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Life Cycle Analysis of Fuel Cell Technology

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ABSTRACT. Fuel cells are recognized as an emerging power generation system for the future. Fuel cells make use of mostly hydrogen gas as their input fuel, which is extracted from various processes involving emissions and energy consumption. A complete understanding of environmental impacts associated with fuel cell during its entire life cycle, starting from extraction of fuel, through manufacturing, operation and ultimately to the disposal stage is greatly required. The current paper reviews various life cycle analysis studies on fuel cell technology. Such an approach would demand the support of informatics tools to analyze and manage information. The paper aims at assessing various environmental informatics tools available to support the life cycle studies. The paper investigates, in particular, the environmental contributions of various components and materials during the production process of hydrogen fuel. Energy requirements and reduction in air emissions have been studied in comparison with alternative technologies such as IC engines, wind and solar energy.

Keywords: fuel cell, life cycle assessment, informatics tools, environmental impacts, green house gas emissions, energy consumption, hydrogen economy

1. Introduction

Transforming today's non-sustainable energy usage into a globally sustainable energy economy is one of mankind's key challenges for the current century. This transformation process encompasses a multitude of different aspects – technological, social, and economical. The ecological investigation should take into account the full life cycle of that system (Pehnt, 2001). Growing concerns about the global warming effect and exhausting crude oil stocks have led to an interest in hydrogen as a fuel. The efficiency of applying new hydrogen technologies, for example proton exchange membrane fuel cell (PEMFC) vehicles (Larminie and Dicks, 2003), depends on the characteristics of the many steps and chains involved. These include production, distribution and, finally, conversion of the chemical energy of hydrogen into mechanical work in a vehicle. Adequate evaluation of environmental impact and energy consumption throughout the overall hydrogen production and utilization phase, in comparison with that for other fuels like gasoline, is critical for making appropriate strategic decisions about its competitiveness in the future. In order to assess fuel cells' environmental benefits, however, the whole life-cycle has to be considered. In fact, it is explicit that operating life causes very low impact on the environment, but on the other hand fuel cell production, disposal and impacts related to hydrogen production and transport probably may have a significant burden on the environment. By analyzing the whole life-cycle of the system, it may be possible to assess which part of the process presents the most relevant environmental load and one can find out possible solution for the environmental performance improvements.

Of all the fuel cell types, PEMFCs are of particular importance for their use in mobile and small-medium-sized stationary applications. The interest in PEMFC applications is rapidly growing, especially because of the commitment of automobile manufacturers to develop fuel cell driven cars. Therefore, LCA of PEMFC seems appropriate to evaluate the whole system of fuel cells (Pehnt, 2001). For this purpose, the production and utilization of PEMFC was reviewed in this paper. On the whole, the current review provides an overview of life cycle analysis studies on fuel cell technology. In particular, the paper aims at assessing various environmental informatics tools available to support the life cycle studies.

1.1. Fuel Cell Theory

The discovery of the fuel cell is generally attributed to Sir William R. Grove who, in 1839 depicted the first useful fuel cell in his article On the Gas (Félix Gasser, 2005). Fuel Cells are electrochemical energy converters. They can be regarded as black-boxes (Figure 1) converting chemical energy contained in a fuel directly into electrical energy while gene-

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rating heat and water as by-products (Félix Gasser, 2005).

The basic mechanism underlying this conversion is the same as the one for batteries. The primary difference is that the battery contains the reactants (i.e. fuel and oxidant) that generate electricity whereas these reactants need to be supplied externally to the fuel cell. In other words, a battery needs to be thrown away or recharged once those reactants are depleted while the fuel cell can be refueled more easily and quickly by either refilling the tank with fuel (hydrogen) or replacing the fuel reservoir. In this respect they are comparable to internal combustion engines (ICE) which, when provided with fuel and air, generate mechanical power with heat and exhaust gases as byproducts.

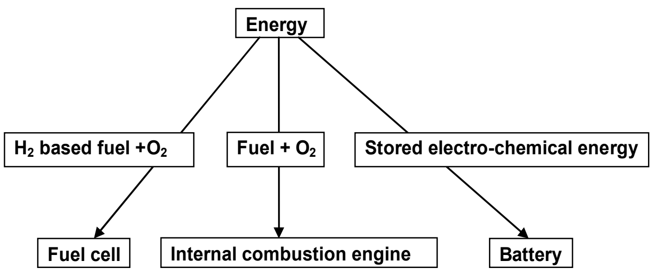

Figure 1. Schematic representation of different energy (battery, fuel cell and internal combustion engine) converters in the form of black-boxes.

