loss and the exergy loss related to land use. The internal exergy loss is equal to the total exergy input minus the total exergy output of the considered technological system, i.e. the green hydrogen production supply chain, during its life cycle. The Cumulative Exergy Demand (CExD) version 1.05 [24] reported by SimaPro is used to determine the total exergy input. The total exergy output consists of the exergy value of the produced hydrogen and the amounts of emissions and waste flows reported by SimaPro times their standard exergy values [25]. Since it is undoable to calculate the exergy values of the more than 1000 emissions listed by SimaPro, this is limited to the exergy values of the largest emissions, i.e. at least 95 % by mass. The abatement exergy loss is calculated by multiplying the amounts of carbon dioxide, sulphur dioxide, nitrogen oxides and phosphate emissions reported by SimaPro with the amount of exergy needed to abate them to the level required by legislation, i.e. 5.86 MJ/kg [26,27], 57 MJ/kg, 16 MJ/kg and 18 MJ/kg [28], resp. The calculation is limited to these emissions because data about other substances have not yet been found in literature. The exergy loss related to land use stems from the notion that land that is occupied by a technological system cannot be used by nature to capture new exergy from solar energy. This exergy loss is calculated from the amounts and types of land use including duration reported by SimaPro and a worldwide average exergy loss of 215 GJ per hectare per year [12]. The worldwide average exergy loss is based on the net amount of biomass production when land is not occupied, i.e. the Net Primary Production (NPP), and an average biomass conversion factor of 42.9 MJ exergy per kg of carbon [29,30]. The types of land use related to the growing of trees and/or other types of biomass are not considered to prevent double-counting of land use. The types of land use related to marine ecosystems are not considered because of the very small amount of solar energy that is captured by these land types [31].

3. Assessed hydrogen supply chains

Sections 3.1 to 3.3 describe the four hydrogen supply chains, i.e. hydrogen produced with solar energy in Algeria followed by pipeline transport (section 3.1), hydrogen produced offshore and onshore with wind energy (section 3.2) and hydrogen produced with solar energy in Saudi Arabia and transported as ammonia (section 3.3). These sections are mostly identical to the supply chain descriptions in the previous study [14]. Section 3.4 about the storage of hydrogen and ammonia in Rotterdam has been newly added.

3.1. Hydrogen production with solar energy in Algeria

The research on hydrogen production with solar energy in Algeria is initiated by Ambagts [32]. Ultrapure water generated from sea water is electrolysed with electricity from solar energy in the south of Algeria (Adrar). The produced gaseous hydrogen is transported via pipelines to the port of Rotterdam and the oxygen by-product is vented, which is common practice when it cannot be used directly in a subsequent process [33]. The reason for choosing Adrar as the location of the photovoltaic and electrolysis installations is that it is close to several pipelines for (natural) gas transport [32,34]. Below, the subsystems of this hydrogen supply chain are briefly described. A more detailed description of the modelling in SimaPro is provided by Stougie et al. [13].

The ultrapure water is generated from sea water by reverse osmosis, i.e. desalination, followed by ultra-purification. Since direct use of the salt by-product in this area is unknown, it is not treated as a by-product. The electricity is generated by open ground PV installations which are assumed to be cleaned with pure water produced by the sea water desalination system. Transport of the water from the desalination unit to the location of the PV and electrolysis installations takes place via a pipeline with a length of 170 km. The electrolyser is a proton exchange membrane water electrolyser (PEMWE), which is modelled based on the information provided by Bareiß et al. [33] and Sharma et al. [35]. Per kg of hydrogen, the PEMWE consumes 9 kg of water and 55 kWh of electricity. The lengths of the pipelines for transport of hydrogen from Adrar to Rotterdam have been calculated at 500 km onshore in Africa, 30 km offshore from Africa to Europe and 2070 km of onshore transport in Europe. The model of the pipelines includes a zinc coating with a thickness of 130 μm at the inside to prevent hydrogen leakage. Table 1 summarizes the main components of the model.

3.2. Hydrogen from wind energy in the North Sea

Offshore and onshore options for the production of hydrogen from seawater with electric power generated by the Borssele 1&2 wind farms in the North Sea are considered, as described by Bryson [36]. The

Table 1
SimaPro model for 1 kg of hydrogen produced with solar energy in Algeria [13].

Product/name of the process	Amount
Water, ultrapure {RER}| water production, ultrapure with tap water via reverse osmosis from sea water | Cut-off, U	9 kg
Transport, pipeline, onshore, petroleum {RoW}| processing | Cut-off, U, without the emission of 'Oils, unspecified' to soil (i.e., water transport)	9/1000*170 tkm
Electricity, low voltage {AU}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U, with tap water from sea water including water transport	55 kWh
PEM Electrolyser incl BoP 1 MW | production | Cut-off, U, newly built	1/(15*24*365*7) piece
Transport, pipeline, onshore, long distance, natural gas {DZ} | processing | Cut-off, U[a]	1/1000*500*71.9/6.60 tkm
Transport, pipeline, offshore, long distance, natural gas {DZ} | processing | Cut-off, U[a]	1/1000*30*71.9/6.60 tkm
Transport, pipeline, onshore, long distance, natural gas {NO} | processing | Cut-off, U[a]	1/1000*2070*71.9/6.60 tkm

[a] Without natural gas leakage and with the addition of a zinc coating (i.e., hydrogen transport).

offshore option produces the hydrogen at sea and subsequently transports the hydrogen via pipelines to Rotterdam. In the onshore option, the generated electricity is transferred to the port of Rotterdam, where it powers an electrolyser. Below, the subsystems of this hydrogen supply chain that are different from the subsystems of the hydrogen production with solar energy in Africa system (section 3.1) are briefly described. A more detailed description of the modelling in SimaPro is provided by Stougie et al. [13].

