Assessment of the sustainability of hydrogen supply chains by conducting LCA and exergy analysis including exergy replacement costs

Lydia Stougie[a], Alessandro Lima[b], Hedzer van der Kooi[c],
Gijsbert Korevaar[d] and Alicia Valero[e]

[a] *Delft University of Technology, Faculty of Technology, Policy and Management, Delft, Netherlands, l.stougie@tudelft.nl, CA*
[b] *Research Institute for Energy and Resource Efficiency of Aragón (Institute Energaia), University of Zaragoza, Zaragoza, Spain, atruta@unizar.es,*
[c] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, Netherlands (retired), jvdkooi@casema.nl,*
[d] *Rotterdam University of Applied Sciences, CoE HRTech Rotterdam, Netherlands, g.korevaar@hr.nl,*
[e] *Research Institute for Energy and Resource Efficiency of Aragón (Institute Energaia), University of Zaragoza, Zaragoza, Spain, aliciavd@unizar.es*

Abstract:

Hydrogen is considered as an alternative to fossil energy carriers such as natural gas. A difficulty with hydrogen is its volumetric density at environmental conditions. This research compares six green hydrogen supply chains: offshore wind energy in the Netherlands is used for offshore hydrogen production, offshore wind energy in the Netherlands is used for onshore hydrogen production, solar energy in Saudi Arabia is used for green ammonia production followed by deep sea ammonia transport and ammonia cracking, solar energy in Saudi Arabia and Algeria is used for the production of hydrogenated dibenzyltoluene (DBT) followed by deep sea transport and return of the dehydrogenated DBT, and a combination of wind and solar energy in Spain is used for hydrogen production followed by pipeline transport to the Netherlands. The hydrogen supply chains are assessed with the ReCiPe 2016, Environmental Footprint 3.0 (EF3.0) and Total Cumulative Exergy Loss (TCExL) methods plus a combination of the TCExL method with Exergy Replacement Costs (ERCs). The inclusion of ERCs in the assessment appeared to enlarge the difference between the exergetic scores of the hydrogen supply chains. According to the results, the wind Netherlands offshore option is preferred, but the difference between the exergetic assessment results of both Dutch wind options is small. The wind Netherlands onshore hydrogen production and wind/solar PV Spain pipeline options appear second or third best and the solar PV Saudi Arabia ammonia option seems the least-preferred option. It is recommended that a more detailed investigation of the hydrogen supply chains be conducted before firm conclusions are drawn about the preference of the hydrogen supply chains and that attention is paid to the economic and social aspects of sustainability as well. The use of exergy in the sustainability assessment of technological systems is recommended because of its independence of changing and subjective (environmental) models and weighting factors.

Keywords:

Hydrogen Supply; Sustainability; LCA; Total Cumulative Exergy Loss; Exergy Replacement costs.

1. Introduction

The Netherlands is known for a widespread use of natural gas by households and industry, which goes back to the discovery of a major natural gas field in the province of Groningen, Netherlands, in 1959. The threat of climate change, earthquakes in the province of Groningen as well as geopolitical issues resulted in a search for alternative energy carriers, such as hydrogen produced with renewable energy [1-3].

One of the initiatives that has been taken is the H-vision project [4,5]. This project aims to produce hydrogen from residual gases originating from refineries in the port of Rotterdam area and natural gas off the grid including storage of the resulting carbon dioxide in empty gas fields beneath the North Sea. Another initiative is the PosHYdon project [6], which deals with the use of wind energy for offshore hydrogen production. The import of hydrogen produced with solar energy in North Africa followed by pipeline transport to Europe is mentioned as well [7,8].

The sustainability assessment of the six hydrogen supply chains considers the whole supply chain from a life cycle perspective. In this way, problem-shifting between the different phases of a life cycle and/or sustainability aspects is prevented [9]. An environmental life cycle assessment (LCA) is used to assess the environmental sustainability of the hydrogen supply chains. Exergy analysis is used to quantify the exergy loss (also known as the loss of work potential) caused by the supply chains, because exergy is needed for every process and activity to take place, exergy loss cannot be made visible with energy analyses and because of the relationship between exergy and sustainability [10]. The exergy loss is determined with the Total Cumulative Exergy Loss (TCExL) method, which calculates the exergy loss caused by a technological system including its supply chains during the phases of construction, operation and decommissioning [11]. In this research, the TCExL is extended with Exergy Replacement Costs (ERCs) of minerals to account for the exergy that would be needed to replace the minerals into their original conditions after being dispersed at the end of their use phase [12].