1.2. Advantages of Fuel Cell

The main advantage of a fuel cell with respect to a traditional energy converter is its high conversion efficiency. Moreover, the efficiency increases with diminishing load, a very interesting characteristic for the transportation sector where part load operation is the rule and ICEs run at reduced efficiency in low load conditions. The other advantages of fuel cells include (Félix Gasser, 2005):

1. Very low emissions: The actual emission level depends on the fuel. True zero-emission performance is achieved with the H_2/O_2 fuel cell since the only reaction product is water. Additionally, no toxic nitrogen oxides (NOX) are generated. This is the main advantage when used in vehicles, as there is a requirement to reduce vehicle emissions, and even eliminate them within cities. However, it should be noted that, at present, emissions of CO_2 are nearly always involved in the production of hydrogen that is needed as the fuel. Even if natural gas or petrol is used as a fuel through a reforming process, CO_2 emissions will be lower than a comparable ICE due to the fuel cell's higher efficiency.

2. Low noise levels: Since the electrochemical reaction is a conversion process that requires no moving parts, operation of the fuel cell is completely silent. A fuel cell system, with all the necessary accessories for cooling, power conversion and air and fuel supply will emit some noise, mainly due to the air compressor.

3. System scalability: Due to their construction, fuel cell systems are modular power generators (Grove, 1845).

4. Simplicity: The essentials of a fuel cell are simple and few moving parts. This can lead to highly reliable and long-lasting systems.

1.3. Disadvantages of Fuel Cell

The fact that hydrogen is the preferred fuel in fuel cells is one of their principal disadvantages. However, there are those who hold that this is a major advantage. It is envisaged that as fossil fuels run out, hydrogen could become the major world fuel and energy vector. It might be generated, for example, by massive arrays of solar cells electrolyzing water (Larmine and Dick, 2003).

1.4. Types of Fuel Cells

Fuel cells are typically classified by either their operating temperature or the type of electrolyte. A brief description of each of the types is as follows (Félix Gasser, 2005):

Proton Exchange Membrane Fuel Cells (PEMFC) or Polymer Electrolyte Fuel Cells (PEFC) are based on a solid polymer electrolyte. Fast startup times, low temperature operation and high power densities make them an easy to use technology especially for portable or transport applications. CO poisons the catalyst and so the hydrogen fuel has to be very pure. Because the polymer membrane has to be kept well humidified for good proton conduction, water management is one of the critical aspects of successfully running a PEMFC.

Direct Methanol Fuel Cells (DMFC) are similar in construction to PEM fuel cells. Since liquid methanol can be used as a fuel, no external fuel processing is required and high energy storage densities can be achieved. Unfortunately, the polymer membrane is not impermeable to liquid methanol and the resulting fuel crossover reduces overall system efficiency.

Alkaline Fuel Cells (AFC) are based on a liquid, concentrated aqueous KOH electrolyte. AFCs can operate with non-precious metal catalysts (typically nickel) and therefore have a cost advantage over other types of fuel cells. The use of a liquid electrolyte requires an additional electrolyte re-circulation system. Unfortunately, CO_2 is a poison for the liquid electrolyte and needs to be scrubbed from process air. Typically, the use of AFCs has been limited to niche applications such as military and space applications.

Phosphoric Acid Fuel Cells (PAFC) are based on a liquid acid electrolyte. Due to their higher operating temperature, they are less sensitive to CO impurities in the fuel and water management is less of an issue. Additionally, they exhibit excellent long term stability. Their relatively long start-up times and low power densities limit their application to stationary power or co-generation plants.

Molten Carbonate Fuel Cells (MCFC) are based on a liquid molten carbonate electrolyte and generally exhibit very high conversion efficiencies. A high operating temperature allows direct use of non noble catalysts along with direct internal processing of fuels such as natural gas. Relatively long start-up times and low power densities again limit their application to stationary power or CO generation plants. Corrosion can be problem.