The Borssele 1&2 wind farm is located 23 km from Westkapelle. Based on a capacity factor of 48 %, 79 TWh of electricity is generated during its lifetime. Its 94 wind turbines are of the type Siemens Gamesa 8.0–167 DD with an installed capacity of 8 MW each. The wind turbines are connected to the offshore platform named Alpha with inter-array cables. In the offshore option (Table 2), an electrolysis unit is situated at the Alpha substation, which is followed by pipeline transport of the produced hydrogen to Rotterdam.

The onshore option (Table 3) includes conversion of the electricity into 220 kV AC at the Alpha substation followed by electricity transport via two export cables to the Borssele substation at the coast where the electricity is converted into 380 kV and supplied to the high voltage electricity grid. In Rotterdam, the HVAC is converted into DC for the electrolyser. Electricity losses in the export and high-voltage cables as well as during transformation have been considered.

Table 2
SimaPro model for 1 kg of offshore hydrogen from wind energy at the North Sea [13].

Product/name of the process	Amount
Water, ultrapure {RER}| water production, ultrapure with tap water via reverse osmosis from sea water | Cut-off, U	9 kg
Electricity, high voltage {NL}| electricity production, wind, 8 MW Borssele turbine, offshore | Cut-off	55*1.02 kWh
PEM Electrolyser incl BoP 1 MW | production | Cut-off, U, newly built	1/(15*24*365*7) piece
Offshore inter-array cables Borssele 1&2	167*(1/79E9)*(55*1.02) km
Offshore substation Borssele 1&2	(1/79E9)*(55*1.02) piece
Transport, pipeline, offshore, long distance, natural gas {NO} | processing | Cut-off, U[a]	1/1000*85/6.60*71.9 tkm
Transport, pipeline, long distance, natural gas {NL} | processing | Cut-off, U[a]	1/1000*2/6.60*71.9 tkm

[a] Without natural gas leakage and with the addition of a zinc coating (i.e., hydrogen transport).

Table 3
SimaPro model for 1 kg of onshore hydrogen from wind energy at the North Sea [13].

Product/name of the process	Amount
Water, ultrapure {RER}| water production, ultrapure with tap water via reverse osmosis from sea water| Cut-off, U	9 kg
Electricity, high voltage {NL}| electricity production, wind, 8 MW Borssele turbine, offshore | Cut-off	55*1.06 kWh
PEM Electrolyser incl BoP 1 MW | production | Cut-off, U, newly built	1/(15*24*365*7) piece
Offshore inter-array cables Borssele 1&2	167*(1/79E9)*(55*1.06) km
Offshore substation Borssele 1&2	(1/79E9)*(55*1.06) piece
Onshore substation Borssele 1&2 (two substations)	2*(1/79E9)*(55*1.06) piece
Offshore export cables Borssele 1&2	(2*61)*(1/79E9)*(55*1.06) km
Electricity, high voltage {NL}| market for | Cut-off, U[a]	55*1.06 kWh

[a] Without electricity production.

3.3. Hydrogen from ammonia produced with solar energy in Saudi Arabia

This green hydrogen production option is inspired by the initiative of the NEOM Green Hydrogen Company (NGHC) to build world's largest green ammonia plant in Oxagon, Saudi Arabia [37] and the research by Poli [38]. The hydrogen needed as feedstock is produced at the same location by electrolysis of ultrapure desalinated water and the nitrogen feedstock originates from air separation. Both systems are powered by electricity generated with bifacial solar panels. The liquid ammonia is shipped to Rotterdam and is subsequently converted into gaseous hydrogen with an autothermal ammonia reformer. Below, the supply chain is described in more detail.

The model of the subsystem that supplies ultrapure water is the same as the model used for the production of hydrogen with solar energy in Algeria, but with a water transport distance of zero because the green ammonia plant and electrolyser installation are located close to the sea. The model of the generation of electricity from solar energy is also similar, but its output is multiplied by 1.1 because it is assumed that the bifacial solar panels [39] located in Saudi Arabia generate 10 % more electricity than the non-bifacial solar panels located in Algeria [40].

The ecoinvent process 'Nitrogen, liquid {RoW}| air separation, cryogenic | Cut-off, U' is used to model the production of nitrogen. It has been adapted by changing the origin of all electricity consumed by the process into electricity originating from the bifacial solar panels. Similar to the supply chain 'Hydrogen production with solar energy in Algeria', the oxygen by-product is vented.

The green ammonia production plant is modelled based on data provided by Chisalita et al. [41], who describe the synthesis of liquid ammonia at 340 bar and 500 °C from hydrogen and nitrogen compressed to 340 bar by a compressor with an efficiency of 85 %. The ecoinvent process named 'Ammonia, liquid {RER} - ammonia production, steam reforming, liquid - Cut-off, U' has been adapted for this purpose (Table 4). The number of pieces of the chemical factory mentioned in the original ecoinvent process has been multiplied by 25/50 to correct for the 50 years of lifespan of the chemical factory according to the ecoinvent dataset and the functional unit with a lifetime of 25 years used in this research.

The ammonia is stored for three days in a liquid storage tank before being transported overseas by a tanker, both at atmospheric pressure and a temperature of −34 °C [42]. Traditionally, polyurethane foam is used as insulation material for offshore transportation [43]. The insulation thickness of ammonia and LNG storage tanks equals about 9 and 18 cm, resp. [42]. Based on these numbers, it was calculated that the amount of insulation material, i.e. polyurethane foam, needed for a ship with a volumetric storage capacity of 140,000 m^3 and consisting of 4

Table 4
Model of the green ammonia production plant, based on Chisalita et al. [41].