The following hydrogen supply chains are assessed: offshore wind energy in the Netherlands for offshore and onshore electrolysis of water, solar energy in Saudi Arabia for electrolysis and ammonia production followed by deep-sea transport to the Netherlands and ammonia cracking, solar energy in Saudi Arabia and Algeria for electrolysis followed by transport as hydrogenated dibenzyltoluene (DBT) and transport of the dehydrogenated DBT back to the country of hydrogenation [13,14], and a newly added supply chain in which a combination of wind and solar energy in Spain is used for electrolysis of water followed by pipeline transport.

2. Environmental and exergetic sustainability assessment

2.1. System boundaries and functional unit

All hydrogen supply chains start with the extraction of materials and energy carriers from earth and end with the delivery of 1 kg of gaseous hydrogen with a purity of 99% at 30 bar in the port of Rotterdam area, after three days of storage. The substance that is stored depends on the way of hydrogen transport, e.g. the supply chain that includes long-distance ammonia transport includes ammonia storage, etc. The lifetime of the system components is set at 25 years. In case of components with another lifetime, these components are scaled to this lifetime, except for gas pipelines, electricity grids and other long-distance infrastructure of which the original lifetime of 40 to 60 years is kept.

2.2. Environmental Life Cycle Assessment

The LCA software tool SimaPro release 9.6.0.1 [15] is used to model the hydrogen supply chains. The background processes originate from the ecoinvent database 3 [16], with a few exceptions. Two life cycle impact assessment methods are used to assess the environmental sustainability, i.e., the commonly used ReCiPe 2016 method version 1.04 [17] and the Environmental Footprint 3.0 method [18], since applying the EF method is recommended by the European Commission [19]. The ReCiPe 2016 method, default perspective, is used to calculate its endpoint indicators damage to human health, ecosystem diversity and resource availability and its midpoint indicators global warming, land use and water consumption. The Environmental Footprint 3.0 method is used to calculate its total indicator and the midpoint indicators climate change, land use and water use.

2.3. Total Cumulative Exergy Loss

The Total Cumulative Exergy Loss (TCExL) method can be regarded as a combination of, or extension to, several exergy analysis and LCA methods, i.e., Cumulative Exergy Consumption (CExC), Cumulative Exergy Consumption and Abatement (CExCA), Cumulative Exergy Extraction from the Natural Environment (CEENE), and Exergetic Life Cycle Assessment (ELCA) [11,20,21]. The TCExL consists of the following three components: internal exergy loss, abatement exergy loss and the exergy loss related to land use. The internal exergy loss, also known as exergy destruction, equals the total input of exergy to the technological system during its lifecycle minus the exergy of the outputs. It is calculated from the Cumulative Exergy Demand (CExD) version 1.05 [22] and the amounts of emissions and waste flows reported by SimaPro in combination with the standard exergy values of emissions and waste flows, e.g. [23]. This is limited to the largest emissions, i.e. 95% by mass, because of the more than 1000 emissions listed by SimaPro. The abatement exergy loss considers the emissions of carbon dioxide, sulphur dioxide, nitrogen oxides and phosphate emissions since abatement exergy loss values of other emissions have not yet been found in literature. It is calculated by multiplying the amounts of emissions reported by SimaPro with the following abatement exergy values: 5.86 MJ/kg [24,25], 57 MJ/kg, 16 MJ/kg and 18 MJ/kg [26], resp. The TCExL component that is related to land use takes into account that land that is occupied by a technological system cannot be used by nature to capture new exergy from solar energy. The exergy loss caused by land use is calculated from the amounts of land use reported by SimaPro, the Net Primary Production (NPP), which represents the net amount of biomass production on land that is not occupied, and an average biomass conversion factor of 42.9 MJ exergy per kg of carbon [27,28]. This results in a worldwide average exergy loss of 215 GJ per hectare per year [11]. Land use types related to the growing of trees and/or other types of biomass are not considered to prevent doublecounting of land use. Neither are land use types related to marine ecosystems considered because of the very small amount of solar energy that is captured [29].

