Delft University of Technology

Document Version
Accepted author manuscript

Licence
CC BY-NC-SA

Citation (APA)
Stougie, L., van der Kooi, H. J., & Korevaar, G. (2024). Sustainability assessment of supply chains for green hydrogen production. In *37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems* Curran Associates, Inc..

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

SUSTAINABILITY ASSESSMENT OF SUPPLY CHAINS FOR GREEN HYDROGEN PRODUCTION

Lydia Stougie[1]*, Hedzer van der Kooi[2], Gijsbert Korevaar[1,3]

[1]Delft University of Technology, Faculty of Technology, Policy and Management, Delft, Netherlands

[2]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, Netherlands (retired)

[3]Rotterdam University of Applied Sciences, CoE HRTech Rotterdam, Netherlands

*Lydia Stougie: l.stougie@tudelft.nl

ABSTRACT

Natural gas is widely used by households and industry in the Netherlands, but the threat of climate change, earthquakes in the province of Groningen caused by natural gas extraction and the availability of natural gas on the world market necessitate the search for alternative energy carriers, such as hydrogen gas. Various supply chains for hydrogen production have the attention of scientists, policy makers and companies, especially green ways of hydrogen production such as hydrogen production from water or biomass with renewable electricity originating from biomass, wind, solar energy or hydropower as energy carrier. This study compares offshore and onshore electrolysis of desalinated water with electricity from wind farms in the Netherlands, electrolysis with electricity from solar parks in Algeria followed by hydrogen transport via pipelines to the Netherlands and ammonia production with solar energy in Saudi Arabia followed by deep-sea transport and ammonia cracking to hydrogen in the Netherlands. The sustainability assessment is carried out from a life cycle perspective to prevent problem shifting between different life cycle phases and/or sustainability aspects. The environmental sustainability is determined by applying the Life Cycle Impact Assessment methods ReCiPe 2016 and Environmental Footprint 3.0 (EF). The Total Cumulative Exergy Loss (TCExL) method is used to calculate the exergy losses caused by the hydrogen supply chains during their life cycle. The endpoint score of each assessment method indicates that offshore electrolysis with wind energy is the preferred supply chain, with 8.3E-2 Pt (ReCiPe), 1.5E-3 Pt (EF) and 1.1E3 MJ (TCExL) per kg of gaseous hydrogen in Rotterdam, and that the preference order of the other supply chains is undecided. According to the scores of midpoint indicators GWP/climate change, land use and water consumption/use, the offshore wind option is preferred, with e.g. 0.89 kg CO_2-eq., 0.023 m^2a crop-eq. land use and 0.0046 m^3 water consumption, the onshore wind option is second-best (e.g. 1.5 CO_2-eq.), the supply chain with solar energy from Algeria third-best (e.g. 5.6 kg CO_2-eq.) and the supply chain with solar energy from Saudi Arabia (13 kg CO_2-eq.) ends as the least-preferred option. It is advised that the systems be investigated in more detail before firm conclusions are drawn about the order of preference and that the supply chains are extended with the storage of hydrogen or ammonia in Rotterdam. It is recommended that also attention be paid to the economic and social pillars of sustainability assessment and to exergetic sustainability assessment of technological systems in general because of the independence of exergetic assessment results of changing and subjective models, weighting factors and other variables.

1 INTRODUCTION

The discovery of a huge natural gas field in the province of Groningen, Netherlands, in 1959 resulted in a high penetration of the use of natural gas in Dutch households and industry. However, the threat of climate change and earthquakes in the province of Groningen as a result of natural gas extraction stimulated the search for alternative energy carriers such as hydrogen gas. Various ways of hydrogen production and supply have the attention of scientists, policy makers and companies. For example, the

production of hydrogen from natural gas with capture and storage of the resulting carbon dioxide and hydrogen production from renewable sources, also known as green hydrogen production (NWP, 2022; Hers *et al.*, 2018; Leguijt *et al.*, 2022). The latter implies that the hydrogen is not only produced from a renewable source such as water or biomass, but also that the energy carriers needed for the production are renewable and originate from e.g. wind, solar energy or hydropower.