Adaptations to the ecoinvent process 'Ammonia, liquid {RER} - ammonia production, steam reforming, liquid - Cut-off, U (1 kg)'	
Added	**Amount**
Inputs from nature	
Water, cooling, salt, ocean	0.83135 kg
Inputs from technosphere: materials/fuels	
Hydrogen produced in Saudi Arabia (NGHC project)	0.18878 kg
Nitrogen produced in Saudi Arabia (NGHC project)	0.87445 kg
Cast iron {ROW}| production | Cut-off, U[a]	0.000192 kg
Inputs from technosphere: electricity/heat	
Electricity, generated with bifacial solar panels in Saudi Arabia	1.70903 MJ
Emissions to air	
Hydrogen, low. pop.[b]	0.0104 kg
Nitrogen, low. pop.[b]	0.0429 kg
Emissions to water	
Water, ocean	0.83135 kg
Modified	
Chemical factory, organics {RER}| construction | Cut-off, U	times (25/50) piece
Deleted	
All other inputs, emissions and outputs	

[a] 0.20 kg catalyst per ton NH_3 consisting of (mass%): 96 Fe, 1 KOH, 3 Al_2O_3. It is assumed that cast iron can be used to represent Fe. The latter two components could not be found in the SimaPro databases.
[b] The composition of the emissions is not specified. The ratio between the amounts of hydrogen and nitrogen has been calculated from the amounts of feedstocks and ammonia product.

cargo tanks is approximately half the amount of insulation material needed for an LNG tanker. Therefore, the ecoinvent process 'Tanker, for liquefied natural gas {GLO}| tanker production, for liquefied natural gas | Cut-off, U' has been transformed into a tanker for liquid ammonia by multiplying the amounts of polyurethane, flexible foam by 0.5. The input data of the aforementioned ecoinvent process was used to calculate the amount of polyurethane foam needed for transforming the ecoinvent process 'Liquid storage tank, chemicals, organics {RoW}| production | Cut-off, U' into a tank for the storage of liquid ammonia, which resulted in the following extra inputs from technosphere (materials/fuels): 403 kg of 'Polyurethane, flexible foam {RER}| market for polyurethane, flexible foam | Cut-off, U' and 1911 kg of 'Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U'.

During land storage, a boil-off rate of 0.02 %/day and 0.068 kWh/kg of electricity for reliquefaction of ammonia is assumed [44]. Cooling down the storage tanks before the ammonia is loaded onto the ship and pump energy for the loading itself amount at 1.45 and 0.346 MJ per ton of loaded ammonia [42], resp. It is assumed that the electricity needed during storage and loading originates from the bifacial solar panels. The liquid storage tank of the ecoinvent database has a volume of 16,000 m^3 and a lifetime of 50 years. Assuming that 85 % of the tank volume can be used for storing ammonia and an ammonia density of 682.8 kg/m^3 [42], it can be calculated that for storing 1 ton of ammonia for 3 days (1 [ton]* 3 [days])/(16,000 [m^3]*85 %*682.8 [kg/m^3]/1000 [kg/ton]*50 [years]*365.25 days/year) = 1.769E-08 pieces of the ammonia storage tank are needed (Table 5).

The distance between Oxagon and Rotterdam is calculated at 6576 km. During sea transport from Oxagon to Rotterdam, all boil-off gas (BOG) is used in the propulsion system. Based on the data provided by Song et al. [42], BOG can fulfil 3.98/(3.98 + 31.92) = 11 % of the required amount of fuel. Therefore, the ecoinvent process 'Transport, freight, sea, tanker for liquefied natural gas {GLO}| transport, freight, sea, tanker for liquefied natural gas | Cut-off, U' has been modified by multiplying the amounts of fuel and emissions to air by 0.89. As described above, the insulation of the tanker has been modified by multiplying the amounts of polyurethane, flexible foam by 0.5. Based on the research by Song et al. [42], it is assumed that 106785.46 ton of ammonia arrives in Rotterdam.

Table 5
Model of the land storage and loading of ammonia based on Song et al. [42].

New model	
Added	**Amount**
Outputs to technosphere: Products and co-products	
Ammonia, stored for three days on land and loaded on ship	107063.04 ton
Inputs from technosphere: materials/fuels	
Ammonia, liquid | Haber-Bosch green ammonia production	109248 ton
Ammonia, liquid storage tank	(107063.04*3)/(16,000*85%*682.8/1000*50*365.25) piece
Inputs from technosphere: electricity/heat	
Electricity, generated with bifacial solar panels in Saudi Arabia	109248*0.02/100)*3*0.068*3.6+107063.04*(1.45+0.346)/1000 GJ

In Rotterdam, the ammonia is unloaded and stored for three days before it is converted into gaseous hydrogen. The model of the unloading and land storage in Rotterdam is similar to the model of the land storage and loading in Oxagon, but with the exceptions that cooling down of the storage tanks (onboard the tanker) is not needed and that electricity from the Dutch electricity grid is used for unloading and cooling during land storage (section 3.4). After storage on land, 106784.37 ton of ammonia remains [42].