2.4. Exergy replacement costs

The exergy replacement costs (ERCs) are used in combination with the TCExL method to consider the exergy that would be needed to replace the minerals into their original conditions after they have been dispersed at the end of their use phase [12]. Since the ERC of a limited amount of input minerals is available, the TCExL and ERC methods are combined by replacing the CExD value used in SimaPro with the ERC of the input minerals of which the ERC is known. The CExD values in MJ/kg for each substance are calculated from the CExD values in MJ and the amounts in kg reported by SimaPro. Table 1 presents an overview of the substances of which the ERC is known.

Table 1. *Substances of which the Exergy Replacement Costs (ERCs) instead of the cumulative exergy demand (CExD) is used when combining the TCExL method with the ERCs.*

Substance	ERC [MJ/kg]	CExD [MJ/kg]	Substance	ERC [MJ/kg]	CExD [MJ/kg]
Aluminium	627.3	5.73	Lanthanum	39.33	87.5
Cadmium	5898	8.58	Lead	36.62	4.29
Calcite	2.616	0.01	Magnesite	136.2	1.05
Cerium	97.19	26.25	Manganese	15.64	4.44
Chromium	4.537	5.43	Neodymium	78.42	157.5
Cobalt	10871	192.5	Praseodymium	577.1	1500
Fluorine	182.66	63	Silver	7371	6300
Gadolinium	478.1	4200	Tantalum	482828	818000
Gallium	144828	4500	Tellurium	2235699	278.3
Gold	553250	0.045	Tin	426.4	630
Gypsum	15.41	0.045	Zinc	1627	6.79
Iron	17.75	2.52	Zirconium	654.4	161.5

3. Assessed hydrogen supply chains

3.1. Hydrogen from wind energy in the North Sea

The hydrogen supply chain makes use of electricity generated by the Borssele 1&2 wind farms in the Dutch North Sea, as described by Bryson [30]. The electricity is used to power a proton exchange membrane water electrolyser (PEMWE). The PEMWE consumes 9 kg of water and 55 kWh of electricity per kg of hydrogen and has a capacity of 15 kg/h hydrogen production and a lifetime of 7 years [31,32]. The following two variants of the hydrogen supply chain are considered: offshore hydrogen production followed by hydrogen transport via pipelines to Rotterdam and onshore hydrogen production in Rotterdam after transmission of the generated electricity to Rotterdam. Both options make use of ultrapure desalinated sea water. A more detailed description of the two options is provided by Stougie et al. [33]. The supply chains have been extended with hydrogen liquefaction, 3 days of storage and recompression to 30 bar in Rotterdam [13].

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

Electricity generated by bifacial solar panels in Oxagon, Saudi Arabia is used for electrolysis of ultrapure desalinated sea water, cryogenic air separation and ammonia production [34,35]. The liquid ammonia is shipped to Rotterdam. After 3 days of storage the ammonia is led through an ammonia autothermal reformer resulting in a mixture of hydrogen and nitrogen, which is followed by compressing the mixture to 20 bar, pressure swing adsorption to recover the hydrogen and compression of the resulting hydrogen to 30 bar. A more detailed description is provided by Stougie et al. [14,36].

3.3. Hydrogen from solar energy transported via dibenzyltoluene

Dibenzyltoluene (DTB) is considered a promising liquid organic hydrogen carrier (LOHC) [37] that can carry nine hydrogen molecules per DBT molecule via hydrogenation/dehydrogenation with storage and transport properties similar to diesel. Two locations for the production of DBT and hydrogen are considered: Saudi Arabia and Algeria. The model of the hydrogen supply chain considers a solar parabolic trough in the vicinity of the hydrogen production location to produce the steam needed for DBT production. The electricity needed for hydrogen production and DBT hydrogenation originates from a photovoltaic, open ground installation in Saudi Arabia or Algeria. The model includes production of ultrapure water, water transport (Algeria option), 3 days of storage of DBT and hydrogenated DBT (H18-DBT), pipeline transport of H18-DBT to the harbour

(Algeria option), deep sea transport to Rotterdam, 3 days of H18-DBT storage, dehydrogenation, hydrogen compression to 30 bar, 3 days of DBT storage and DBT transport to Saudi Arabia or Algeria. A more detailed description of the model is provided by Stougie et al. [14].