Solid Oxide Fuel Cells (SOFC) are based on a solid oxide electrolyte conducting oxygen O_2^- ions. As with the MCFC, the high operating temperature translates into non-noble catalysts, direct internal hydrocarbon fuel processing and high quality waste heat that can be utilized in combined-cycle power plants. Additionally, high power densities along with high efficiencies can be attained. Slow start-up times dictate their primary use as stationary power or co-generation plants.

1.5. PEMFC Electrochemical Reactions

The schematic of a PEMFC is given in Figure 2. At the anode catalyst layer, oxidation reactions in which hydrogen is oxidized to protons on the surface of the platinum catalyst take place by the following mechanism:

$$H_2 + 2Pt \rightarrow 2(Pt{-}H_{ads}) \quad (1a)$$

At the cathode catalyst layer, a reduction reaction takes place in which oxygen is reduced in the presence of protons and electrons on the surface of the platinum catalyst. The complex reaction mechanism is a multi-step, multi-species reaction, which is very difficult to understand and characterize in electro-chemical terms. Parthasarathy et al. (1992) proposed the following mechanism:

$$M + O_2 \rightarrow M \bullet\bullet O_2 \quad \text{(fast, adsorption step)} \quad (1b)$$

$$M \bullet\bullet O_2 + H^+ + e- \rightarrow M \bullet\bullet O_2H \quad \text{(rate-determining step)} \quad (1c)$$

$$M \bullet\bullet O_2H + 3H^+ + 3e- \rightarrow 2H_2O \quad \text{(rapid step, unknown)} \quad (1d)$$

where, M is the platinum catalyst metal. The overall cathode reaction is:

$$O_2 + 4H^+ + 4e- \rightarrow 2H_2O \quad (2)$$

The overall reaction is:

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O \quad (3)$$

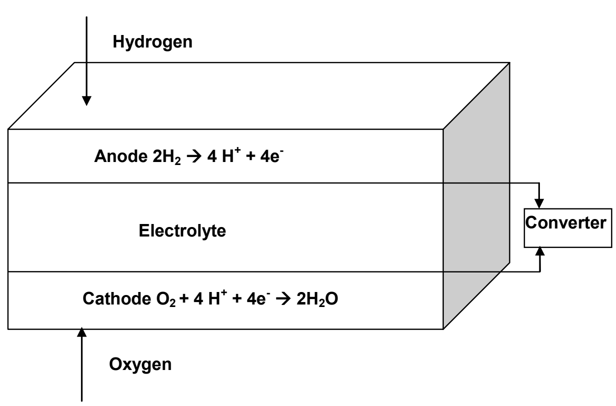

Figure 2. Schematic of a fuel cell.

2. Life Cycle Assessment of Energy Systems

Life cycle assessment (LCA) is a tool for the assessment of potential environmental impacts of products and services through the entire life cycle ("cradle-to-grave approach"), from the exploration and exploitation of materials and fuels to the production of the investigated objects and the disposal/recycling of the objects. The LCA basically consists of four steps:

The Goal and Scope Definition in which the investigated product, the data sources and system boundaries are described and the functional unit -- i.e. the reference of all related input and output is defined.

The Inventory Analysis -- the data collection and calculation procedures to quantify relevant inputs and outputs" (ISO 14040, 1997).

The potential impacts of the inputs and outputs of the Inventory Analysis are then determined by the Impact Assessment which categorizes and aggregates the environmental interventions. For that purpose, impact categories, such as global warming, are defined and characterization factors calculated to determine the contributions of different substances to that particular impact category.

The Interpretation analysis, the findings from the inventory analysis and the impact assessment are combined to give recommendations or draw conclusions.

The life cycle of automobile technology includes all the major steps required to make up the life cycle of that system. Two major cycles make up the total life cycle of the automobile; the "vehicle cycle" and the "fuel cycle". The "vehicle cycle" follows the sequences below:

Vehicle material production: Energy use and greenhouse gas emissions from vehicle materials production are counted in this stage. In ICE vehicles and fuel cell vehicles, the steel used to produce the vehicle is counted for. In addition to the steel, the materials needed to produce the fuel cell such as polymer membrane, platinum as catalyst, graphite, etc., are also considered in this part of the analysis.

