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Assessment of the sustainability of various ways of hydrogen production and supply by applying LCA and exergy

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Abstract:

The Netherlands is known for its high penetration of natural gas use in households and industry, but the threat of climate change and earthquakes in the province of Groningen, caused by natural gas production, stimulate the search for alternatives, such as hydrogen gas. Various ways of producing and supplying hydrogen have the attention of scientists, companies and policy makers. This study compares the following three ways of green hydrogen production: 1) a photovoltaic system in Africa is used to produce hydrogen from sea water, followed by pipeline transport to Rotterdam, Netherlands, 2) electricity generated by the offshore Borssele 1&2 wind farm in the Netherlands is used for the offshore production of hydrogen from sea water followed by pipeline transport to Rotterdam, or 3) the electricity generated by this offshore wind farm is transmitted to Rotterdam where it is used for onshore production of hydrogen from sea water. The sustainability of the three systems is assessed from a life cycle point of view. The environmental LCA resulted in ReCiPe 2016 endpoint indicators and the midpoint indicators GWP, land use and water consumption. The exergetic sustainability assessment applied the Total Cumulative Exergy Loss (TCExL) method. The preferred system according to the results of the environmental LCA and the exergetic sustainability assessment is the wind energy system including offshore hydrogen production. The results are not unanimous as to which system is the second-best. The three systems need to be investigated in more detail before firm conclusions can be drawn. It is recommended that attention also be paid to the economic and social pillars of sustainability, and to the exergetic sustainability of technological systems in general, as exergetic assessment results are independent of changing and subjective models, weighting factors and other variables.

Keywords:

Hydrogen; Sustainability assessment; Life cycle assessment; Total cumulative exergy loss; Green hydrogen.

1. Introduction

The Netherlands is known for its high penetration of the use of natural gas in households and industry, which is a result of the discovery of the huge gas field in the province of Groningen in 1959. The threat of climate change and earthquakes, caused by gas production, made in necessary to reduce the use of this Groningen gas. Alternatives are being sought in natural gas from abroad and the transition from natural gas to hydrogen gas as an energy carrier. Various ways of hydrogen production and supply have the attention of scientists, companies and policy makers. For example, improving conventional production processes of hydrogen from natural gas, known as grey hydrogen production, and including capture and storage of carbon dioxide emissions, known as blue hydrogen production. Another example is green hydrogen production, i.e., the hydrogen is produced from a renewable source such as water or biomass and the energy needed for the production is renewable as well, e.g. biomass, wind, solar energy or hydropower.

For the sustainability assessment of the various ways of hydrogen production, it is important to consider the whole supply chain as well as a life cycle perspective to prevent problem-shifting between the different phases of a life cycle and/or sustainability aspects [1]. In addition, it is important to pay attention to the loss of work potential, also known as the 'quality of energy' or exergy, because exergy is needed for every process and activity to take place. 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 [2].

Currently, almost all hydrogen in the world is produced by steam reforming of natural gas; natural gas and steam under high pressure are converted into hydrogen and carbon dioxide. In the Netherlands, about 0.8 million ton per year of hydrogen is produced which results in a carbon dioxide emission of about 12.5 million ton per year [3]. The H-vision project [4] in the Netherlands aims to produce hydrogen from residual gases supplied by refineries in the port of Rotterdam area (90%) and natural gas off the grid (10%) in combination with the capture of the resulting carbon dioxide and storage of the carbon dioxide in empty gas fields beneath the North Sea [5]. Other ideas and initiatives are offshore hydrogen production with wind energy, e.g. the

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PosHydon project [6], and producing hydrogen with solar energy in North Africa followed by pipeline transport to Europe, e.g. [7,8].

This research compares the following ways of green hydrogen production: using solar energy in North Africa for electrolysis of purified seawater followed by pipeline transport of the hydrogen to the Netherlands [9] and using wind energy in the North Sea for offshore and onshore electrolysis of purified sea water in combination with transport of electricity and/or hydrogen [10].

2. Sustainability assessment

The sustainability of the ways of hydrogen production is assessed by carrying out an environmental life cycle assessment (LCA) and an exergetic life cycle assessment by applying the Total Cumulative Exergy Loss (TCExL) method [11].