The model of the conversion of ammonia into hydrogen is based on the research by Jang and Han [45], who describe an ammonia autothermal reformer. Their reformer operates at a pressure of 4 bar with a conversion efficiency of 98 %, a yield of 82.5 % and ruthenium as the catalyst. The ammonia flow and hydrogen production rate amount at 1365 and 200 kg per day, resp. A molar balance was used to calculate that the hydrogen is part of a mixture with about 54 vol% hydrogen and 46 vol% nitrogen, i.e. 200 kg of hydrogen is accompanied with about 2390 kg of nitrogen. Since this new autothermal reformer is non-existent in the SimaPro databases, it was decided to model the subsystem similar to the ammonia production plant but then with only the aforementioned amounts of ammonia and hydrogen/nitrogen as input and output, resp., and multiplying the standard number of pieces of a chemical factory used in such a chemical process by the number of kg output, i.e. 2590, and by 25/50 to correct for the lifetime of 50 years compared to the 25 years lifetime of the functional unit (Table 6).

The subsequent compression of the hydrogen/nitrogen mixture to 20 bar is followed by pressure swing adsorption (PSA) to obtain high purity hydrogen [45]. The compression to 30 bar of the resulting hydrogen is added because of the functional unit applied in this research. The ecoinvent process 'Compressed air, 800 kPa gauge {RER}| compressed air production, 800 kPa gauge, >30 kW, average generation | Cut-off, U' is used to model compression. The electricity needed for the compression is assumed to be 'Electricity, low voltage {NL}| market for | Cut-off, U' and is calculated at about 0.22 and 0.17 kWh/kg, resp. The compressor has a capacity of 300 kW and an assumed lifetime of 90.000 h versus the 25 years of the functional unit, which results in 0.22/(300*90.000)*25/(90.000/(365*24)) pieces of the compressor

Table 6
Model of the conversion of ammonia into hydrogen, based on Jang and Han [45].

Adaptations to the ecoinvent process 'Ammonia, liquid {RER} - ammonia production, steam reforming, liquid - Cut-off, U'	
Modified	**Amount**
Product	
Hydrogen/nitrogen mixture	(200+2390) kg
Inputs from technosphere: materials/fuels	
Ammonia	1365 kg
Chemical factory, organics {RER}| construction | Cut-off, U	times (200+2390)*(25/50) piece
Deleted	
All other inputs, emissions and outputs	

Table 7
SimaPro model for 1 kg of hydrogen from the solar PV ammonia system.

Product/name of the process	Amount
Water, ultrapure {RER}| water production, ultrapure with tap water via reverse osmosis from sea water| Cut-off, U	14.9 kg
Electricity, low voltage {AU}| bifacial electricity production, photovoltaic, 570 kWp open ground installation, multi-Si with tap water from sea water including transport| Cut-off, U	91.0 kWh
Nitrogen, liquid {RoW}| air separation, cryogenic | Cut-off, U	7.66 kg
Hydrogen produced in Saudi Arabia (NGHC project)	1.65 kg
Ammonia production, liquid (Haber-Bosch with electricity)	8.76 kg
Ammonia, storing on land and loading on ship	8.59 kg
Transport, Liquid Ammonia Tanker - adapted from Transport, freight, sea, tanker for liquefied natural gas {GLO}| transport, freight, sea, tanker for liquefied natural gas | Cut-off, U	56.5 tkm
Ammonia, unloading and storing for 3 days on land	8.56 kg
Ammonia cracking, autothermal reactor (per kg H_2/N_2)	16.25 kg
H_2/N_2 compression	16.25 kg
Pressure swing adsorption (per kg H_2 recovered)	1 kg
Hydrogen compression to 30 bar	1 kg

(#p) for the compression of 1 kg hydrogen/nitrogen mixture to 20 bar. The amounts of lubricating oil and waste mineral oil are assumed to be proportional to the calculated #p over the original #p. The amounts of steel, probably meant for building a compressed air station, are set at zero. The compression to 30 bar after the PSA has been modelled similarly. The model of the PSA is a modified version of the ecoinvent process 'Helium {GLO}| purification | Cut-off, U'. The electricity needed for the PSA is modelled as 'Electricity, medium voltage {NL}| market for | Cut-off, U', and is assumed to be about 25 % of the original amount because of the high pressure of the input. From the documentation about the ecoinvent process, the required amount of adsorbent is estimated/calculated at 0.38 kg per kg of purified hydrogen and the recovery rate is assumed to equal 80 % [46].

Contrary to previous research [14], the overall model of the solar PV ammonia option consists of the subsystems in parallel (Table 7). This parallel way of modelling enables a more detailed investigation of the contributions of the subsystems to the overall score of the solar PV ammonia option. The models of the three other supply chains for green hydrogen production are parallel models as well.

3.4. Storage of ammonia and hydrogen in Rotterdam

It is likely that ammonia instead of hydrogen is stored in Rotterdam when hydrogen is transported to Rotterdam in the form of ammonia. Therefore, the supply chains have been extended with the storage of the energy carriers, in liquid form, in Rotterdam, as planned in the Rotterdam port area, e.g. Refs. [47,48]. The model that describes hydrogen from ammonia produced with solar energy in Saudi Arabia includes three days of liquid ammonia storage after unloading the ammonia tanker in Rotterdam. A longer period of storage can be considered by multiplying the amount of energy needed for cooling and the use of the liquid storage tank with the number of storage days over the originally three storage days.