3.4. Hydrogen production with wind and solar energy in Spain

The Aragón region in Spain is known for electricity generation from renewable energy sources, being one of Europe's regions with the highest potential for renewable energy surplus because of its high wind and solar PV potential in combination with a low population density [38]. Assuming that wind and solar energy are the only two sources, the share of wind energy accounts for 73% and solar energy for 27% [39]. The ecoinvent processes 'Electricity, high voltage {ES}| electricity production, wind, >3MW turbine, onshore | Cut-off, U' and 'Electricity, low voltage {ES}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U' are used to model the electricity generation needed for the electrolysis. The water needed for hydrogen production via electrolysis is assumed to originate from a water source in the vicinity, e.g. the Ebro river, and is modelled as 'Water, ultrapure {RER}| market for water, ultrapure | Cut-off, U'. After compression from 30 to 80 bar, the hydrogen is transported via a pipeline to Rotterdam, where it is liquefied and stored for 3 days before it is regasified to hydrogen at a pressure of 30 bar. The length of the pipeline from Aragón to Rotterdam is calculated at about 1700 km. The gas pipeline is a modified natural gas pipeline with a zinc coating of 130 μm at the inside to prevent hydrogen leakage. The difference in density and heating value of natural gas and hydrogen is accounted for 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 [40,41], the assumed conditions during pipeline transport. Table 2 shows the SimaPro model of this supply chain.

Table 2. *SimaPro model for 1 kg of hydrogen from wind and solar energy in Spain and transported via a gas pipeline.*

Product/name of the process	Amount [unit]
Electricity, high voltage {ES}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	55*(73/100) kWh
Electricity, low voltage {ES}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U	55*(27/100) kWh
Water, ultrapure {RER}| market for water, ultrapure | Cut-off, U	9 kg
PEM Electrolyser incl BoP 1 MW | production | Cut-off, U, newly built	1/(15*24*365*7) piece
Hydrogen compression from 30 to 80 bar (per kg hydrogen)	1 kg
Transport, pipeline, onshore, long distance, natural gas {NO} without natural gas leakage plus zinc coating| processing | Cut-off, U	1/1000*1700*(71.9/6.60) tkm
Hydrogen, liquefaction in Rotterdam	1 kg
Hydrogen, liquid, storing for 3 days on land	1 kg
Hydrogen, regasification in Rotterdam	1 kg

4. Results and discussion

The environmental LCA with ReCiPe 2016 as the LCIA method resulted in the indicator scores presented in Table 3. According to the endpoint indicator scores, the option in which (offshore) wind energy in the Netherlands is used for offshore production of hydrogen followed by pipeline transport to Rotterdam is preferred and a combination of (onshore) wind and solar PV in Spain followed by pipeline transport of the produced hydrogen scores second-best. The scores of onshore hydrogen production from offshore wind in the Netherlands and the options which use DBT as a hydrogen carrier are more or less the same. The option with intermediate ammonia production and transport appears least-preferred. The endpoint scores are mainly influenced by the damage category Human health since this category amounts at 93 to 97% of the total endpoint score.

The midpoint indicator scores show that the wind offshore option is preferred, the wind onshore option scores second-best and that the ammonia option is least-preferred. The difference between the GWP indicator scores of the three other options is not very large, except for the land use and water consumption midpoint indicators because the wind/solar PV Spain option clearly scores better than the LOHC options. In general, the solar PV options result in a higher land use, which is understandable because of the higher land use of PV installations compared to wind farms.

The GWP midpoint indicator scores of 0.98 to 1.6 kg CO_2-eq. per kg of hydrogen of both wind options are comparable with the about 1 kg CO_2-eq per kg of hydrogen produced via electrolysis powered by wind energy found in literature [42]. The GWP scores of the pure solar PV options are higher than the reported 2.4 kg CO_2-eq. per kg of hydrogen [42], but this may be explained by their long transport distances. This could also explain why the wind/solar PV Spain option scores in between.

***Table 3.** Results of the ReCiPe 2016 method for 1 kg of hydrogen in Rotterdam, Netherlands.*

	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
Endpoint indicators per damage category* [Pt]						
Human health	0.13	0.60	0.65	0.57	0.57	0.35
Ecosystems	0.005	0.019	0.048	0.037	0.038	0.022
Resources	0.00053	0.00091	0.0052	0.0046	0.0045	0.0038
Total [Pt]	0.14	0.62	0.70	0.61	0.62	0.37
Normalised	100	460	516	452	455	276
Midpoint indicators						
GWP [CO_2-eq.]	0.98	1.6	11	8.2	8.9	7.3
Land use [m^2a crop eq.]	0.029	0.086	2.7	1.6	1.7	0.50
Water consumption [m^3]	0.0060	0.018	0.28	0.15	0.17	0.087