According to TNO (n.d.(a)), about 0.8 million ton per year of hydrogen is produced in the Netherlands without capture and storage of carbon dioxide, which results in approximately 12.5 million ton per year of carbon dioxide emissions. Several initiatives are being taken to make the production of hydrogen more sustainable. An example is the H-vision project described by H-vison (n.d.) and Porthos (n.d.) which aims at producing hydrogen for 90% from residual gases originating from refineries in the port of Rotterdam area and for 10% from natural gas off the grid, followed by capturing and storing the resulting carbon dioxide in empty gas fields beneath the North Sea. Another example is the PosHYdon project (PosHYdon, n.d.), which deals with offshore hydrogen production with electricity from wind energy. Importing hydrogen from abroad, e.g. that is produced with solar energy in North Africa followed by pipeline transport to Europe (Van Wijk and Wouters, 2021, Timmerberg and Kaltschmitt, 2019) is considered as well.

The sustainability assessment takes into account the whole supply chain from a life cycle perspective. The latter prevents problem-shifting between the different phases of a life cycle and/or sustainability aspects, as described by Finnveden *et al.* (2019). Another aspect of the sustainability assessment is that attention is paid to the loss of work potential, also known as the 'quality of energy' or exergy. This is important 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 (2020). 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 (Stougie, 2014).

In a previous study, Stougie *et al.* (2022) assessed the offshore and onshore electrolysis of water with electricity from wind farms in the Netherlands and the electrolysis of water with electricity from solar parks in Algeria followed by hydrogen transport via pipelines to the Netherlands. They applied the ReCiPe 2016 and Total Cumulative Exergy Loss (TCExL) methods. This research also considers ammonia production with solar energy in Saudi Arabia followed by deep-sea transport and ammonia cracking to hydrogen in the Netherlands. Furthermore, the results obtained with the ReCiPe 2016 and TCExL methods are compared with the results of applying the Environmental Footprint (EF) method version 3.0 since the European Commission recommends applying the EF method (EU, 2021).

2 SUSTAINABILITY ASSESSMENT

The sustainability assessment of the green hydrogen supply chains consists of environmental life cycle assessment (LCA) and exergetic life cycle assessment, more specific the Total Cumulative Exergy Loss (TCExL) method described by Stougie and Van der Kooi (2016).

2.1 Functional unit and system boundaries

The sustainability assessment focuses on the supply chain of 1 kg of gaseous hydrogen at 30 bar at the port of Rotterdam from an LCA perspective. This implies that the assessed supply chains start with the extraction of materials and the production of energy carriers from earth and include all required production processes as well as transport. The storage of hydrogen at the port of Rotterdam and the use of hydrogen are not included. The lifetime of the system components is considered to be 25 years. Components with another lifetime are scaled to this lifetime except for long-distance infrastructure such as gas pipelines and electricity grids of which the original lifetime of 40 to 60 years is kept.

2.2 Environmental Life Cycle Assessment

The LCA software tool SimaPro release 9.5.0.2 (Pré, n.d.) is used for the environmental LCA. SimaPro comes with several databases of which, with only a few exceptions, the ecoinvent database 3 (ecoinvent,

n.d.) is used to model the background processes of the hydrogen supply chains. Similar to Stougie *et al.* (2022), the following method is applied to assess the environmental sustainability of the hydrogen supply chains: the ReCiPe 2016 method version 1.04 (Huijbregts *et al.*, 2016), default perspective, with its endpoint indicators damage to human health, ecosystem diversity and resource availability plus its midpoint indicators global warming, land use and water consumption. In addition, the Environmental Footprint 3.0 method (PRé, 2022) is used as a second method to calculate the total environmental impact of the supply chains and its midpoint indicators climate change, land use and water use. The lower an environmental score, the more sustainable a system is.

