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Zhao, Guangling; Pedersen, Allan Schrøder

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Life cycle assessment of hydrogen production and consumption in an isolated territory

Guangling Zhao*, Allan Schrøder Pedersen

Technical University of Denmark Department of Energy Conversion and Storage, Frederiksborgvej 399, 4000 Roskilde, Denmark
* Corresponding author. Guangling ZHAO Tel.: +045-935-11-49;.*E-mail address:* guaz@dtu.dk

Abstract

Hydrogen produced from renewables works as an energy carrier and as energy storage medium and thus hydrogen can help to overcome the intermittency of typical renewable energy sources. However, there is no comprehensive environmental performance study of hydrogen production and consumption. In this study, detailed cradle to grave life cycle analyses are performed in an isolated territory. The hydrogen is produced on-site by Polymer Electrolyte Membrane (PEM) water electrolysis based on electricity from wind turbines that would otherwise have been curtailed and subsequently transported with gas cylinder by road and ferry. The hydrogen is used to provide electricity and heat through fuel cell stacks as well as hydrogen fuel for fuel cell vehicles. In order to evaluate the environmental impacts related to the hydrogen production and utilisation, this work conducts an investigation of the entire life cycle of the described hydrogen production, transportation, and utilisation. All the processes related to the equipment manufacture, operation, maintenance, and disposal are considered in this study.

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Keywords: Life cycle assessment; PEM electrolysis; Hydrogen; Fuel cell

1. Introduction

Up to now, problems with fluctuating and intermittent electricity from renewable power sources have only occurred in local power grids with a high percentage of renewables. In the future, high percentages of renewable electricity are expected to be fed into larger power grids too, Hydrogen is a carbon-free energy source, which makes hydrogen attractive for decarbonising electricity consumption and mobility in the energy system [1]. The issue is that hydrogen is not a primary energy source but only an energy carrier that needs to be obtained from other energy sources. Hence, the environmental and energy performance of hydrogen energy system strongly depends on the hydrogen donor and the energy source of the conversion process. Hydrogen generation technologies produce hydrogen from hydrogen-containing materials such as fossil fuels, biofuels, and water [2,3]. Currently natural gas is still the main source of hydrogen production. With no doubt that, the most sustainable hydrogen production processes are water electrolysis powered by using electricity from renewable energy sources [4].

The hydrogen produced can be stored and distributed in pressure tanks when needed. With water electrolysis, the electrical energy is produced by the electrochemical process of hydrogen and oxygen from the air [5,6]. By fuel cell vehicles, hydrogen can be used as sustainable fuel for vehicles to substitute fossil fuel and electricity in the transportation sector [7]. Even though, hydrogen has the potential to have lower environmental impacts of meeting energy demands especially CO_2 emissions. The impacts from the manufacture and disposal of the electrolysis and fuel cell equipment must be taken into account when the impact during operation is shifted away [8,9]. In this sense, comprehensive analyses are required in order to evaluate the environmental suitability of hydrogen energy systems. Regarding environmental aspects, LCA is an effective analytical tool for investigating the entire range of

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environmental impacts of all phases of an industrial activity, from raw materials acquisition to the final disposition of several hydrogen application processes, comparing the environmental impacts of conventional energy supply fossil fuels. Life Cycle Assessments (LCAs) have been carried out for various techniques of hydrogen production and fuel cell stacks [9,10]. Polymer electrolyte membrane (PEM) electrolysis and PEM fuel cell technology are these technologies, which have been the current commercial scale. They are also the more popular stack technologies by offering the prospects of cheaper and simpler construction [11].

The objective of this paper is to evaluate the potential environmental impact of hydrogen production by water electrolysis and hydrogen application for electricity production based on PEM fuel cell stack and application for mobility by hybrid fuel cell vehicles. In order to achieve this objective, it is important to consider all the processes related to the water electrolysis, PEM fuel cell, and hybrid vehicles, and not only the operation itself but also the manufacturing process.

2. Methodology

LCA is a methodology for estimating the potential environmental impacts associated with a product or service considering the entire life cycle from the extraction of raw materials, through the manufacturing, packaging and marketing processes, the use, re-use and maintenance of the product, and onto its eventual recycling or disposal as waste at the end of its useful life [12]. LCA has the strength of modeling the 'carbon footprint' of renewable energy technologies [13,14]. LCA is, therefore, the ideal tool for comparing the environmental impacts of competing products and identifying key areas where improvements could be made

Based on ISO standard, the LCA process consists of goal definition and scoping (Identifies the purpose of the study defining the system under consideration), inventory analysis (identifying and quantifying the consumption and release of materials), impact assessment (assessing the effects of these activities), and interpretation (evaluation of the results)[15].