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

The options were studied in more detail by looking at the subsystems which contribute most to the endpoint scores and increasing and decreasing the amounts of these subsystems by plus and minus 10%, resp. The varied subsystems are the following: PEMWE (wind offshore), export cables (wind onshore), PV electricity and electricity for ammonia storage in Rotterdam (ammonia), PV electricity (both DBT options), the ratio between wind and solar PV and electricity needed for liquefaction (wind/solar PV Spain). In addition, the influence of the origin of the copper used for the export cables of the wind offshore option was investigated by changing its origin into 100% European instead of from Asia and the Pacific as well, and the influence of the recovery rate during the pressure swing adsorption used to recover hydrogen from the hydrogen/nitrogen mixture after ammonia cracking was investigated by changing the recovery rate from 80% to 90%. It becomes clear from Table 4 that varying the amounts of the aforementioned processes with plus and minus 10% does not change the order of preference, but that changing the origin of the copper used for the export cables of the wind onshore option would result in an endpoint score comparable to the wind/solar PV Spain option and that a 90% recovery rate of the PSA would no longer result in a highest endpoint score for the ammonia option.

***Table 4.** Sensitivity analysis regarding the ReCiPe 2016 endpoint indicator results.*

	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
Endpoint indicator [Pt]						
Default	0.14	0.62	0.70	0.61	0.62	0.37
Minimum	*0.13*	*0.58*	*0.67*	*0.59*	*0.61*	*0.36*
Maximum	*0.14*	*0.67*	*0.73*	*0.64*	*0.64*	*0.39*
Copper of 100% European origin	n/a	0.38	n/a	n/a	n/a	n/a
90% recovery pressure swing adsorption	n/a	n/a	0.63	n/a	n/a	n/a

The endpoint indicator results obtained with the Environmental Footprint 3.0 method (Table 5) show that the wind offshore hydrogen option is preferred as well and that the wind/solar PV Spain options scores second-best, but the difference between the wind/solar PV Spain and wind onshore hydrogen options is not very large. Again, the ammonia option appears to be the least-preferred and both DBT options score in between.

Table 5. Results of the Environmental Footprint 3.0 method for 1 kg of hydrogen in Rotterdam.

	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
Endpoint indicator [mPt]						
Total score	0.59	1.7	3.2	2.4	2.5	1.3
normalised	100	280	530	403	421	225
Midpoint indicators [µPt]						
Climate change	26	42	300	215	232	190
Land use	0.41	0.45	1.6	1.5	1.4	0.57
Water use	1.2	1.7	12	8.0	8.9	6.7

A comparison between the normalised values of the midpoint indicator scores of both LCIA methods is shown in Table 6. From looking at the scores related to GWP/Climate change it is clear that they are (almost) identical. The same holds for land use and water consumption/use by both wind Netherlands options. With regard to the other options, the normalised ReCiPe 2016 land use scores are about 40 to 50% of those calculated with the EF3.0 method while water consumption (ReCiPe) amounts at 150 to 175% of the water use (EF3.0). An explanation for this difference could be that both methods calculate these indicators in a different way which becomes apparent when the use of land and water is quite different, i.e. wind versus solar energy, and because the EF3.0 indicators are presented in points, i.e. the EF3.0 method includes normalisation.

Table 6. *Comparison of the normalised midpoint indicator scores of the ReCiPe 2016 and Environmental Footprint 3.0 methods.*

	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
ReCiPe [-]						
GWP	100	164	1176	842	909	746
Land use	100	296	9498	5487	6049	1716
Water consumption	100	290	4663	2435	2762	1448
Environmental footprint 3.0 [-]						
Climate change	100	164	1176	842	909	745
Land use	100	293	19893	13737	15088	3647
Water use	100	258	3159	1512	1720	836