Vehicle assembly: The energy required and greenhouse gas emissions for transport of vehicles during assembly are quantified here. Because of the complex supply chain in the automobile industry and the associated difficulty in estimating vehicle assembly energy requirements, assembly energy is typically estimated as a linear function of vehicle mass.

Vehicle distribution: The energy needed and greenhouse gas emissions during the transport of a vehicle from the assembly line to the dealership are counted in this stage.

Vehicle maintenance: It includes energy consumption and greenhouse gas emissions during maintenance and repair over the lifetime which is assumed to be 300,000 km.

Vehicle disposal (recycling): After a vehicle's life, the automobile is shredded. The disposal energy is the sum of energy needed to move the bulk from the dismantler to a shredder and the shredding energy.

While, the "fuel cycle" follows the sequences described below:

Feedstock production: Energy consumption and greenhouse gas emissions during the production of the raw materials in order to obtain the fuel needed (either hydrogen or gasoline).

Feedstock transport: The raw material for gasoline and hydrogen has to be transported to the refineries and reforming plants. Energy consumption and greenhouse gas emissions during the transport of raw materials are counted in this stage.

Fuel production: Energy consumption and greenhouse gas emissions during refining of the raw materials.

Fuel distribution: Distribution of the gasoline and hydrogen. Detailed discussion is to follow in later sections.

Fuel use: It is during the vehicle use. It includes energy consumption (fuel) and greenhouse gas emissions during the consumption (burning) of fuel.

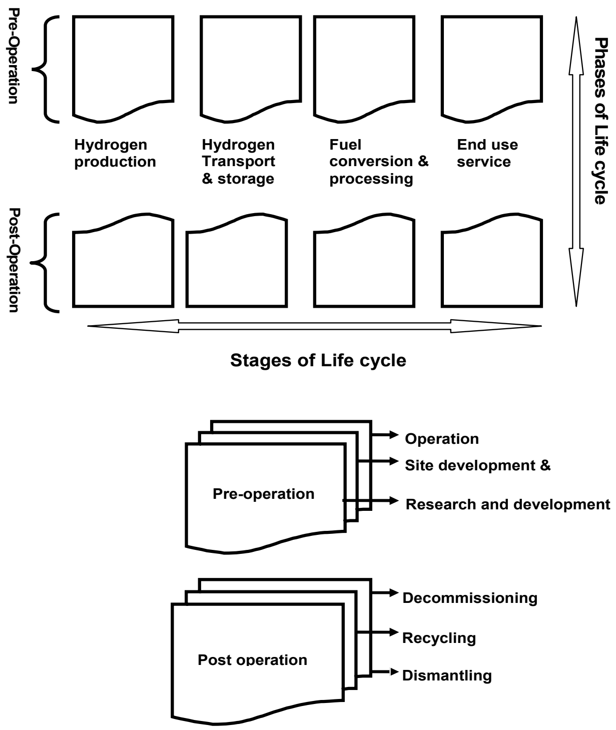

Figure 3. Boundaries concept for hydrogen production life cycle inventory.

A complete Life Cycle Assessment (LCA) in the fuel/ transportation industry should be performed following these basic steps: For each stage in the life cycle (vehicle operation, fuel distribution, fuel production, feedstock transportation and storage, and feedstock extraction and processing) the idea is to quantify the water, soil and air emissions for different phases of the project. These phases are pre-operation (R&D, Site Development and Construction), operation and post-operation (Recycling, Decommissioning and Dismantling). Figure 3 provides a graphical representation of these boundaries. The impact on the environment should be assessed and somehow compared after the inventory analysis. Photo-oxidant formation, acidification, eutrophication, global warming, stratospheric ozone depletion, ecotoxicological impacts, bio-diversity reduction, and habitat alterations are examples of environmental impacts. In the current review the vehicle material production and assembly in vehicle cycle is alone focused in detail.

The environmental impacts of conventional power plants or combustion engines are usually dominated by the fuel production and combustion. The construction of the plant and the infrastructure required are usually an order of magnitude less environmentally relevant than the energy conversion because of the high throughput and the long lifetime of the system. It is useful to investigate future energy systems such as PEMFC at an early stage of market development. This is, of course, coupled with the methodological problem of anticipating technological (e.g. future energy consumption for certain production steps) and societal (e.g. the choice of energy carriers for the electricity mix) developments.