The models of the options onshore wind (gaseous hydrogen produced in Rotterdam), offshore wind and the solar energy plus pipeline transport from Algeria (gaseous hydrogen is transported to Rotterdam via pipelines) need to be extended with hydrogen liquefaction, storage and recompression to 30 bar. The amounts of electricity needed for liquefaction, cooling/reliquefaction of boil-off gas and cryogenic compression to gaseous hydrogen at 30 bar were assumed to equal 5.88 kWh, 4.07 kWh and 0.0136 kWh per kg of hydrogen delivered [44], resp. In case of the onshore and offshore options, it is assumed that the electricity originates from the onshore hydrogen from wind energy at the North Sea option. For this purpose, the SimaPro model of the onshore wind supply chain [13] has been modified by leaving out the inputs ultrapure water and the electrolyser, and by changing the hydrogen product into generated electricity (in the same amount as the electricity generated with wind energy used as an input). The installations needed for (re)liquefaction and cryogenic compression have not yet been considered. The liquid hydrogen storage tank, with an assumed insulation thickness of 66 cm [42], was modelled in the same way as the liquid ammonia storage tank (section 3.3). This resulted in an extension of the ecoinvent process 'Liquid storage tank, chemicals, organics {RoW}| production | Cut-off, U' with two inputs from technosphere (materials/fuels): 3149 kg of 'Polyurethane, flexible foam {RER}| market for polyurethane, flexible foam | Cut-off, U' and 14949 kg of 'Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U'. Based on a liquid hydrogen density of 71 kg/m^3 and an ullage of 10 % [49], it was calculated that for storing 1 ton of hydrogen for 3 days 1.607E-7 pieces of the hydrogen storage tank are needed. Assuming a boil-off rate of 0.1 % per day [44,49], the electricity needed for storing 1 ton of hydrogen for three days amounts at (1000 [kg/ton] * 0.1 [%] * 3 [days] * 4.07 [kWh/kg] * 3.6 [MJ/kWh]), i.e. about 44 MJ/ton.

3.5. Overview of the hydrogen supply chains

An overview of the main characteristics of the assessed hydrogen supply chains is provided in Table 8. The data originate from public

Table 8
Overview of main characteristics of the hydrogen supply chains.

	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
Renewable electricity generation				
Type	PV park	Wind farm	Wind farm	PV park (bifacial)
Location	Algeria	Netherlands	Netherlands	Saudi Arabia
Capacity	n/a	0.8 GW	0.8 GW	4 GW (solar and wind)
Hydrogen/ammonia production				
Technology	PEMWE	PEMWE	PEMWE[a]	PEMWE, Haber-Bosch
Capacity	n/a	n/a	n/a	600 ton/day (as green ammonia)
Long distance transport				
Medium	hydrogen	hydrogen	electricity	ammonia
Mode	pipeline with zinc coating	pipeline with zinc coating	electricity grid	deep sea tanker
Distance	500 km onshore (Africa), 30 km offshore, 2070 km onshore (Europe)	85 km offshore, 2 km onshore	61 km (export cable length)	6576 km
Liquid storage in Rotterdam				
Component	hydrogen	hydrogen	hydrogen	ammonia
Ammonia conversion				
Technology	–	–	–	autothermal reforming
Capacity	–	–	–	n/a

[a] Hydrogen production after electricity transport.

Table 9
Results of the ReCiPe 2016 method for 1 kg of hydrogen in Rotterdam.

	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
Endpoint indicators per damage category [Pt]				
Human health	4.0E-1	1.3E-1	6.0E-1	6.5E-1
Ecosystems	3.0E-2	5.0E-3	1.9E-2	4.8E-2
Resources	5.1E-3	5.3E-4	9.1E-4	5.2E-3
Total [a]	4.3E-1	1.4E-1	6.2E-1	7.0E-1
idem, normalised	*321*	*100*	*460*	*519*
Midpoint indicators				
GWP [CO_2-eq.]	9.4E+0	9.8E-1	1.6E+0	1.2E+1
Land use [m^2a crop eq.]	1.3E+0	2.9E-2	8.6E-2	2.7E+0
Water consumption [m^3]	1.4E-1	6.0E-3	1.8E-2	2.8E-1

[a] The default weighting of the ReCiPe 2016 method has been applied, i.e. 40, 40 and 20 %, resp.

information about planned facilities as well as additional calculations needed for this research (sections 3.1 to 3.4).

4. Results and discussion

Table 9 shows the results of the environmental LCA with the ReCiPe 2016 method. According to the normalised endpoint indicators, the offshore production of hydrogen from wind energy followed by pipeline transport to Rotterdam is preferred. The second-best option appears to be the production of hydrogen from solar energy in Algeria followed by pipeline transport to Rotterdam and as third-best the onshore production of hydrogen from wind energy. The highest environmental impact is caused by the production of hydrogen and conversion of hydrogen into ammonia in Saudi Arabia followed by deep-sea transport and conversion of ammonia into hydrogen in Rotterdam. More than 90 % of the endpoint scores is caused by the damage category human health.

The new (parallel) model of the ammonia option enables a better comparison of the contributions of the subsystems to the endpoint scores of the four hydrogen supply chains. Fig. 1 shows the subsystems which contribute the most to the endpoint score when three days of hydrogen or ammonia storage in Rotterdam is included, i.e. the processes that together account for at least 80 % of one of the endpoint scores.

The influence of the duration of hydrogen storage in Rotterdam, which was varied between 3, 10 and 30 days, on the endpoint score appeared negligible. This is in line with the small contribution of hydrogen storage compared to the influence of hydrogen liquefaction and the assumption that all boil-off gas is reliquefied during storage.

When looking at the three ReCiPe 2016 midpoint indicators global warming potential (GWP), land use and water consumption of Table 9, the order of preference is quite different. I.e., the preferred option is still the offshore wind option, but second-best is the onshore wind option while the supply chain with solar energy in Saudi Arabia followed by ammonia transport appears to be the least preferred. Especially when looking at land use and water consumption, the midpoint scores of the wind options are considerably lower than the scores of the solar energy options. This is understandable because of the higher land use of the PV installations in an area where water is not abundant.