2.3 Exergetic life cycle assessment

The TCExL method used for the exergetic LCA consists of the following three components (Stougie (2014), Stougie and Van der Kooi (2016), Stougie *et al.* (2019): 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. This internal exergy loss is calculated from the Cumulative Exergy Demand (CExD) version 1.05 (Bösch *et al.*, 2007) calculated by SimaPro and the amounts of emissions and waste flows reported by SimaPro times their standard exergy values, e.g. Szargut (2007). 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. 95% by mass. The abatement exergy loss refers to the exergy loss caused by abatement of the system's emissions and waste flows to the level required by legislation. This is limited to the emissions of carbon dioxide, 5.86 MJ/kg (Dewulf *et al.* (2000), Van der Vorst *et al.* (2019), sulphur dioxide, 57 MJ/kg, nitrogen oxides, 16 MJ/kg, and phosphate emissions,18 MJ/kg (Cornelissen, 1997), because data about other substances have not yet been found in literature. The exergy loss caused by the system's 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. The net amount of biomass production when land is not occupied, i.e. the Net Primary Production (NPP), and the average biomass conversion factor of 42.9 MJ exergy per kg of carbon (Haberl *et al.*, 2007, Alvarenga *et al.*, 2013) result in a worldwide average exergy loss of 215 GJ per hectare per year (Stougie, 2014). The amounts and types of land use including period of use, in m^2a, are calculated by SimaPro. Double-counting of land use is prevented by not taking into account the types of land use related to the growing of trees and/or other types of biomass. The types of land use related to marine ecosystems are not taken into account because of the very small amount of solar energy that is captured by these land types, as described by Dewulf *et al.* (2007).

3 ASSESSED HYDROGEN SUPPLY CHAINS

3.1 Hydrogen production with solar energy in Algeria

This research on hydrogen production with solar energy in Algeria is initiated by Ambagts (2021). 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 (Bareiß *et al.* (2019). 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, as described by Ambagts (2021) and Sahouane *et al.* (2019). 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.* (2022).

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.* (2019) and Sharma *et al.* (2020).

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.

3.2 Hydrogen from wind energy in the North Sea

An offshore and an onshore option for the production of hydrogen from seawater with electric power generated by the Borssele 1&2 wind farms in the North Sea is considered, as described by Bryson (2021). The 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.* (2022).

The Borssele 1&2 wind farm is located 23 km from Westkapelle. Based on a load factor of 48%, 79 TWh of electricity is generated per year. 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 an electrolysis unit is situated at the Alpha substation, which is followed by pipeline transport of the produced hydrogen to Rotterdam. The onshore option includes conversion of the electricity into 220 kV AC at the Alpha substation followed by transport via 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 taken into account.

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 (NEOM, 2023) and the research by Poli (2022). 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 (5 Capitals, 2022) located in Saudi Arabia generate 10% more electricity than the non-bifacial solar panels located in Algeria (TNO, n.d. (b)).

The ecoinvent process 'Oxygen, liquid {RoW}| air separation, cryogenic | Cut-off, U' is used to model the production of nitrogen. It has been adapted by changing the product from oxygen into nitrogen, i.e. changing 1 kg of oxygen product into 1/23.1*75.5 = 3.27 kg of nitrogen product, and by changing the origin of all electricy 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.* (2020), 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 1). 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.

Table 1: Model of the green ammonia production plant, based on Chisalita *et al.* (2020)

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

* 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.
** 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.

In line with the research by Song *et al.* (2022), 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. Traditionally, polyurethane foam is used as insulation material for offshore transportation (Ye *et al.* (2022)). According to Song *et al.* (2022), the insulation thickness of ammonia and LNG storage tanks equals about 9 and 18 cm, resp. 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 cargo tanks is approximately half the amount of insulation material needed for an LNG tanker. Accordingly, 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 1191 kg of 'Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U'.

According to Song *et al.* (2022), 0.84 GJ of electricity per ton of ammonia is needed for (mainly) processing boil-off gas (BOG) during land storage. 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, 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 (Song *et al.* (2022)), 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 2).