The results obtained with the TCExL method and the TCExL method in combination with exergy replacement costs (ERCs) are shown in Tables 7 and 8, resp. As with the previous assessment methods, the wind Netherlands with offshore hydrogen production is the preferred option and the ammonia option is the least-preferred. However, the difference between the scores of both wind Netherlands options is small. The wind/solar PV Spain option scores third-best and is followed by the two DBT options, of which the scores are quite similar. With both methods, the internal exergy loss of the two wind Netherlands options amounts at 90 to 95% of the TCExL, while the internal exergy loss caused by the other options amounts at 72 to 79% (TCExL) and 77 to 81% (TCExL/ERC). It is learnt that the CExD and especially the CExD combined with ERCs is considerably higher for options that make use of solar PV, which is understandable because of the larger amount of minerals needed for the construction of the PV installations. The exergy loss related to land use amounts at 11 to 13% for the options with solar PV, while this amounts 0 to 1% for the wind energy options and 4 to 5% for the wind/solar PV Spain option. This is not unexpected because of the land use for ground PV installations. From comparing the normalised TCExL scores per option, it becomes clear that the combination with ERCs results in a 5% higher normalised value of the wind onshore and wind/solar PV Spain options and a 13% higher normalised value of the other options. In other words, the combination with ERC enlarges the difference in TCExL scores of the hydrogen supply chains.

Table 7. *Results of the TCExL method for 1 kg of hydrogen in Rotterdam.*

[MJ]	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
CExD	255	275	531	377	412	331
Hydrogen product	118	118	118	118	118	118
Exergy of emissions & waste flows	12	30	48	26	27	13
Total exergy output	130	148	167	144	145	132
Internal exergy loss	125	127	364	234	267	199
Abatement exergy loss	5.7	11	60	47	50	40
Exergy loss land use	0.53	1.6	60	44	48	12
TCExL	131	139	484	325	365	252
normalised	100	106	369	248	278	192

Table 8. *Results of the TCExL method with exergy replacement costs (ERCs) for 1 kg of hydrogen in Rotterdam.*

[MJ]	Wind Netherlands offshore H_2	Wind Netherlands onshore H_2	Solar PV Saudi Arabia via ammonia	Solar PV Saudi Arabia via DBT	Solar PV Algeria via DBT	Wind/solar PV Spain via pipeline
CExD/ERCs	259	286	609	432	473	351
Hydrogen product	118	118	118	118	118	118
Exergy of emissions & waste flows	12	30	48	26	27	13
Total exergy output	130	148	167	144	145	132
Internal exergy loss	129	138	443	288	328	219
Abatement exergy loss	5.7	11	60	47	50	40
Exergy loss land use	0.53	1.6	60	44	48	12
TCExL	135	150	562	379	426	272
normalised	100	111	416	281	315	201

Figure 1 presents an overview of the normalised total scores of all applied sustainability assessment methods compared to the total scores of the wind Netherlands offshore hydrogen production supply chain. This figure clearly shows that the wind Netherlands offshore hydrogen supply chain is preferred according to all assessment methods but that the difference with the wind Netherlands onshore hydrogen production supply chain is small according to the TCExL and TCExL/ERC results. It is also shown that the wind/solar PV Spain option with hydrogen transport via a pipeline can be regarded as the second- to third-best option and that the supply chain solar PV Saudi Arabia via ammonia appears the least-preferred. However, it is learnt from the sensitivity analysis (Table 4) that the ReCiPe 2016 score of the wind Netherlands onshore supply chain would become comparable with that of the wind/solar PV Spain supply chain assuming that all copper needed for the export cables originates from Europe and that the ReCiPe 2016 score of the ammonia supply chain would become comparable with that of the wind Netherlands onshore and DBT supply chains if it is assumed that 90% of hydrogen is recovered during pressure swing adsorption.