Defining the goal and scope is the first phase of LCA. The purpose of the study is identified in this phase, so is the functional unit and system boundary. The objective of this paper is to assess the potential environmental impact of integrating hydrogen into the energy system in the isolated land. The choice of the functional unit can strongly affect the impact results of LCA studies. In this paper, the application of hydrogen is an energy source for both electricity supply and fuel for the transport sector. In order to describe the potential environmental impact of hydrogen production and use, and compare the two energy applications of hydrogen, the functional unit is defined as 1 kg hydrogen produced and consumed.

The selection of system boundaries needs to reflect the goal of the study. The system boundary is built by employing system expansion based on the methodology of consequential LCA [16]. The replaced energy is identified following the methodology of identifying marginal technology [17]. On the Orkney islands, the electricity is supplied by the renewable source (wind and tidal turbine) and co-generation based on natural gas. The marginal technology is identified as the electricity generation technology from natural gas. For the mobility, the marginal technology is identified both in the long term and short term. Hybrid electric vehicles (HEVs) are bought for the mobility to replace diesel combustion vehicle. The electric battery is the backup energy supply in case there is not enough hydrogen supply, as the hydrogen hasn't become commercial transport fuel so far. In the short the term, as the HEVs will run on electricity without hydrogen supply if there was no hydrogen production, the replaced energy source is electricity generated from natural gas. In the long term, if the hydrogen becomes larger quantity production and is supplied as a commercial transport fuel, the hydrogen vehicles will replace the conventional vehicles based on fossil fuel which is diesel in our study.

The system boundary starts from electricity production from the wind turbine and ends of the hydrogen energy applications to replace energy sources from the energy system (Fig. 1.). The whole system includes electricity produced from a wind turbine, PEM electrolysis stack unit, hydrogen storage, hydrogen transportation, and PEM fuel cell stack unit and hybrid vehicle and the replaced energy. The electrolysis stack unit is installed close to the wind turbine facilities. After produced, hydrogen is transported to the fuel cell stack site to supply electricity and heat for the building on the harbor and to the refueling station to supply fuel for the hybrid electric vehicles (HEVs) on the islands. The electrolysis stack unit includes electrolysis cell stack, cooling system, water and hydrogen separators pumps, auxiliary equipment (transformer, cables, display panel, etc.). The hydrogen generation stage covers all processes in the lifecycle of PEM electrolysis from the extraction of natural resources via generation of hydrogen down to the disposal of the electrolysis equipment. The hydrogen application stage covers fuel cell unit system, which covers fuel cell stack manufacture, operation, and disposal after it's lifetime. Hybrid vehicle use both fuel cell stack and the battery as the auxiliary sources of HEVs. Fuel cell stack is the main energy source. Transportation by lorry and ferry distribution is considered in the system.

Three scenarios are developed combining the hydrogen application technologies and replaced energy sources (Table 1.). In scenario S1, the hydrogen application is fuel cell stack with electricity as the energy product. In the scenario S2 and S3, the hydrogen application is HEVs. The replaced energy source is from the local the Orkney Islands. The replaced electricity and heat is generated by the cogeneration from natural gas. For the mobility, two replaced energy source are considered which are electricity and diesel.

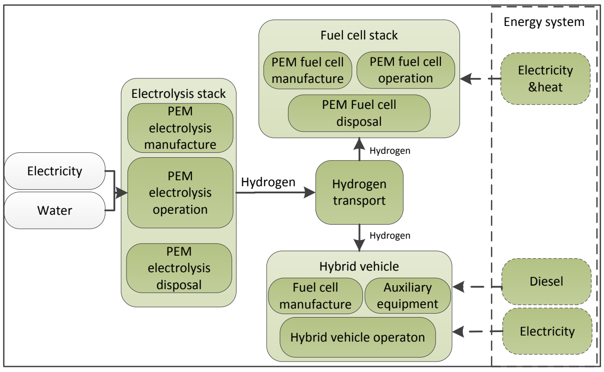

Fig. 1. System boundary of hydrogen production and application

Table 1. The scenarios developed for the hydrogen energy applications

Scenario	Power source	Hydrogen production	Hydrogen application	Replace energy	Replaced energy
S1	Wind energy	PEM electrolysis	PEM fuel cell stack	Electricity	Natural gas
S2	Wind energy	PEM electrolysis	HEVs	Electronic vehicle	Natural gas
S3	Wind energy	PEM electrolysis	HEVs	Diesel vehicle	Diesel

Life Cycle Inventory (LCI), where data collection is performed, including calculation and allocation procedures. Data to be used in the LCA based information could be classified into two categories: specific data also referred to as primary data, selected secondary data referred to as generic data. As a general rule, specific data have been used if available. Generic data have been used in cases where there is a lack of specific data or if a product consists of many components. In this paper, the specific data collected from the manufacturer include the manufacturing of electrolysis stack unit, fuel cell stack unit, and fuel cell stack for the HEVs. The material and energy consumption of producing electrolysis stack unit and fuel cell stack is obtained. Some of the equipment (pump, auxiliary equipment, etc.) is from Ecoinvent database. The disposal of electrolysis component assumed with consulting the experts. The transport distances are 10 km by road and 11 km by ferry.