The GWP midpoint indicator scores of 0.98–1.6 kg CO_2-eq. per kg of hydrogen for both wind options are comparable to the about 1 kg CO_2-eq. per kg of hydrogen for water electrolysis via wind energy mentioned by Cetinkaya et al. (2012) [50]. The 9.4 and 12 kg CO_2-eq. per kg of hydrogen for the solar PV options are higher than the reported 2.4 kg CO_2-eq. per kg hydrogen [50]. This could be explained by the long distances of intercontinental pipeline transport of hydrogen and deep-sea transport of ammonia, resp. Except for the ammonia option, the GWP of the options is considerably lower than the nearly 12 kg CO_2-eq. per kg of hydrogen when hydrogen is produced by steam reforming of natural gas [50]. The environmental impact, especially of the ammonia option, is expected to decrease with a more renewable Dutch electricity mix.

The results of the environmental sustainability assessment with the Environmental Footprint 3.0 method are shown in Table 10. The offshore wind option is preferred, which is similar to the results obtained with the ReCiPe 2016 method. The second-best option seems to be the onshore wind supply chain, but the difference with the score of the solar energy from Algeria option is not large. The least-preferred option seems to be the solar energy from Saudi Arabia via ammonia option.

When looking at the scores of the ReCiPe midpoint indicator GWP and the EF midpoint indicator climate change, the orders of preference are identical, i.e. offshore wind is preferred, onshore wind is second-best and both solar options score considerably worse than both wind energy options, with solar energy from Saudi Arabia being the least-preferred option. When looking at the EF midpoint indicators land and water use, the difference between the scores is much smaller than with the ReCiPe midpoint scores, but the order of preference is the same for both methods and both indicators. It is remarkable that the relative GWP and climate change scores of the ReCiPe 2016 and EF 3.0 are very similar while the land and water use scores of the ReCiPe 2016 and EF 3.0 methods are very different. However, it must be noted that the ReCiPe midpoint scores are presented in m^2a and m^3, resp., while the units of

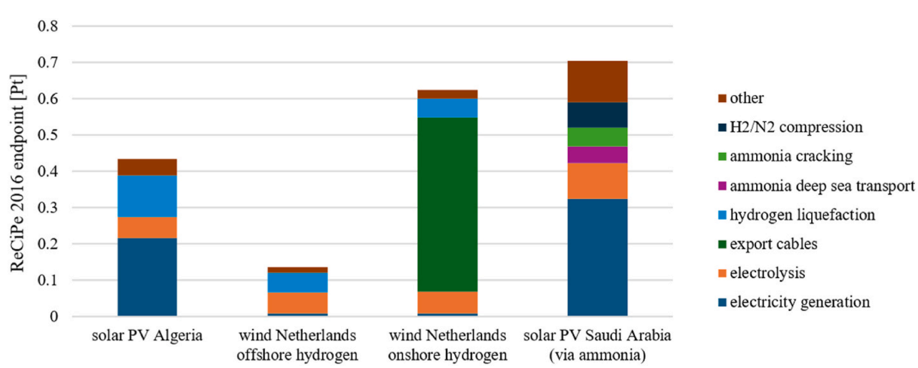

Fig. 1. Subsystems that contribute most to the ReCiPe 2016 endpoint scores of the options.

Table 10
Results of the Environmental Footprint 3.0 method for 1 kg of hydrogen in Rotterdam.

[Pt]	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
Endpoint indicator				
Total score	1.9E-3	5.9E-4	1.7E-3	3.2E-3
idem, normalised	*318*	*100*	*280*	*531*
Midpoint indicators				
Climate change	2.5E-4	2.6E-5	4.2E-5	3.0E-4
Land use	5.1E-5	4.5E-7	1.3E-6	9.0E-5
Water use	2.7E-5	2.1E-6	5.4E-6	6.6E-5

Table 11
Results of the TCExL method for 1 kg of hydrogen in Rotterdam.

[MJ]	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
CExD	**3.6E2**	**2.5E2**	**2.7E2**	**5.3E2**
Hydrogen product	1.2E2	1.2E2	1.2E2	1.2E2
Exergy of emissions and waste flows	2.2E1	1.2E1	3.0E1	4.9E1
Total exergy output	**1.4E2**	**1.3E2**	**1.5E2**	**1.7E2**
Internal exergy loss	2.2E2 (71 %)	1.2E2 (95 %)	1.3E2 (91 %)	3.6E2 (75 %)
Abatement exergy loss	5.2E1 (17 %)	5.7E0 (4 %)	1.1E1 (8 %)	6.1E1 (12 %)
Exergy loss land use	3.6E1 (12 %)	5.3E-1 (0 %)	1.6E0 (1 %)	5.9E1 (12 %)
TCExL	**3.0E2**	**1.3E2**	**1.4E2**	**4.8E2**
idem, normalised	*231*	*100*	*106*	*370*

the EF 3.0 scores are Pt, i.e., the numbers have been normalised and weighted.

Table 11 presents the results of the exergetic sustainability assessment. Again, the offshore wind option seems the preferred option, but the difference with the onshore wind option is small. Least preferred is the option solar PV in Saudi Arabia with ammonia as an intermediate product, which could be explained by the extra conversion steps needed for converting hydrogen into ammonia and vice versa, resulting in a higher internal exergy loss. The difference between the two types of options with regard to the used renewable energy source clearly visible when looking at the percentual contributions of the three components of the TCExL indicator. The higher abatement exergy loss of the two solar options could be explained by the emissions related to the longer transport distance compared to both wind options. The higher exergy loss caused by land use is likely caused by the larger area that is needed for the PV installations of both solar options compared to the wind options.