2.1. Functional unit and system boundaries

This research assesses the production of 1 kg of gaseous hydrogen including its transport to the port of Rotterdam, Netherlands from an LCA perspective starting with the extraction of materials and energy carriers from earth. The storage of hydrogen at the port of Rotterdam is not included. The same holds for the use of the hydrogen. All system components are assumed to have a lifetime of 25 years. Components with a longer or shorter lifetime are scaled to the lifetime of 25 years, with the exception of long-distance infrastructure such as continental gas pipelines and electricity grids, of which the original lifetime of 40 to 60 years is kept.

2.2. Environmental Life Cycle Assessment

The environmental LCA has been carried out with the help of the LCA software tool SimaPro release 9.2.0.2 [12] and its accompanying databases. With only a few exceptions, the background processes of the ecoinvent database version 3 [13] have been used to model the background processes of the hydrogen production systems. The ReCiPe 2016 method version 1.04 [14], default perspective, has been selected to calculate the damage to human health, ecosystem diversity and resource availability endpoint indicators and the GWP, land use and water consumption midpoint indicators related to the assessed systems. The lower its ReCiPe indicator score, the more sustainable a system is.

2.3. Exergetic life cycle assessment

The Total Cumulative Exergy Loss (TCExL) method [2,11,15] is used for the exergetic LCA. This TCExL consists of the following three parts: the internal exergy loss caused by a technological system including supply chains during its life cycle, the exergy loss caused by abatement of this system's emissions and waste flows to an acceptable level, and the exergy loss caused by the system's land use.

The internal exergy loss equals the Cumulative Exergy Demand (CExD) version 1.05 [16] reported by SimaPro minus the amounts of emissions and waste flows reported by SimaPro times their standard exergy values, e.g. [17]. However, this is limited to the exergy values of the largest emissions, i.e. 95% by mass, since it is undoable to calculate the exergy values of the more than 1000 emissions listed by SimaPro. The abatement exergy loss includes the emissions of carbon dioxide, 5.86 MJ/kg [18,19], sulphur dioxide, 57 MJ/kg, nitrogen oxides, 16 MJ/kg, and phosphate emissions,18 MJ/kg [20], because data about other substances have not yet been found in literature.

The exergy loss related to land use is calculated from the land use reported by SimaPro multiplied by a worldwide average exergy loss of 215 GJ/ha.year [2], which is based on the Net Primary Production (NPP), i.e. the net amount of biomass production when land is not occupied and an average biomass exergy conversion factor of 42.9 MJ exergy per kg of carbon [21,22]. The types of land use related to the growing of trees or other biomass are not considered to prevent double-counting. Neither are the types of land use related to marine ecosystems because of the very small amount of solar energy that is captured [23].

3. Assessed hydrogen supply chains

3.1. Hydrogen production with solar energy in Africa

Solar energy in Africa is used to power an electrolysis unit that produces hydrogen from ultrapure water generated from sea water. Its oxygen by-product is vented, which is common practice unless it can be used directly in a subsequent process [24]. The gaseous hydrogen is transported via pipelines to the port of Rotterdam. Similar to [9,25], the location of the photovoltaic and electrolysis units is chosen to be in the south of Algeria (Adrar), because several pipelines for (natural) gas transport are in the vicinity. The modelling of the system components is described in the following sections.

3.1.1. Production of ultrapure water

The water feedstock needed for hydrogen production via electrolysis needs to be very pure. Since surface water is not abundant in Africa and the use of ground water as described by Mahmah et al. [26] is not considered a sustainable option, it was decided to use sea water instead.

The subsystem that produces ultrapure water from sea water comprises the desalination by reverse osmosis, followed by ultra-purification of the water. The salt by-product from the reverse osmosis is not treated as a by-product since its direct use in this area is unknown. Table 1 shows an overview of the ecoinvent processes used to model this subsystem.

Table 1. SimaPro model for the production of ultrapure water from sea water.