Life Cycle Impact Assessment (LCIA), where the potential environmental effects, related to the results of the inventory analysis, are evaluated. The environmental impacts from the entire life cycle of products and services are addressed. The impact method is a difficult step in certain LCAs, and the inventory analysis may serve as the outcome. Emissions and consumption of resources are evaluated at every stage of the life cycle, thus the environmental impacts from the entire life cycle of products and services are addressed. The impact method is based on ILCD 2011 Midpoint. In the system boundary, the main equipment are the electrolysis stack and fuel cell stack. The main material for producing the equipment is steel, titanium, platinum, and copper, etc.. Electricity and water are the main consumption to producing hydrogen. Seven impacts categories are chosen in this study, because these are main impacts from hydrogen production and application. The seven impact categories are included in the LCIA: Climate change (Global warming potential in kg CO_2 equivalents); Ozone depletion (emission of ozone-depleting gases, in kg CFC-11equivalents); Human toxicity (emission in CTUh); Acidification (emission of acidifying gases, in kg SO_2 equivalents); Eutrophication (emission of eutrphying substances deposit, in kg P equivalents). In addition, this study included two categories that reflect the use of non-renewable/renewable resources with energy content, expressed in kg Sb equivalents, and a category that reflects the use of water consumption, expressed in m^3 water equivalents.

3. Result and Discussion

In this section, the results for seven impact categories of hydrogen energy application were calculated. Table 2. present the impact result of hydrogen for electricity production by fuel cell stack. Compare to the electricity from natural gas, the impacts of hydrogen is negative in climate change, acidification, and eutrophication. The global warming impact reduction is 7.81 kg CO_2-eq per 1kg hydrogen produced and consumed.

One of the reasons for GHG reduction is due to the electricity for PEM electrolysis is from a wind turbine. The CO_2-eq emission is mainly from electrolysis unit, especially the electrolysis manufacture. The impacts of Ozone depletion, Human toxicity, water resource depletion and mineral fossil are higher from hydrogen than from electricity than the electricity production from natural gas. The largest contribution of the impacts is due to the electrolysis unit, which is mainly electrolysis manufacture, as the electricity is based on wind energy.

The electrolysis efficiency is about or below 40%, which means that less 40% of electricity absorbed by the electrolysis is converted to the hydrogen. Based on current fuel cell technology, the efficiency of the fuel cell is also about or below 40%, which means maximum 40% of hydrogen is converted to electricity production. There will be at least more than 80% of the energy loss in the whole system (from the electricity absorbed by electrolysis to the end of electricity production).

Table 3. presents the impact results of hydrogen for mobility by hybrid vehicles. The system includes electrolysis unit, hybrid vehicle manufacture (vehicle manufacture, fuel cell battery, electric battery), transport (both road and ferry transport). The substituted scenario is the electric vehicle. Compare to the electric vehicles, the impacts from hydrogen application of hybrid vehicle is negative regarding climate change, acidification, and water resource depletion. On the contrary, there is the slightly higher impact on ozone depletion, human toxicity, eutrophication, and resource depletion compare with the electric vehicles. The carbon reduction is 13.40 kg of CO_2-eq per 1kg hydrogen produced and consumed.

From Table 2. and Table 3., we can tell that even though the carbon reduction is significant by implementing hydrogen into the energy system, the other impacts cannot be ignored like ozone depletion, human toxicity, and non-renewable resource depletion. We can also see that impacts of the 7 impact categories are mainly from electrolysis unit. Electrolysis unit includes the electrolysis manufacture and operation.

During manufacture stage, the consumption of metals like Platinum and titanium is another major reason causing higher impact, as the recycling of these metals is not considered due to data limitation.