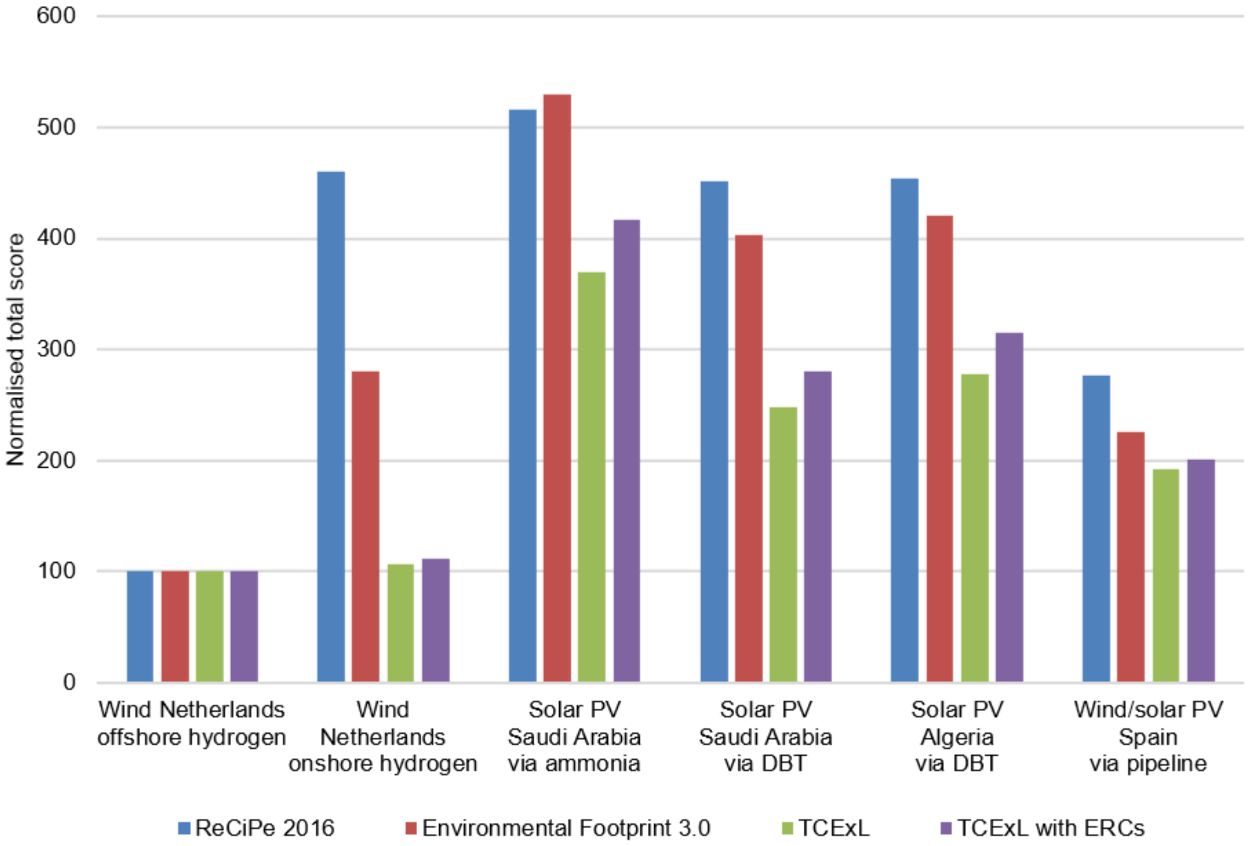

Figure 1. *Normalised scores of the six hydrogen supply chains across the three sustainability assessment methods.*

5. Conclusions and recommendations

The environmental and exergetic sustainability of six green hydrogen supply chains has been assessed from a life cycle point of view: offshore and onshore electrolysis with electricity from Dutch offshore wind farms (wind Netherlands offshore hydrogen and wind Netherlands onshore hydrogen options, resp.), hydrogen and ammonia production with solar PV in Saudi Arabia followed by ammonia deep sea transport (solar PV Saudi Arabia via ammonia option), hydrogen production and hydrogenation of dibenzyltoluene (DBT) with solar energy in Saudi Arabia and Algeria, followed by deep sea transport and return of the dehydrogenated DBT (solar PV Saudi Arabia via DBT and solar PV Algeria via DBT options, resp.) and the use of onshore wind and solar PV for hydrogen production in Spain followed by pipeline transport to the Netherlands (wind/solar PV Spain via pipeline option).

According to the results, the wind Netherland offshore hydrogen production is the preferred option, but the difference between the exergetic scores of both wind Netherlands options is small. The environmental assessment results indicate that the wind/solar PV Spain with pipeline transport of the hydrogen is second-best, although the ReCiPe 2016 score of the wind Netherlands onshore option would become similar if the copper used in the export cables is of 100% European origin. The solar PV Saudi Arabia via ammonia appears the least-preferred option, but its ReCiPe 2016 score would become comparable with the wind Netherlands onshore and DBT options assuming that the hydrogen recovery during pressure swing adsorption equals 90 instead of 80%.

When the TCExL method is combined with exergy replacement costs (ERCs) the differences between the scores of the hydrogen supply chains become larger.

It is recommended to investigate the hydrogen supply chains in more detail before firm conclusions are drawn about the preference of hydrogen supply chains. It is also recommended to pay attention to the economic and social pillars of sustainability.

The use of sustainability assessment methods that include exergy is recommended because exergy losses are independent of changing and subjective (environmental) models and weighting factors.

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