3. Environmental Informatics for LCA of Fuel Cells

LCA is difficult to tackle and challenging than traditional impact assessment methods, because it has to deal with such environmental issues as impacts to and relations with the global warming, the waste problem, and the problem of hazardous substances. In addition, obviously we need a win-win situation between environment and corporate profitability. Therefore, one should examine various aspects of the environmental issues as well as performance of the product, deal with a huge amount of data, and make critical decisions based on uncertain data and unreliable future prospect to achieve a balanced design solution. This is the domain where environmental informatics may play a crucial role, since engineering informatics aims at supporting knowledge-intensive engineering tasks from initial conception to product disposal. Numerous studies that describe important directions of LCA supported by environmental informatics are available in literature. Some of the earliest Life Cycle Inventory models for alternative fuel/propulsion system options were developed by Mark Delucchi at University of California at Davis during the period 1987 ~ 1993. Delucchi has continued to update his work (Delucchi, 1996). Delucchi's spreadsheet model predicts emissions of greenhouse gases and criteria pollutants from a large number of alternative fuel/vehicle options. The model is comprehensive in scope including fuel cycles, vehicle operation, manufacture, service, etc., in predicting GHG and criteria pollutants. Concerning the life cycle of the fuel alone, Contadini et al. published three papers on this topic. The first paper (Contadini et al., 2002) deals with the methodology, while the other two (Contadini et al., 2000, 2003) focus mainly on uncertainties in LCA. A model called Fuel Upstream Energy and Emission Model (FUEEM) is developed to analyze life cycle impacts of future fuel cell vehicles and fuels. Michael Wang of Argonne National Laboratory has produced another life cycle model (Wang, 2002) named Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET). Hackney and de Neufville (2001) developed and presented a LC spreadsheet model for comparing criteria pollutant, GHG emissions, and energy use and cost of alternative fuel/vehicle options.

The analysis carried out using GREET relies on many inputs to the software. The GREET model calculates the energy use and emission rates of various combinations of vehicle technologies and fuels on a per-mile basis. The GREET model relies on the efficiency of each step in obtaining and refining the fuel in order to calculate the energy consumption. The carbon dioxide emissions associated with the obtaining and refining of the fuel, are calculated based on the methods used. GREET follows a built in table with emission factors for each step. In addition, GREET relies on the lower heating values of the fuel in its calculation. Built in tables with the fuel properties are found in GREET. These tables can be modified. The energy use and emissions of electricity generation are need ed in GREET for two purposes: electricity usage of upstream fuel production activities and electricity use in electric vehicles (EVs) and grid-connected hybrid electric vehicle (HEVs). The GREET model calculates emissions associated with electricity generation from residual oil, NG, coal, and uranium.

Research on the capabilities of hydrogen fuel cell technology in relation to conventional and other alternative transport solutions has been undertaken in the LCA context using a variety of methods. The Comparison of Transport Fuels conducted by Beer et al. (2001) referenced the GREET model and examined a very broad range of transport fuel alternatives. The only hydrogen pathway examined was production from steam reforming of natural gas, which is just one of the many possible pathways. Colella et al. (2005) evaluated the change in emissions and energy use from an instantaneous change to a hydrogen fuel cell vehicle fleet. Granovskii et al. (2006) conducted an LCA of hydrogen fuel cell and gasoline vehicles using a first-principal methodology, which was based on theoretical calculations of the required economic and energetic data. Zamel and Li (2006) performed an LCA of fuel cell and internal combustion engine vehicles in Canada, with fuel-cycle calculations carried out using GREET (Wang, 1999) and vehicle cycle data derived from published literature. Ally and Pryor (2007) established a benchmark LCA model, which can be applied to a wide range of scenarios and advanced modeling applications. Ahluwalia et al. (2004) studied the fuel economy of light-duty vehicles powered by fuel cells in compareson with conventional gasoline internal combustion vehicles. The investigation was based on the modelling of a theoretical fuel cell engine, with energy efficiency estimations taken from the literature of possible component suppliers. Schafer et al. (2006) used a Matlab Simulink program to back calculate the fuel efficiency for theoretical light-duty vehicles using petrol, diesel, and hydrogen fuel-cell drive train technology representative of the year 2020.