Fig. 2 presents an overview of the normalised total scores of the three sustainability assessment methods of Tables 9–11 The offshore production of hydrogen with electricity from wind energy is preferred, but it depends on the assessment method which option scores second-best, third-best etc.

Several assumptions had to be made when modelling the supply chains. In addition to Fig. 1, Table 12 shows a numerical overview of the contributions of processes and their components to the ReCiPe 2016 endpoint indicator scores. This overview is used as input to the sensitivity analysis.

Table 13 presents the results of the sensitivity analysis regarding the ReCiPe 2016 endpoint indicators. The score of the offshore hydrogen option varies between 0.13 and 0.15 Pt, which is considerably lower than the scores of the other options. The solar PV Algeria option scores second-best with 0.41–0.48 Pt, but the score of the onshore hydrogen option would become 0.38 Pt when the copper originating from Asia and the Pacific used for the export cables would be replaced with copper originating from Europe. Another assumption, not visible in Fig. 1 nor Tables 12 and is the percentage of hydrogen that is recovered during the pressure swing adsorption of the solar energy from Saudi Arabia via ammonia option. Assuming 90 % instead of 80 % recovery would lower the score to 90 % of the default score, i.e. 0.63 Pt, which is comparable to the score of the onshore hydrogen production option. This makes that the offshore hydrogen option is preferred, but that the order of preference of the other options is unsure. As mentioned in section 2.1, this research does not differentiate between existing and new infrastructure. The results would be different if existing infrastructure is not included in the comparison.

The results of the sensitivity analysis with regard to the Environmental Footprint (Table 14) confirm that the offshore hydrogen option is preferred and that the solar PV Saudi Arabia option is the least preferred according to the results of the LCIA method Environmental Footprint 3.0. It is undecided whether the solar PV Algeria or the onshore hydrogen option is the second-best option.

Table 15 presents the results of the sensitivity analysis with regard to the TCExL indicator. The difference between the two wind energy options is too small to decide which of the two is preferred, the solar PV

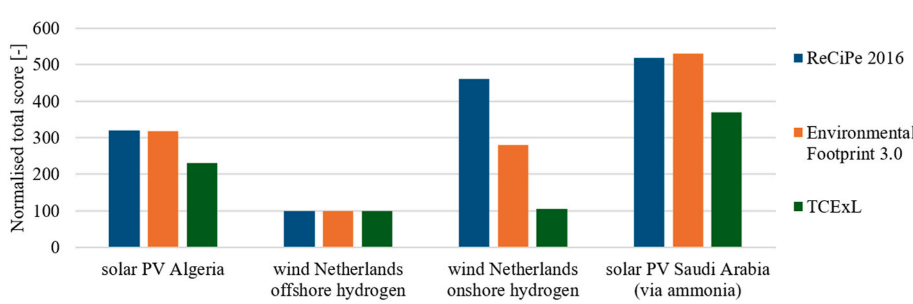

Fig. 2. Normalised results of the three assessment methods.

Table 12
Main contributions of subsystems to the ReCiPe 2016 Endpoint results.

[%]	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
Contributions				
Electricity generation	50	6	1	46
of which PV panel, multi-Si wafer[a]	*30*			*30*
Electrolyser	13	43	9	14
Export cables	n/a	n/a	78	n/a
of which copper (RAS)[b]			*45*	
Hydrogen liquefaction	26	39	8	n/a
Ammonia deep sea transport	n/a	n/a	n/a	7
Ammonia cracking	n/a	n/a	n/a	7
H_2/N_2 compression	n/a	n/a	n/a	10
Subtotal	**89**	**88**	**96**	**84**

[a] With about 1/3 originating from Europe (RER) and 2/3 from outside of Europe (based on panel area).
[b] About 1/3 of the copper originates from Asia and the Pacific (RAS) according to the ecoinvent process 'Copper {GLO} market for'.

Table 13
Sensitivity analysis regarding the ReCiPe 2016 endpoint indicator.

	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
ReCiPe endpoint score [Pt]				
Default	0.43	0.14	0.62	0.70
minimum	*0.41*	*0.13*	*0.38*	*0.63*
maximum	*0.48*	*0.15*	*0.69*	*0.74*
Variations [% of default endpoint score]				
Electricity generation				
+ 10 %	*105*	*n/a*	*n/a*	*105*
- 10 %	*95*	*n/a*	*n/a*	*95*
PV panel, multi-Si wafer 100 % Europe or 100 % outside of Europe	*no difference*	-	-	*no difference*
Electrolyser				
+ 10 %	-	*104*	-	-
- 10 %	-	*96*	-	-
Export cables				
+ 10 %	*n/a*	*n/a*	*108*	*n/a*
- 10 %	*n/a*	*n/a*	*92*	*n/a*
copper 100 % ex RER	*n/a*	*n/a*	*61*	*n/a*
Hydrogen liquefaction				
+ 10 %	*103*	*104*	*101*	*n/a*
- 10 %	*97*	*96*	*99*	*n/a*
Hydrogen recovery during pressure swing adsorption (default 80 %)				
90 %	*n/a*	*n/a*	*n/a*	*90*
Hydrogen loss in the supply chain				
10 %	*110*	*110*	*110*	*n/a*

Algeria option scores third-best and the solar PV Saudi Arabia is least preferred. It is also learned from comparing Tables 13–15 that the influence of the variations of the sensitivity analysis on the TCExL scores is somewhat different from the influence on the two environmental indicators, especially the variation of the hydrogen loss in the supply chain. This is understandable because the amount of hydrogen product does not change and therefore the internal exergy loss does not scale linearly with the hydrogen loss.