Table 2: Model of the land storage and loading of ammonia based on Song *et al.* (2022)

New model	
Added	**Amount [ton]**
Outputs to technosphere: Products and co-products	
Ammonia, stored for three days on land and loaded on ship	*107063.04*
Inputs from technosphere: materials/fuels	
Ammonia, liquid | Haber-Bosch green ammonia production	*109248*
Ammonia, liquid storage tank [piece]	*(107063.04*3)/(16,000*85%*682.8/1000*50*365.25)*
Inputs from technosphere: electricity/heat	
Electricity, generated with bifacial solar panels in Saudi Arabia [GJ]	*109248*0.84+107063.04*(1.45+0.346)/1000*

The distance between Oxagon and Rotterdam is calculated at 6576 km. During the sea transport from Oxagon to Rotterdam, all BOG is used in the propulsion system. Based on the data provided by Song *et al.* (2022), 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.* (2022), it is assumed that 106785.46 ton of ammonia arrives in Rotterdam.

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. According to Song *et al.* (2022), 106784.37 ton of ammonia remains after storage on land.

The model of the conversion of ammonia into hydrogen is based on the research by Jang and Han (2024), 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 3).

Jang and Han (2024) mention the subsequent compression of the hydrogen/nitrogen mixture to 20 bar followed by pressure swing adsorption (PSA) to obtain high purity hydrogen. The compression to 30 bar of the resulting hydrogen is added because of the f.u. applied in this research. The ecoinvent process 'Compressed air, 800 kPa gauge {RER}| compressed air production, 800 kPa gauge, >30kW, 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 hours versus the 25 years of the f.u., which results in 0.22/(300*90.000)*25/(90.000/(365*24)) pieces of the compressor (#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% (Uehara, 2009).

Table 3: Model of the conversion of ammonia into hydrogen, based on Jang and Han (2024)

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

4 RESULTS AND DISCUSSION

The results of the environmental LCA with the ReCiPe 2016 method are presented in Table 4. The normalised endpoint indicators show that the offshore production of hydrogen from wind energy followed by pipeline transport to Rotterdam is preferred. The production of hydrogen from solar energy in Algeria followed by pipeline transport to Rotterdam scores second-best. This is followed by the onshore production of hydrogen from wind energy. 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 appeared to have the highest environmental impact. The damage category human health accounts for more than 90% of the endpoint scores. From looking in more detail into the results for this damage category, it became clear that the following subsystems contribute most to the endpoint scores of the four systems: the PV-system, the electrolyser, the export cables and the use of Dutch electricity for compression of the hydrogen/nitrogen mixture, resp. The amounts of these subsystems were decreased and increased by 10% during a sensitivity analysis, which resulted in a max 7-8% decrease/increase of the endpoint indicator total scores without changing the order of preference. Besides, the scores of the ammonia option are largely influenced by the assumption that 80% of the hydrogen is recovered during the pressure swing adsorption, but even with 100% recovery the ammonia option appears to have the largest environmental impact.

The order of preference is quite different when looking at the three ReCiPe 2016 midpoint indicators global warming potential (GWP), land use and water consumption. I.e., the offshore wind option is still preferred, but now the onshore wind option scores second-best and the supply chain with solar energy in Saudi Arabia followed by ammonia transport appears to be the least preferred. When looking at land use and water consumption, the midpoint scores of both solar energy options are considerably higher than the scores of the wind 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 0.89 to 1.5 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). The 5.6 and 13 kg CO_2-eq. per kg of hydrogen for the solar PV

options are higher than the 2.4 kg CO_2-eq. per kg hydrogen of Cetinkaya *et al.* (2012). The difference may be caused 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 caused by steam reforming of natural gas (Cetinkaya *et al.*, 2012). The environmental impact, especially of the ammonia option, is expected to decrease with a more renewable Dutch electricity mix.

Table 4: Results of the ReCiPe 2016 method for 1 kg of hydrogen in Rotterdam, Netherlands

	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	3.0E-1	7.9E-2	5.5E-1	7.1E-1
Ecosystems	2.2E-2	3.4E-3	1.8E-2	5.2E-2
Resources	3.5E-3	4.7E-4	8.5E-4	6.4E-3
Total [Pt]	3.2E-1	8.3E-2	5.7E-1	7.7E-1
Idem, normalised	*386*	*100*	*689*	*922*
Midpoint indicators				
GWP [CO_2-eq.]	5.6E+0	8.9E-1	1.5E+0	1.3E+1
Land use [m^2a crop eq.]	1.3E+0	2.3E-2	7.9E-2	2.8E+0
Water consumption [m^3]	1.1E-1	4.6E-3	1.6E-2	2.7E-1

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

Table 5 presents the results of the environmental sustainability assessment with the Environmental Footprint 3.0 method. Like with the ReCiPe 2016 method, the offshore wind option is preferred. The onshore wind supply chain seems to be second-best, but the difference with the score of the solar energy from Algeria option is too small to distinguish between the two options according to the sensitivity analysis. The solar energy from Saudi Arabia via ammonia option appears to be the least-preferred.