The North American (General Motors, 2001) and European (General Motors, 2002) studies undertaken by GM used a theoretical simulation to estimate the fuel consumption of a wide range of alternative propulsion systems in comparison with the benchmark gasoline internal combustion engine. The modeling software was proprietary and used a database of component performance maps to calculate the power and energy flow through the vehicle, accounting for all inefficiencies and losses. It was claimed that the models had been validated against several conventional and hybrid powertrains, as well as electric vehicle concept cars, with a fuel economy error within 1% of the test results. A study by Rousseau and Sharer analyzes and compares internal combustion engine vehicles and fuel cell vehicles from by a well-to-wheel perspective using GCtool, PSAT, and GREET (computer software used to analyze the life cycle of vehicles). Baratto and Diwekar (2005) carried out studies on life cycle assessment of fuel cell based auxillary power units. Different models were used for the different stages of the life cycle in this study. The fuel life cycle was based on the GREET model by Argonne National Laboratory. The system operation is evaluated by the Aspen model. Life cycle of system production was carried out with the help of the LCA software tool SimaProTM 5.1. For the calculation of energy-related emissions, IDEMAT 2001 database was used.

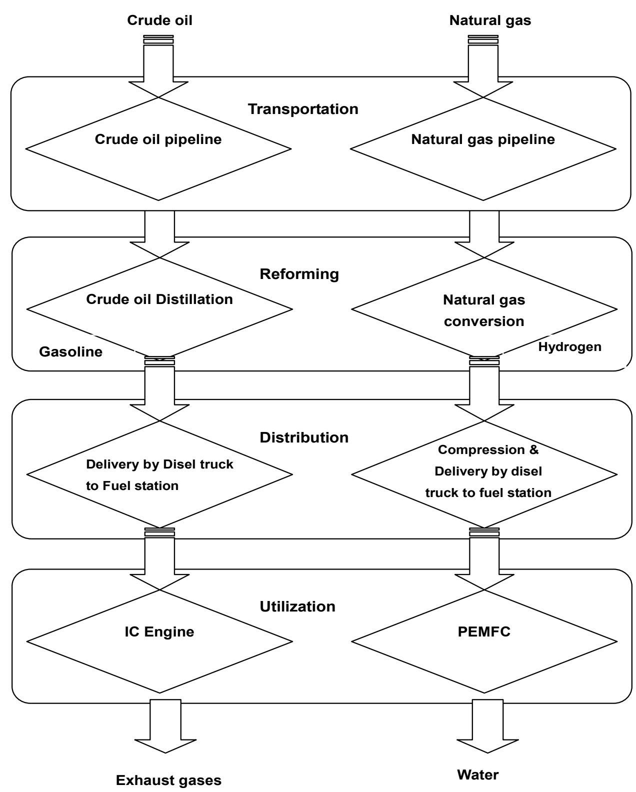

Figure 4. Principal steps in utilizing fossil fuels in two vehicle types.

4. Inventory and Impact Analysis of Life Cycle Stages

4.1. Vehicle Material Production and Vehicle Assembly – PEMFC Production Process

The production process consists of separate steps: the production of the gas diffusion electrode (GDE) including the application of the catalyst; the production of the membrane; joining of GDE and membrane; the fabrication of the bipolar plate; the assembly of the stack; and subsequent testing.

For each of these steps, the required inputs, including materials, ancillary substances and electricity, as well as direct emissions during production were determined by Pehnt (2001). The context of this LCA is a production plant in Germany with consistent German production data. The cumulated environmental impacts of the study are given in Table 1.

4.2. Feedstock Production

Hydrogen and gasoline represent the final products of several modern technologies. The conventional production methods are reforming of natural gas (hydrogen) and crude oil distillation (gasoline). The principal technological steps in crude oil and natural gas utilization in vehicle types are presented in Figure 4. Use of environmentally benign renewable technologies to generate hydrogen is considered attractive. The principal technological steps in the utilization of solar and wind energy to produce hydrogen is presented in Figure 5.