Product/name of ecoinvent process
Water, ultrapure {RER}| water production, ultrapure with tap water via reverse osmosis from sea water| Cut-off, U
Added
Tap water {GLO}| tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage | Cut-off, U
Deleted
Tap water {RER}| market group for | Cut-off, U

3.1.2. Power generation from solar energy

Several parties are interested in the generation of power from solar energy in the Sahara area of northern Africa, e.g. [7,27,28]. The power generation systems that are mentioned are several types of Concentrated Solar Power (CSP) systems and PhotoVoltaic (PV) systems. In line with [9], preference is given to a PV system because the moving parts of CSP systems are more susceptible to damage [29] and because of the higher need of water for the cooling system of the power cycle, which needs to be cool while the temperature in the Sahara is high.

Based on the availability of ecoinvent database processes of open ground PV installations (instead of PV panels installed on roofs of buildings), the process describing an open ground PV installation located in Australia was selected, since the solar irradiation in Australia is comparable to the northern part of Africa [9]. The use of tap water for cleaning the PV panels is included in this model and has been replaced with pure water produced by the sea water desalination system. Furthermore, the transport of water from the desalination unit to the electrolysis site has been modelled by including 170 km [9] of pipeline transport. Since the ecoinvent database doesn’t include long distance water transport, an onshore petroleum pipeline has been adapted for this purpose, i.e., the petroleum emissions during transport are set at zero. Table 2 presents an overview of the ecoinvent database processes used to model power generation from solar energy.

Table 2. SimaPro model for power generation from solar energy.

Product/name of ecoinvent process
Electricity, low voltage {AU}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U
Added
Tap water {GLO}| tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage | Cut-off, U
Amount of tap water times 170 km of *Transport, pipeline, onshore, petroleum {RoW}| processing* | *Cut-off, U*, which has been modified by deleting the emission of ‘Oils, unspecified’ to soil
Deleted
Tap water {RER}| market group for | Cut-off, U

3.1.3. Electrolysis

The most mature type of electrolyser for producing hydrogen from water is the alkaline electrolyser [24]. The newer proton exchange membrane water electrolyser (PEMWE) is more expensive, but has advantages such as a high energy efficiency, the provision of hydrogen that is highly compressed and pure, and a flexible dynamic operation [24,30]. The PEMWE is newly modelled in SimaPro based on the information provided by [24], who report the amounts of materials needed for an 1 MW PEMWE stack separate from the main materials and assumed masses of a PEMWE balance of plant (BoP). According to [24], the stack has a lifetime of 7 years, while the lifetime of the BoP equals 20 years. The materials mentioned by [24] are not specified with regard to origin and/or purity. Table 3 provides an overview of the materials (ecoinvent processes) that have been selected for the SimaPro model of the PEMWE. The occupation and transformation of land are taken from the ecoinvent process named ‘Fuel cell, polymer electrolyte membrane, 2kW electrical, future {RoW})| production | Cut-off, U’ since no detailed data for the PEMWE are available. Its capacity amounts to 15 kg/h hydrogen production [24,30].

Table 3. SimaPro model for the PEM water electrolyser (PEMWE), based on [24].

Product/name of ecoinvent process		
Fuel cell, polymer electrolyte membrane, 2kW electrical, future {RoW})| production | Cut-off, U		
Added	Amount [kg]	Deleted
Titanium, primary {GLO}| market for | Cut-off, U	528	Everything, except the inputs from nature related to occupation and transformation
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	27	
Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	100	
Copper {GLO}| market for | Cut-off, U	4.5	
Idemat2021 Nafion	16	
Activated carbon, granular {GLO}| market for activated carbon, granular | Cut-off, U	9	
Platinum {GLO}| market for | Cut-off, U♣	0.75	
Platinum {GLO}| market for | Cut-off, U	0.075	
Steel, low-alloyed {GLO}| market for | Cut-off, U	4800*7/20♣♣	
Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	1900*7/20	
Aluminium, primary, cast alloy slab from continuous casting {GLO}| market for | Cut-off, U	100*7/20	
Copper {GLO}| market for | Cut-off, U	100*7/20	
Polyethylene, low density, granulate {GLO}| market for | Cut-off, U	300*7/20	
Electronic component, active, unspecified {GLO}| market for | Cut-off, U	1100*7/20	
Lubricating oil {GLO}| market for | Cut-off, U	200*7/20	
Concrete, normal {GLO}| market group for concrete, normal | Cut-off, U	5600/2400*7/20♣♣♣	

♣ This should have been iridium, but iridium is not in the SimaPro databases.