The orders of preference according to the scores of the EF midpoint indicator climate change and the ReCiPe midpoint indicator GWP 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 land and water use, the difference between the scores is much smaller than with the ReCiPe midpoint scores. 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 m2a and m3, resp. while the units of the EF 3.0 scores are Pt, i.e., the numbers have been normalised and weighted.

Table 5: Results of the Environmental Footprint 3.0 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 indicator [Pt]				
Total score	1.6E-3	4.8E-4	1.5E-3	3.3E-3
Idem, normalised	*338*	*100*	*325*	*692*
Midpoint indicators [Pt]				
Climate change	1.5E-4	2.3E-5	3.9E-5	3.4E-4
Land use	8.9E-7	4.0E-7	4.4E-7	2.0E-6
Water use	4.5E-6	1.1E-6	1.6E-6	1.3E-5

The results of the exergetic sustainability assessment are presented in Table 6. The preferred option is, again, the offshore wind option, but the difference with the onshore wind option is small. The solar PV in Saudi Arabia with ammonia as an intermediate product is the least-preferred option. This could be explained by the extra conversion steps needed for converting hydrogen into ammonia and vice versa, resulting in a higher internal exergy loss. When looking at the percentual contributions of the three components of the TCExL indicator, the difference between the two types of options with regard to the renewable energy source that is used is clearly visible. 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.

Table 6: 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	**2.9E2**	**2.3E2**	**2.5E2**	**5.6E2**
Hydrogen product	1.2E2	1.2E2	1.2E2	1.2E2
Exergy of emissions and waste flows	1.8E1	9.9E0	2.8E1	5.0E1
Total exergy output	**1.4E2**	**1.3E2**	**1.5E2**	**1.7E2**
Internal exergy loss	1.6E2 (71%)	1.0E2 (95%)	1.0E2 (90%)	3.9E2 (75%)
Abatement exergy loss	3.1E1 (14%)	5.0E0 (5%)	1.0E1 (9%)	6.9E1 (13%)
Exergy loss land use	3.5E1 (16%)	4.1E-1 (0%)	1.5E0 (1%)	6.0E1 (12%)
TCExL	**2.2E2**	**1.1E2**	**1.2E2**	**5.2E2**
idem, normalised	*208*	*100*	*107*	*480*

Figure 1 presents an overview of the normalised total scores of the three sustainability assessment methods of Tables 4 to 6. It is shown that the offshore production of hydrogen with electricity from wind energy is preferred, but it depends on the assessment method which option is second-best, third-best etc. As mentioned before, several assumptions had to be made when modelling the supply chains. However, 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.