Table 2. LCIA results of 1kg hydrogen application for electricity supply

Impact category	Unit	Electrolysis unit	Fuel cell stack unit	Road transport	Ferry transport	Electricity, natural gas	Total
Climate change	kg CO_2 eq	1.78	3.40E-04	1.34 E-03	5.23 E-04	-9.59	-7.81
Ozone depletion	kg CFC-11 eq	1.10E-05	1.39E-10	2.48E-10	3.87E-11	-4.99E-12	1.10E-05
Human toxicity	CTUh	2.10E-06	3.08E-10	4.40E-10	2.86E-11	-5.24E-07	1.58E-06
Acidification	molc H+ eq	6.93E-07	3.20E-06	9.31E-06	2.77E-06	-0.11	-0.11
Eutrophication	kg P eq	2.38E-05	5.35E-07	3.63E-06	6.62E-07	-3.15E-05	7.68E-4
Water resource depletion	m^3 water eq	0.10	-7.05E-06	2.07E-07	3.08E-05	0	0.10
Mineral, fossil & renewable resource depletion	kg Sb eq	3.46E-07	6.48E-08	8.65E-08	1.43E-09	-1.48E-06	-9.78E-07

Table 3. LCIA results of 1kg hydrogen application for mobility

Impact category	Unit	Electrolysis unit	Hybrid vehicle	Road transport	Ferry transport	Electric vehicle	Electricity, natural gas	Diesel vehicle	Diesel consumption	Total
Climate change	kg CO_2 eq	1.78	3.31	1.34 E-03	5.2 E-04	-2.9	-15.6			-13.40
								-4.1	-33.9	-32.9
Ozone depletion	kg CFC-11 eq	1.1E-05	1.7E-06	2.5E-10	3.9E-11	-2.4E-07	-8.1E-12			1.2E-05
								-4.4E-07	-6.6E-06	5.6E-06
Human toxicity	CTUh	2.1E-06	1,0E-05	4.4E-10	2.9E-11	-6.3E-06	-8.52E-07			5.1E-06
								-3.5E-06	-7.6E-07	8.0E-06
Acidification	molc H+ eq	6.9E-07	0.041	9.3E-06	2.8E-06	-0.022	-0.17			-0.15
								-0.03	-0.21	-0.20
Eutrophication	kg P eq	2.4E-05	5.4E-03	3.6E-06	6.6E-07	2.9E-4	-5.12E-3			3.0E-3
								-0.04	-0.88	-0.91
Water resource depletion	m3 water eq	0.10	-0.023	2.1E-07	3.1E-05	-3.5E-3	0			0.07
								-2.1E-03	-4.3 E-03	0.07
Mineral, fossil & renewable resource depletion	kg Sb eq	3.5E-07	2.2 E-03	8.7E-08	1.4E-09	-2.1E-3	-2.4E-06			1.5E-4
								-4,4E-03	-7.9E-05	-2.2E-03

The results referred to hydrogen production and applications are shown in Table 2. and Table 3.. Firstly climate change is the largest impacts from the hydrogen application system boundary. Secondly, the carbon emissions are much higher from the process of hydrogen for mobility than that from hydrogen for electricity generation. The impacts from hydrogen for electricity and mobility are compared with the conventional supply. For the hydrogen for electricity application, CO_2 emissions from hydrogen generation and application system are much lower than the conventional electricity supply. The hydrogen vehicle is compared to the electric vehicle and inter diesel combustion vehicle with the same standard. The climate change impacts from hydrogen for mobility are higher than that of hydrogen for electricity production, due to the vehicle manufacturer. However, the potential carbon reduction of hydrogen for mobility is higher than that of hydrogen for electricity. The reason is that the CO_2 emissions from mobility are much higher than that from electricity generation in general.

The uncertainty of this study is related to the system chosen and data quality. The system boundary is developed according to the context of an isolated island, which has a high renewable energy supply. The marginal technology is also identified based on the energy system on the Islands. It needs to address the consequence of integrating hydrogen into the energy system on a larger scale. The data for this analysis is collected based on current technology development. As PEM water electrolysis and PEM fuel cell stack are the technology under research and development, it would be a higher uncertainty with the technology and the manufacturer.

4. Conclusion

The aim of the current paper was to present the results of an LCA analysis of hydrogen production and application in an isolated territory. The system boundary includes hydrogen production by PEM electrolysis, hydrogen transportation, hydrogen application for electricity by PEM fuel cell stack unit, and mobility by hybrid electric vehicle. Electricity production based on natural gas as substituted energy is also considered in the system expansion in this study. The substituted mobility is the electric vehicle. It is interesting to investigate the results starting from the analysis of the single-phase constituted by the manufacturing of the unit in order to finally verify whether the results of the whole study, referred to 1 kg of hydrogen produced and consumed. The LCIA method of ILCD is chosen to do the analysis. The results show that there is significant carbon reduction by implanting hydrogen by water electrolysis. The environmental benefit is higher for mobility purpose than the electricity production in this study.

The research is conducted based on PEM technology on current development. The major impact of hydrogen application into the energy system is from hydrogen production stage. With the technology research and development, the results would be changed. There are also other water electrolysis technologies such as alkaline electrolysis cell (AEC) and solid oxide electrolysis cell (SOEC). Further research about LCA analysis of electrolysis technologies needs to be conducted.

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