♣♣ The amounts related to the Balance of Plant (BoP) of the electrolyser have been multiplied with 7/20 to correct for the different lifetimes of the stack (7 years) and the BoP (20 years) [24].

♣♣♣ The density of concrete is assumed to be 2400 kg/m^3. Unit of the amount is m^3 instead of kg.

According to [24], 9 kg of water and 55 kWh of electricity are needed per kg of hydrogen, which is included in the overall model of the hydrogen from Africa system.

3.1.4. Hydrogen transport

The produced hydrogen is transported from Adrar in Algeria to the port of Rotterdam in the Netherlands via onshore and offshore pipelines. The lengths of the pipelines used in the model are the following: 500 km onshore in Africa, 30 km offshore from Africa to Europe and 2070 km of onshore transport in Europe [9].

The onshore and offshore pipelines are modifications of the ecoinvent processes for natural gas transport named ‘Transport, pipeline, onshore, long distance, natural gas {DZ} | processing | Cut-off, U’, ‘Transport, pipeline, offshore, long distance, natural gas {DZ} | processing | Cut-off, U’ and ‘Transport, pipeline, onshore, long distance, natural gas {NO} | processing | Cut-off, U’, i.e., the leakage of natural gas emissions from the pipelines is set at zero and the ecoinvent process ‘Zinc coat, pieces {RER}| zinc coating, pieces | Cut-off, U’ is used to model a zinc coating, of 130 μm thickness, at the inside of the pipelines, of which it is assumed that it prevents hydrogen leakage. The number of square metres zinc coating is calculated from the outer diameter and thickness of the pipes times the number of km pipe length per ton*kilometre (tkm), which is the unit used in these ecoinvent processes. The outer diameter and thickness equal 1.2 and 0.012 m, resp. [31].

An uncertainty in the adaption of natural gas pipelines for hydrogen transport is the difference in density and heating value of natural gas and hydrogen. In this research, the following two variants are considered. The first one is accounting for the difference in density by multiplying the tkm of hydrogen transport with the density of natural gas (71.9 kg/m^3) over the density of hydrogen (6.60 kg/m^3), since volume is an important aspect of transport. These densities are at 80 bar and 6 °C [32,33], the assumed conditions during pipeline transport. The second variant is neglecting the differences in density and heating value. The compression of hydrogen before the pipeline transport is not modelled separately, because of the lack of a suitable ecoinvent process and time constraints.

3.1.5. Overall system

The previously described system components are combined in the overall model. This model takes into account the scaling of the system components to the functional unit of 1 kg of hydrogen as well. E.g., the PEMWE has a capacity of 15 kg/h hydrogen production and a lifetime of 7 years, which results in a scaling factor of 1 kg over the number of kg produced during its lifetime, i.e. 1/(15*24*365*7). Table 4 shows the model of the overall system.

Table 4. SimaPro model for 1 kg of hydrogen from the hydrogen from Africa system.

Product/name of the process	Amount [unit]
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 kW
PEM Electrolyser incl BoP 1 MW | production | Cut-off, U, newly built	1/(15*24*365*7)
Transport, pipeline, onshore, long distance, natural gas {DZ} | processing |♣	1/1000*500*71.9/6.60
Transport, pipeline, offshore, long distance, natural gas {DZ} | processing |♣	1/1000*30*71.9/6.60
Transport, pipeline, onshore, long distance, natural gas {NO} | processing |♣	1/1000*2070*71.9/6.60

♣ Cut-off, U, without natural gas leakage and with the addition of a zinc coating (i.e., hydrogen transport)

3.2. Hydrogen from wind energy in the North Sea

This research considers two options for the production of hydrogen from sea water with electric power generated by the Borssele 1&2 wind farm in the North Sea. The first option, named the offshore option, produces the hydrogen at sea, which is followed by pipeline transport to Rotterdam. The second option, named the onshore option, transports the electricity to the port of Rotterdam, where an electrolyser is situated. Both options have previously been investigated by [10].