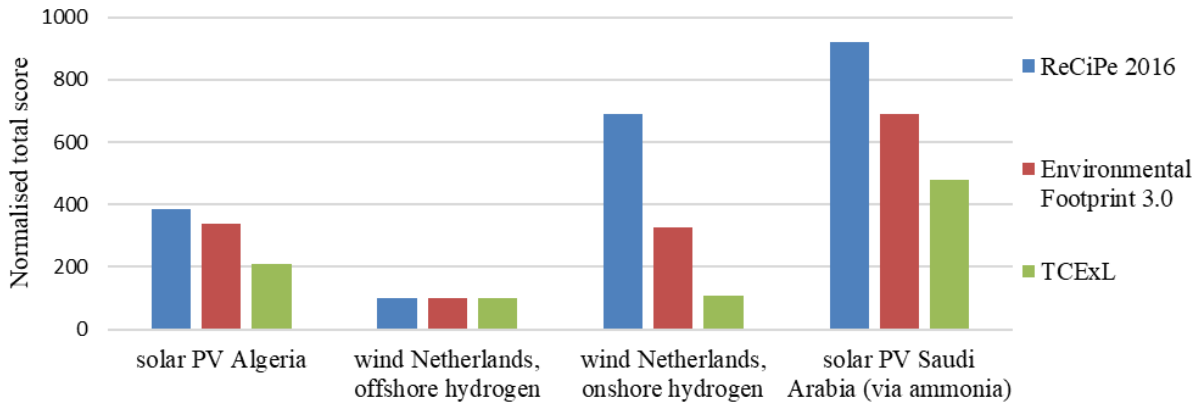

Figure 1: Normalised results of the three assessment methods

It would be interesting to compare the four supply chains when the storage of hydrogen in Rotterdam is taken into account because it is likely that the supply chain with solar energy from Saudi Arabia and deep-sea transport of ammonia will include ammonia storage in Rotterdam instead of hydrogen storage.

5 CONCLUSIONS AND RECOMMENDATIONS

The sustainability of the following four supply chains for green hydrogen production has been assessed by conducting an environmental LCA and an exergetic LCA: offshore and onshore electrolysis with electricity from the Borssele 1&2 wind farms in the Netherlands (offshore and onshore wind 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 total scores of the environmental assessment with the ReCiPe 2016 and Environmental Footprint (EF) 3.0 methods show that the offshore wind option is preferred, but that 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 results of the total cumulative exergy loss (TCExL) method indicate that the offshore wind option is preferred, but the difference with the onshore wind option is small. Of the two solar PV options, the solar PV Algeria option results in a lower TCExL than the solar PV Saudi Arabia option.

The order of preference of the options according to the total scores of the EF and TCExL methods is similar, although sometimes the difference between the scores of the options is small, while the order of preference according to the ReCiPe method is different.

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 production of hydrogen. It is also advised to take into account storage of the energy carrier in Rotterdam since it is likely that ammonia instead of hydrogen is stored in the solar PV Saudi Arabia option. Furthermore, it is recommended that attention be paid to the economic and social pillars of sustainability assessment as well.

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.

REFERENCES

Alvarenga, R.A., Dewulf, J., Van Langenhove, H., Huijbregts, M.A., 2013, Exergy-based accounting for land as a natural resource in life cycle assessment, The International Journal of Life Cycle Assessment, vol. 18, no. 5: p. 939-947.

Ambagts, J., Groene waterstof uit Noord-Afrika, Een levenscyclusanalyse [Green Hydrogen from North Africa, A Life Cycle Assessment] [BSc thesis]. Delft, Netherlands: Delft University of Technology, 36 p.

Bareiß, K., de la Rua, C., Möckl, M., Hamacher, T., Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Applied Energy, vol. 237: p. 862–872, doi: 10.1016/j.apenergy.2019.01.001.

Bösch, M.E., Hellweg, S. Huijbregts, M.A.J., Frischknecht, R., 2007, Applying Cumulative Exergy Demand (CExD) Indicators to the ecoinvent Database. International Journal of Life Cycle Assessment vol. 12, no. 3: p. 181-190, doi:10.1065/lca2006.11.282.

Bryson, L., 2021, De potentie van waterstof in Nederland, Een Life Cycle Assessment van de casus Borssele kavel I & II [The potential of hydrogen in the Netherlands, A Life Cycle Assessment of the case Borssele I&II] [BSc thesis]. Delft, Netherlands: Delft University of Technology. 77 p.

5 Capitals, 2022, NEOM Green Hydrogen Project Component: Hydrogen Complex – Environmental and Social Impact Assessment Executive Summary, June 2022, v1.1, 115 p.

Cetinkaya, E., Dincer, I., Naterer, G.F., 2012, Life cycle assessment of various hydrogen production methods. International Journal of Hydrogen Energy vol. 37: p. 2071-2080, doi:10.1016/j.ijhydene.2011.10.064.