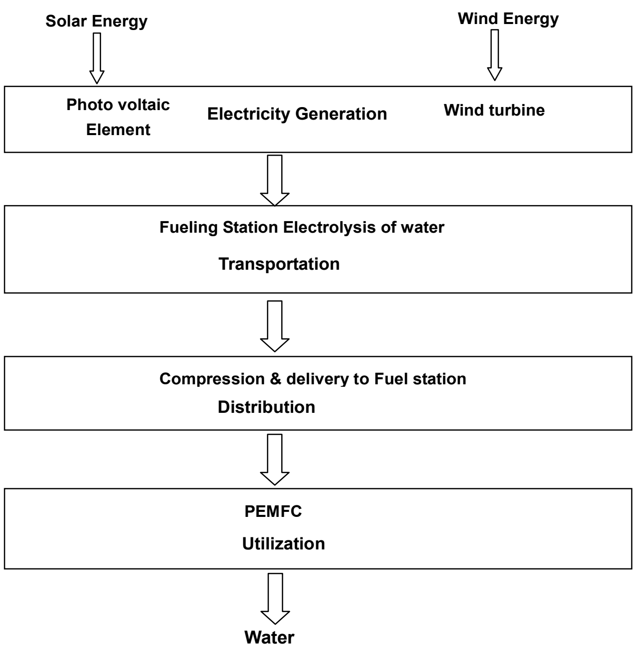

Figure 5. Principal technological steps in utilizing solar and wind energies.

4.3. Feedstock Distribution

Natural gas and crude oil is transported by pipelines. Heat of combustion converted in gas turbine into mechanical energy can be used to compress gas to transport along the pipeline. The consumption of the natural gas energy (*E*cmp) has been evaluated by the formula for isothermal compression (Granovskii et al., 2006):

$$\Delta E_{cmp} = nRT_o / \acute{\eta}_{cmp} \acute{\eta}_{gt} [\ln p_{max} + k \ln (p_{max} / p_{min})] \quad (4)$$

Where n is the molar flow of natural gas, R = 8.314 J / (mol·K) is the universal gas constant, and k is the number of intermediate compressions needed, $\acute{\eta}$ is energy efficiency. This mechanical work is consumed for the initial compression of natural gas from 1 atm to *p*max and to overcome friction resistance. Typical emission from natural gas combustion is given in Table 2.

Table 1. Inventory and Impact Assessment Results of the LCA of Fuel Cell Stacks

	Mobile stack		Stationary stack	
PGM recycling	No	75%	No	90%
Non-renewable primary energy (MJ/kWel)	940	744	5100	1446
Global emissions (kg = kW el)				
CO_2	57	40	275	78
CH_4	0.1	0.1	0.5	0.2
N_2O	0.005	0.005	0.019	0.014
Local regional emissions (kg = kW el)				
SO_2	0.17	0.10	0.73	0.17
CO	0.02	0.02	0.014	0.01
NOx	0.17	0.07	0.74	0.14
NMHC	0.02	0.02	0.09	0.04
Dust and particles	0.03	0.01	0.14	0.03
NH_3	1.4E-03	1.4E-03	2.5E-03	2.0E-03
Benzene	2.7E-05	2.7E-05	4.3E-05	3.6E-05
Impact categories(kg = kW el)				
Global warming potential (CO_2 - eq.)	61	43	293	86
Acidification (SO_2-equivalent)	0.29	0.15	1.25	0.27

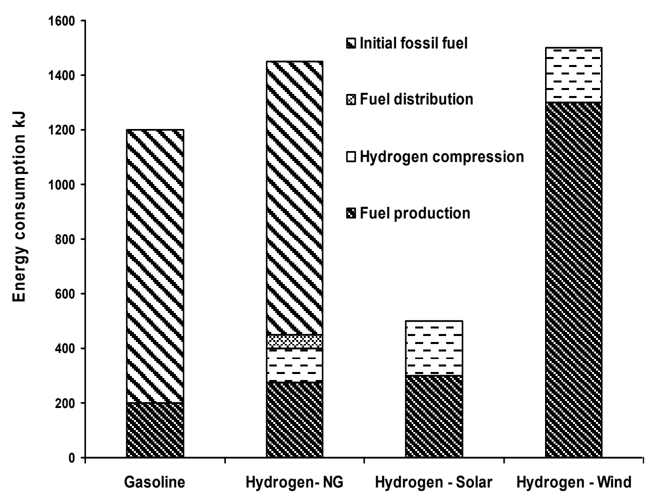

Figure 6. Fossil fuel energy consumption to produce 1 MJ of gasoline and hydrogen applying different technologies.