The Borssele 1&2 wind farm comprises 94 wind turbines with an installed capacity of 8 MW each [34]. They are located at 23 km from Westkapelle (province of Zeeland, Netherlands). Inter-array cables connect the wind turbines with the offshore platform named Alpha. In the onshore option, the 66 kV alternating current (AC) from the wind turbines is converted into 220 kV AC at the Alpha substation, which is followed by transport via export cables to a substation at the coast (in Borssele), where it is converted into 380 kV and supplied to the high voltage electricity grid of the Netherlands for transport to the electrolyser situated in Rotterdam [35]. In the offshore option, only the inter-array cables and substation Alpha are needed, because the electricity from the wind turbines is used to power an electrolysis unit situated at the Alpha substation. Assuming a load factor of 48% [36], the Borssele 1&2 wind farm generates 79 TWh of electricity per year. The following sections describe the subsystems that are different from the subsystems of the hydrogen production with solar energy in Africa system described in section 3.1.

3.2.1. Wind turbines

The wind turbines are supplied by Siemens Gamesa [34] and are of the type 8.0-167 DD [37]. Their rotor diameter equals 167 m and the tower height is about 92 m [38]. They are modelled in SimaPro based on the ecoinvent model of a 2 MW offshore wind turbine. This 2 MW wind turbine has a rotor diameter of 76 m and a tower height of 60 m [39]. The ecoinvent model of the moving parts of the wind turbine is scaled by multiplying the amount of material used for the rotor blades with the rotor diameter of the 8 MW turbine over the rotor diameter of the 2 MW turbine and by increasing the amount of waste glass in line with the waste percentage used for this material in the ecoinvent process (Table 5).

Table 5. Modifications ecoinvent models 2 MW offshore wind turbines.

Product/name of the process	Amount [unit]
Wind power plant, 2MW, offshore, moving parts {GLO}|	
Modifications	
Plastic material used for the rotor blades	29714*(167/76-1)=35579 kg extra
Waste glass {RER}	35579*0.65 kg extra
Wind power plant, 2MW, offshore, fixed parts {GLO}| construction | Cut-off, U	
Modifications	
inputs related to epoxy resins and steel welding	*92/60
inputs related to rolled steel	(amount-8766♣)*92/60
inputs related to copper, lead and PVC materials	0
waste treatment related to steel	*92/60

♣ needed for the sheath of the cable [39]

The ecoinvent model of the fixed parts of the wind turbine is adapted by multiplying the inputs related to the construction of the tower with 92/60, i.e. the tower height of the 8 MW turbine over the tower height of the 2 MW turbine and by removing the inputs related to the network connections since the inter-array cables are modelled separately (Table 6).

3.2.2. Grid components of the Borssele 1&2 wind farm

The SimaPro models of the cables needed to transport the electricity from the wind turbines to the Borssele 1&2 offshore substation Alpha, of the offshore substation Alpha itself, and of the export cables and onshore substation in case of onshore hydrogen production are based on the data provided by Arvesen et al. [40] supplemented with data from Nes [41] where necessary. The lifetime of the grid components according to Arvesen et al. [40] equals 30 years, which is different from the 25 years applied in this research and which is corrected for by multiplying the data with 25/30.

3.2.2.1. Inter-array cables

The 66 kV AC inter-array cables have a total length of 167 km [42]. Based on the information provided by [43], it is concluded that the conductor of the inter-array cables measures 630 mm^2. Arvesen et al. [40] describe the inputs needed for inter-array cables consisting of 83 km of 240 mm^2 and 94 km of 630 mm^2 size conductors for a 600 MW offshore wind farm. It was assumed that these inter-array cables are comparable with 240/360*83 plus 94, i.e., 126 km of inter-array cables with a conductor size of 630 mm^2. Based on the aforementioned, it was decided to model the Borssele 1&2 inter-array cables by multiplying the inputs of [41] by 167/126*25/30, i.e., it is scaled for differences in cable length and lifetime (Table 6).