Chisalita, D-A., Petrescu, L., Cormos, C-C., 2020, Environmental evaluation of european ammonia production considering various hydrogen supply chains, Renewable and Sustainable Energy Reviews, vol. 130, p. 1-14. doi: 10.1016/j.rser.2020.109964.

Cornelissen, R.L., 1997, Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility [dissertation]. Enschede, Netherlands: Twente University.

Dewulf, J., Van Langenhove, H., Mulder, J., Van den Berg, M.M.D., Van der Kooi, H.J., De Swaan Arons, J., 2000, Illustrations towards quantifying the sustainability of technology. Green Chemistry, vol. 2: p. 108-114, doi:10.1039/B000015I.

Dewulf, J., Bösch, M., De Meester, B., Van der Vorst, G., Van Langenhove, H., Hellweg, S., Huijbregts, M., 2007, Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environmental Science & Technology, vol. 41, no. 24: p. 8477-8483, doi: 10.1021/es0711415.

Dincer, I. and Rosen, M.A. (2020). *Exergy: energy, environment and sustainable development*, 3rd Edition, Elsevier Oxford, UK, 724 p.

EC, 2021, Commission recommendation (EU) 2021/2279 of 15 December 2021, Official Journal of the European Union, 30.12.2021.

Ecoinvent Centre (Swiss Centre for Life-Cycle Inventories) St-Gallen, Switzerland.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2019, Recent developments in life cycle assessment. Journal of Environmental Management, vol. 91, no. 1: p. 1-21.

H-vision, n.d., H-visions's hydrogen offers an excellent solution for a rapid and significant cut in carbon emissions, https://www.h-vision.nl/en.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 2007, vol. 104, no. 31: p. 12942-12947.

Hers, S., Scholten, T., Veen, R. van der, Water, S. van de, Leguijt, C. Rooijers, F., 2018, Waterstofroutes Nederland - Blauw, groen en import (in Dutch), Delft, CE Delft, June 2018, Publication No. 18.3K37.075.

Huijbregts, M.A.J., Steinmann Z.J.N., Elshout P.M.F., Stam G., Verones F., Vieira M.D.M., Hollander A., Zijp M., van Zelm R., 2016, ReCiPe 2016: A harmonized life cycle impact assessment, National Institute for Public Health, Bilthoven, Netherlands. RIVM Report No. 2016-0104.

Jang, J., Han, M., 2024, Ammonia autothermal reformer with air side-stream distribution for hydrogen production, International Journal of Hydrogen Energy, vol. 49, p. 1468-1481. doi: 10.1016/j.ijhydene.2023.09.157.

Leguijt, C., Rooijers, F., Van den Toorn, E., Van der Veen, R., Van Cappellen, L., Kampman, B., Weeda, M., Van Dril, T., Lamboo, S., 2022, 50% green hydrogen for Dutch industry, Delft, CE Delft, March 2022, publication no. 22.210426.035.

NEOM, 2023, NEOM Green Hydrogen Company completes financial close at a total investment value of USD 8.4 billion in the world's largest carbon-free green hydrogen plant, Press release of 22 May 2023

NWP, 2022, Routekaart waterstof [Hydrogen roadmap], Nationaal Waterstof Programma, Nov. 2022.

Poli, S., De milieu-impact van een waterstofketen met ammoniaktransport – Levenscyclusanalyse [The environmental impact of a hydrogen chain with ammonia transport – Life Cycle Assessment] [BSc thesis]. Delft, Netherlands: Delft University of Technology, 49 p.

Porthos, n.d., CO2 reduction through storage beneath the North Sea, https://www.porthosco2.nl/en/.

PosHYdon, n.d., For the first time green hydrogen will be produced offshore on an operational platform, https://poshydon.com/en/home-en.

PRé Consultants, Amersfoort, Netherlands. SimaPro LCA software, https://simapro.com.

PRé Sustainability B.V, 2022, SimaPro database manual - Methods library, June 2022, 56 p.

Sahouane, N., Dabou, R., Ziane, A., Neçaibia, A., Bouraiou, A., Rouabhia, A., Mohammed, B., 2019, Energy and economic efficiency performance assessment of a 28 kWp photovoltaic grid-connected system under desertic weather conditions in Algerian Sahara. Renewable Energy, vol. 143: p. 1318–1330. doi: 10.1016/j.renene.2019.05.086.