It must be noted that this research is not meant to perform a detailed LCA, but to get an impression of the performance of different supply chains for green hydrogen production from an environmental and exergetic sustainability point of view.

5. Conclusions and recommendations

An environmental LCA and an exergetic LCA have been conducted to assess the sustainability of the following four supply chains for green hydrogen production: offshore and onshore electrolysis with electricity from the Borssele 1&2 wind farms in the Netherlands (offshore and onshore hydrogen options, resp.), electrolysis with electricity from solar parks in Algeria followed by hydrogen transport via pipelines to the Netherlands (solar PV Algeria option), and electrolysis with electricity from solar parks in Saudi Arabia followed by green ammonia production, its deep-sea transport to the Netherlands and autothermal reforming into hydrogen (solar PV Saudi Arabia option).

The offshore wind option is preferred according to the total scores of the environmental assessment with the ReCiPe 2016 and Environmental Footprint (EF) 3.0 methods, but the preference order of the other options is undecided. The scores of the midpoint indicators GWP/climate change, land use and water consumption/use of both methods are unanimous, i.e., the offshore wind option is preferred, the onshore wind option scores second-best, the Solar PV Algeria option third-best and the solar PV Saudi Arabia option is least-preferred.

The offshore wind option is also preferred according to the results of the total cumulative exergy loss (TCExL) method, but the difference with the onshore wind option is small. The solar PV Algeria option results in a lower TCExL than the solar PV Saudi Arabia option.

The total scores of the EF and TCExL methods result in the same order of preference of the options, although sometimes the difference between the scores of the options is small, while the order of preference

Table 14
Sensitivity analysis regarding the Environmental Footprint 3.0 indicator.

	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
Environmental Footprint score [Pt]				
Default	318	100	280	531
minimum	*300*	*94*	*232*	*474*
maximum	*350*	*110*	*308*	*558*
Variations [% of default Environmental Footprint score]				
Electricity generation				
+ 10 %	*106*	*n/a*	*n/a*	*105*
- 10 %	*94*	*n/a*	*n/a*	*95*
PV panel, multi-Si wafer 100 % Europe or 100 % outside of Europe				
	no difference	-	-	*no difference*
Electrolyser				
+ 10 %	-	*106*	-	-
- 10 %	-	*94*	-	-
Export cables				
+ 10 %	*n/a*	*n/a*	*106*	*n/a*
-10 %	*n/a*	*n/a*	*94*	*n/a*
copper 100 % ex RER	*n/a*	*n/a*	*83*	*n/a*
Hydrogen liquefaction				
+ 10 %	*101*	*102*	*101*	*n/a*
- 10 %	*99*	*98*	*99*	*n/a*
Hydrogen recovery during pressure swing adsorption (default 80 %)				
90 %	*n/a*	*n/a*	*n/a*	*89*
Hydrogen loss in the supply chain				
10 %	*110*	*110*	*110*	*n/a*

Table 15
Sensitivity analysis regarding the TCExL indicator.

	Solar energy plus pipeline transport from Algeria	Wind energy plus offshore production	Wind energy plus onshore production	Solar energy plus deep sea ammonia transport from Saudi Arabia
TCExL [10^8 J]				
Default	3.0	1.3	1.4	4.8
minimum	*2.7*	*1.3*	*1.4*	*5.3*
maximum	*3.4*	*1.6*	*1.6*	*4.2*
Variations [% of default TCExL score]				
Electricity generation				
+ 10 %	*110*	*n/a*	*n/a*	*109*
- 10 %	*90*	*n/a*	*n/a*	*91*
PV panel, multi-Si wafer 100 % Europe or 100 % outside of Europe				
	no difference	-	-	*no difference*
Electrolyser				
+ 10 %	-	*101*	-	-
- 10 %	-	*99*	-	-
Export cables				
+ 10 %	*n/a*	*n/a*	*100*	*n/a*
- 10 %	*n/a*	*n/a*	*100*	*n/a*
copper 100 % ex RER	*n/a*	*n/a*	*102*	*n/a*
Hydrogen liquefaction				
+ 10 %	*103*	*102*	*102*	*n/a*
- 10 %	*97*	*98*	*98*	*n/a*
Hydrogen recovery during pressure swing adsorption (default 80 %)				
90 %	*n/a*	*n/a*	*n/a*	*87*
Hydrogen loss in the supply chain				
10 %	*114*	*119*	*118*	*n/a*

according to the ReCiPe method is different.

The extension of the solar PV Algeria and both wind options with liquid hydrogen storage in Rotterdam made these options better comparable with the solar PV Saudi Arabia option (which yet included liquid ammonia storage in Rotterdam). As a result, it is less certain that the solar PV Saudi Arabia option is the least preferred option. The influence of the duration of storage of hydrogen and ammonia in liquid form, i.e. 3, 10 and 30 days, appeared negligible.

It is recommended to investigate the supply chains for green hydrogen production in more detail before drawing firm conclusions about a preferred system for the supply of hydrogen. Furthermore, it is recommended that attention be paid to the economic and social pillars of sustainability assessment as well. These pillars and other aspects such as geopolitical factors could be integrated into the assessment with a multi-criteria assessment method.

The use of exergetic sustainability assessment methods is recommended because of the independence of exergy losses from changing and subjective models, weighting factors, economic and social variables.

CRediT authorship contribution statement

Lydia Stougie: Writing – review & editing, Writing – original draft. **Hedzer van der Kooi:** Writing – review & editing. **Gijsbert Korevaar:** Writing – review & editing.

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.

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