3.2.2.2 Export cables

The two 220 kV export cables of the Borssele 1&2 wind farm have a capacity of 350 MW and a length of 61 km each [44]. They transport the electricity from the offshore Alpha substation to the onshore substation in Borssele, which is the case in the onshore hydrogen production option only. The export cable described by Arvesen et al. [40] is based upon the NorNed cable, which has a capacity of 700 MW [41], i.e., the same capacity as the two Borssele export cables. Differences are that the NorNed export cable is a HVDC cable with a voltage of 450 kV [40]. Because of the lack of detailed information about the Borssele export cables, it is assumed that they can be modelled by multiplying the amounts of inputs per km of export cable reported by [40] with 25/30, i.e. correcting for the different lifetimes (Table 6).

3.2.2.3. Offshore and onshore substations

The offshore as well as the onshore option for hydrogen production need the offshore high-voltage Alpha substation. The onshore option also needs an onshore substation near the coast in Borssele and an onshore substation near the electrolyser in the port of Rotterdam area for the conversion of HVAC into the DC needed for the electrolyser. It is assumed that the latter substation can be modelled similar to the onshore substation near the coast.

Arvesen et al. [40] provide data about substations used in the North Sea and divide these data into the substation structure, which is needed in case of an offshore substation, and the substation equipment, which is needed for both offshore and onshore substations. More detailed data about e.g. the types of materials needed is provided by Nes [41]. The capacity of these substations is 600 MW, while the Alpha substation has a capacity of 700 MW (2x350 MW) [45]. Based on these data and a lifetime of 25 years, the substation is modelled in SimaPro by multiplying the amounts of inputs reported by [40] with 700/600*25/30 (Table 6).

3.2.3. High voltage electricity transport

The high voltage electricity transport from Borssele to the port of Rotterdam is modelled by selecting the ‘Electricity, high voltage {NL}| market for | Cut-off, U’ process and adapting it in such a way that the production of the transmitted electricity is no longer included.

3.2.4. Overall system

The previously described system components are combined in the overall model. This model takes into account the scaling of the system components to the functional unit of 1 kg of hydrogen as well. E.g., the wind farm consists of 94 wind turbines with a capacity of 8 MW each, a lifetime of 25 years and the capacity factor is assumed to equal 48%, which results in a total power generation during its lifetime of 94*8*1000*24*365*25*(48/100) = 79 TWh. The inverse of this number has to be multiplied by 55, since 55 kWh per kg of hydrogen is needed, to get the portion of the wind farm that is needed to produce 1 kg of hydrogen.

In case of the onshore option, one offshore substation and two onshore substations are needed, e.g. one onshore substation near the coast in Borssele and one in Rotterdam to convert the HVAC into DC for the electrolyser. The length of the pipelines for offshore and onshore hydrogen transport have been estimated at 85 and 2 km, resp. [10].

Table 6. SimaPro models for the grid components, adapted from [40,41].

Inputs	Unit	Inter-array cables♣ (per windfarm)	Export cables♣ (per km)	Offshore substation♣ (per piece)	Onshore substation♣ (per piece)
Copper {GLO}| market for | Cut-off, U	ton	1.89E3	1.41E3	3.61E2	3.61E2
Steel, low-alloyed {GLO}| market for | Cut-off, U	ton	2.01E3	3.52E1	5.61E3	1.44E3
Zinc coat, pieces {RER}| zinc coating, pieces | Cut-off, U	m2	7.12E4	5.65E2		
Lead {GLO}| market for | Cut-off, U	ton	1.28E3	2.49E1		
Polyethylene, high density, granulate {RER}| production | Cut-off, U	ton	3.45E2			
Polypropylene, granulate {RER}| production | Cut-off, U	ton	2.12E2	3.25E0		
Kraft paper, unbleached {GLO}| market for | Cut-off, U	ton		5.96E0	5.87E1	5.87E1
Lubricating oil {RER}| market for lubricating oil | Cut-off, U	ton			4.60E2	4.60E2
Sawnwood, softwood, air dried, planed {RER}| market for | Cut-off, U	ton			1.12E2	1.12E2
Alkyd paint, white, without solvent, in 60% solution state {RER}| market for alkyd paint, white, without solvent, in 60% solution state | Cut-off, U	ton			1.59E1	1.59E1
Epoxy resin insulator, Al2O3 {RER}| production | Cut-off, U	ton			1.18E0	1.18E0
Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, U	kWh	4.45E6	9.37E4	6.78E6	6.78E6
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	MJ	4.45E6	6.43E4	2.71E6	2.71E6
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	tkm	1.16E6	2.38E5	9.46E5	5.26E5
Diesel {Europe without Switzerland}| market for | Cut-off, U♣♣	ton	8.36E1/42.6		2.57E1/42.6	
Heavy fuel oil {Europe without Switzerland}| market for | Cut-off, U♣♣♣	ton		7.79E1/39	1.37E1/39	