Sharma, H., Mandil, G., Zwolinski, P., Cor, E., Mugnier, H., Monnier, E., 2020, Integration of life cycle assessment with energy simulation software for polymer exchange membrane (PEM) electrolysis. Procedia CIRP, vol. 90: p. 176-181. doi:10.1016/j.procir.2020.02.139.

Song, Q., Rivera Tinoco, R., Yang, H. Yang, Q., Jiang, H., Chen, Y., Chen, H., 2022, A comparative study on energy efficiency of the maritime supply chains for liquefied hydrogen, ammonia, methanol and natural gas, Carbon Capture Science & Technology, vol. 4: p. 1-10. doi: 10.1016/j.ccst.2022.100056

Stougie, L., 2014, Exergy and Sustainability – Insights into the Value of Exergy Analysis in Sustainability Assessment of Technological Systems [dissertation]. Delft, Netherlands: Delft University of Technology, 231 p.

Stougie, L., Van der Kooi, H.J., 2016, Possibilities and consequences of the Total Cumulative Exergy Loss method in improving the sustainability of power generation. Energy Conversion and Management, vol. 107, no. 1:60-66, doi:10.1016/j.enconman.2015.09.039.

Stougie, L., Del Santo, G., Innocenti, G., Goosen, E., Vermaas, D., van der Kooi, H., Lombardi, L., 2019, Multi-dimensional life cycle assessment of decentralised energy storage systems. Energy, vol. 182: p. 535-543, doi:10.1016/j.energy.2019.05.110.

Stougie, L., Van der Kooi, H., Stikkelman, R., 2022, Assessment of the sustainability of various ways of hydrogen production and supply by applying LCA and exergy. Proceedings of ECOS 2022, Danmarks Tekniske Universitet (DTU): p. 73-84, doi.org/10.11581/dtu.00000267

Szargut, J., Appendix 1. Standard chemical exergy, Egzergia. Poradnik obliczania I stosowania, Gliwice: Widawnictwo Politechniki Shlaskej.

Timmerberg, S., Kaltschmitt, M., 2019, Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines – Potentials and costs. Applied Energy, vol. 237, no. 1: p. 795-809.

TNO, n.d., 15 dingen die je moet weten over waterstof [15 Things you should know about hydrogen], https://www.tno.nl/nl/aandachtsgebieden/energietransitie/roadmaps/co2-neutrale-industrie/waterstof-voor-een-duurzame-energievoorziening/15-dingen-die-je-moet-weten-over-waterstof>.

TNO, n.d.(b), Bifacial solar panels: more energy and more applications, https://www.tno.nl/en/technology-science/technologies/bifacial-solar-panels/.

Uehara, I., 2009, Separation and Purification of Hydrogen, *In*: Ohta, T., *Energy Carriers And Conversion Systems With Emphasis On Hydrogen - Volume I*, EOLSS Publishers: p. 268-282.

Van der Vorst G., Dewulf J., Van Langenhove H., 2011, Developing Sustainable Technology: Metrics from Thermodynamics. In: Bakshi B.R., Gutowski T., Sekulic D, editors. Thermodynamics and the Destruction of Resources. Cambridge: Cambridge University Press: p. 249-264.

Van Wijk, A.J.M., Wouters, F., 2021, Hydrogen - The Bridge between Africa and Europe. In: Weijnen, M.P.C., Lukszo, Z., Farahani, S., editors. Shaping an Inclusive Energy Transition. Cham, Switzerland: Springer: p. 91-119.

Ye, C., Lin, Y., Pei, F., 2022, Comparative study of three insulation materials installed on type C independent tank for offshore LNG transportation, Cryogenics, vol. 126: p. 1-12, doi.org/10.1016/j.cryogenics.2022.103521.

ACKNOWLEDGEMENT

The authors would like to thank BSc students Janneke Ambagts, Larissa Bryson and Stefan Poli of the Delft University of Technology BSc programme Technische Bestuurskunde for their research in the field of green hydrogen production supply chains.