♣ all inputs should be multiplied with the following scaling factors: inter-array cables: 1/126*25/30, export cable:25/30, offshore and onshore substations: 700/600*25/30

♣♣ MJ of 'Marine vessels, marine gas oil', approximated with diesel with an LHV of 42.6 MJ/kg

♣♣♣ MJ of 'Marine vessels, heavy fuel oil', assumed LHV of 39 MJ/kg

The overall system takes into account electricity losses during transport as well. According to [41], the electricity loss in the export and high-voltage cables equals 0.003569% per kilometre and 1.76% of electricity is lost during transformation. The total length of the export and high-voltage cables needed for 1 kWh of electricity equals 1 times 61 (only one of the two export cables is needed) plus 190 km of high-voltage cable [10], which is 251 km in total. This means that the amount of electricity needed for the electrolysis in the onshore option needs to be multiplied by 1.06, i.e., 1/((1-251*0.003569/100)*(1-1.76/100)$^{\wedge 3}$), and in the offshore option by 1.02, i.e., 1/(1-1.76/100). Tables 7 and 8 show the models of the overall offshore and onshore systems, resp.

Table 7. SimaPro model for 1 kg of offshore hydrogen from wind energy at the North Sea.

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 | ♣	1/1000*85/6.60*71.9
Transport, pipeline, long distance, natural gas {NL} | processing | ♣	1/1000*2/6.60*71.9

♣ Cut-off, U, without natural gas leakage and with the addition of a zinc coating (i.e., hydrogen transport)

Table 8. SimaPro model for 1 kg of onshore hydrogen from wind energy at the North Sea.

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 ♣	55*1.06 kWh

♣ without electricity production

4. Results and discussion

The results of the environmental LCA are presented in Table 9. When looking at the endpoint indicators, the offshore production of hydrogen from wind energy at the North Sea is preferred from an environmental sustainability assessment point of view. Second-best is the production of hydrogen from solar energy in Africa followed by pipeline transport to the Netherlands, while the onshore production of hydrogen from wind energy at the North Sea is the least-preferred option. The total of the endpoint indicators is mainly influenced by the endpoint indicator named Human health, i.e. more than 90%. The subsystems that contribute most to the endpoint scores of the three hydrogen production options are the PV-system, the electrolyser and the export cables, resp. During a sensitivity analysis, the amount of these subsystems was increased and decreased by 10%, which resulted in a 7-8% increase and decrease of the endpoint indicator totals of the options. The order of preference remained the same. When looking at the midpoint indicators global warming potential (GWP), land use and water consumption, the wind energy system with offshore hydrogen production is preferred as well. The preference order of the two other systems has changed since the production of hydrogen with solar energy in Africa followed by pipeline transport to Rotterdam is the least preferred option. Cetinkaya et al. [46] report a GWP of about 1 kg CO_2-eq/kg hydrogen for water electrolysis via wind energy and about 2.4 kg CO_2-eq/kg hydrogen for water electrolysis via solar energy. The results of this research are of the same order of magnitude. The somewhat higher number for water electrolysis via solar energy in this research may be caused by the intercontinental pipeline transport of hydrogen. The GWP of these green ways of hydrogen production are considerably lower than the almost 12 kg CO_2-eq./kg hydrogen for steam reforming of natural gas [46].

Table 9. Results of the environmental LCA per kg of hydrogen in Rotterdam, Netherlands.

	Solar energy in Africa plus hydrogen pipeline transport	Wind energy plus offshore hydrogen production	Wind energy plus onshore hydrogen production
Endpoint indicators per damage category♣ [Pt]			
Human health	3.0E-1	7.9E-2	5.5E-1
Ecosystems	2.2E-2	3.4E-3	1.8E-2
Resources	3.5E-3	4.7E-4	8.5E-4
Total [Pt]	*3.2E-1*	*8.3E-2*	*5.7E-1*
Idem, normalised	*386*	*100*	*689*
Midpoint indicators			
GWP [CO_2-eq.]	5.6E+0	8.8E-1	1.5E+0
Land use [m^2a crop eq.]	1.3E+0	2.3E-2	7.9E-2
Water consumption [m^3]	1.1E-1	4.6E-3	1.6E-2

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

Table 10 presents the results of the exergetic sustainability assessment. Again, the offshore production of hydrogen from wind energy at the North Sea is preferred, but the difference with the second-best onshore production of hydrogen from wind energy at the North Sea is very small. The solar system causes about twice as much exergy loss. It becomes clear from Table 10 that not only its internal exergy loss, but also the abatement exergy loss and exergy loss caused by land use are higher, which is understandable because of the higher (environmental) impact of solar energy systems compared to wind energy systems.

Table 10. Results of the exergetic assessment per kg of hydrogen in Rotterdam, Netherlands.

[MJ]	Solar energy in Africa plus hydrogen pipeline transport	Wind energy plus offshore hydrogen production	Wind energy plus onshore hydrogen production
CExD	2.9E2	2.3E2	2.5E2
Hydrogen product	1.2E2	1.2E2	1.2E2
Exergy of emissions and waste flows	1.8E1	9.9E0	2.8E1
Total exergy output	1.4E2	1.3E2	1.5E2
Internal exergy loss	1.6E2 (71%)	1.0E2 (95%)	1.0E2 (90%)
Abatement exergy loss	3.1E1 (14%)	5.0E0 (5%)	1.0E1 (9%)
Exergy loss land use	3.5E1 (16%)	4.1E-1 (0%)	1.5E0 1%)
TCExL	2.2E2	1.1E2	1.2E2
idem, normalised	*208*	*100*	*107*

Assuming that both ways of assessment are equally important and that the normalised results can be summed up shows that the offshore hydrogen production from wind energy is preferred with a total of 200, that the solar system is second-best with a total of 594 and that the onshore hydrogen production from wind energy is least preferred with a total of 796. It is clear which of the three systems is preferred, but it depends on the rating of the two assessment methods which of the options is regarded second-best.

Furthermore, this research is meant to get an impression of the performance of the three systems, not to do a very detailed LCA. Several assumptions had to be made because of the lack of data, while the decommissioning of newly modelled subsystems such as the electrolyser, inter-array and export cables has not yet been included.

5. Conclusions and recommendations

An environmental life cycle assessment and an exergetic life cycle sustainability assessment of the following three systems for green hydrogen production have been carried out: 1) electrolysis of purified sea water with photovoltaic solar energy in the North of Africa followed by pipeline transport of the produced hydrogen to Rotterdam, Netherlands, 2) electricity produced by the offshore Borssele 1&2 wind farm in the Netherlands is used for offshore hydrogen production from sea water followed by pipeline transport to Rotterdam, Netherlands or 3) the electricity produced by this wind farm is transmitted to Rotterdam and used for onshore hydrogen production from sea water.

The environmental assessment resulting in ReCiPe 2016 endpoint indicators and the midpoint indicators global warming potential, land use and water consumption shows that the wind energy system with offshore hydrogen production is the preferred system. According to the endpoint indicators, the solar energy system is the second best, while the wind energy system with onshore hydrogen production is second-best according to the midpoint indicators.

The TCExL indicator of the exergetic assessment also indicates that the wind energy system with offshore hydrogen production is preferred, but the difference with the wind energy system with onshore hydrogen production is very small. The solar energy system results in about a two times higher exergy loss.

It is recommended to investigate these and other ways of green hydrogen production in more detail before firm conclusions are drawn about a preferred system for the production of hydrogen. It is also advised to consider economic as well as social sustainability aspects.

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.

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