4.4. Fuel Production

Crude oil and natural gas are the main energy commodities used in these processes. The production of gasoline from crude oil is seen to be more efficient than the production of hydrogen from natural gas (Granovskii et al., 2006). Figure 6 presents the fossil fuel energy consumption to produce 1MJ of gasoline and 1MJ of hydrogen applying different technologies. The use of renewable technologies for hydrogen production is characterized by the absence of the direct fossil fuel use. Hydrogen production via wind power and electrolysis has the lowest indirect fossil fuel energy use. The photovoltaic system has the highest fossil fuel energy embodied in materials and equipment.

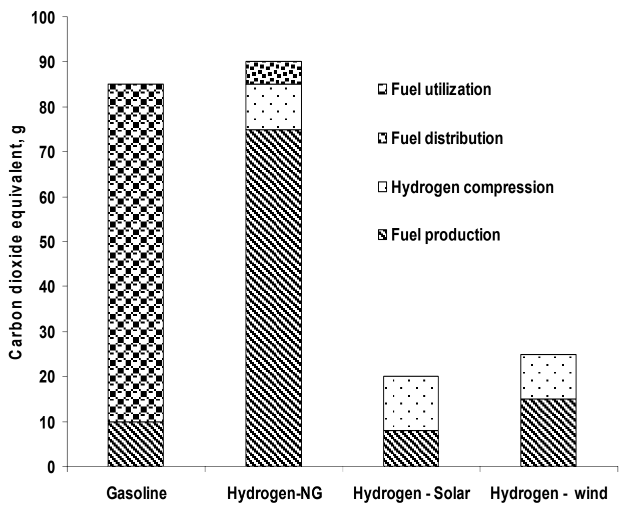

Figure 7. Greenhouse gas emissions accompanying the production and utilization of 1 MJ of gasoline and hydrogen in ICE and PEMFC vehicles, respectively.

Figure 7 illustrates the greenhouse gas emissions for the life cycles of fuels, from production to utilization in vehicles. Since the use of 1 MJ of gasoline is accompanied by the release of 71.7 g of CO_2, gasoline and hydrogen from natural gas are seen to be characterized by almost the same greenhouse gas emissions (Granovskii et al., 2006). Hydrogen production via wind and solar energy reduces greenhouse gas emissions considerably. Accounting for the higher efficiency of a PEMFC engine, greenhouse gas emissions can be reduced by 40% where hydrogen is obtained from natural gas to 86% where hydrogen is obtained from renewable wind energy.

Life cycle assessment has been used to compare hydrogen-fuelled PEMFC vehicles to traditional internal combustion engine vehicles operating on gasoline. Energy efficiencies and greenhouse gas emissions have been evaluated during all process steps. The use of wind power to produce hydrogen via electrolysis, and its application in a PEMFC vehicle, is characterized by the lowest greenhouse gas emissions and fossil fuel energy consumption. However, the economic attractiveness of wind technology depends significantly on the ratio in costs for hydrogen and natural gas. At a cost ratio of 2, capital investments are about five times lower to produce hydrogen via natural gas than to produce hydrogen via wind energy. Photovoltaic presently very expensive and requires best technology to increase the conversion rate. Electrolyzed water must be replaced by that from fuel cell.

4.5. Fuel Distribution

The distribution of compressed hydrogen after its production via natural gas reforming is similar to that for liquid gasoline, but compressed hydrogen is characterized by a lower volumetric energy capacity and higher material requirements for a hydrogen storage tank. Hydrogen distribution is replaced by electricity distribution in cases using wind and solar energy and such distribution has been accounted for in hydrogen production. Compressed hydrogen is distributed to fuelling stations by diesel fuelled trucks. Such distribution is accounted for in hydrogen production. Energy combustion and GHG emissions associated with combustion of diesel fuel used in distribution of hydrogen have also been accounted in studies (Granovskii et al., 2006).

Table 2. Typical Emissions from Natural Gas Conversion

Pollutant	Emissions g/g (NG)
CO_2	2.69
CO	1.88×10^{-3}
CH_4	5.15×10^{-5}
N_2O	4.93×10^{-5}
NO_x	2.24×10^{-5}
SO_2	1.34×10^{-5}
Volatile organic compounds	12.3×10^{-5}
Particulates	17.05×10^{-5}

Table 3. Results of LCA of Fuel Cell Car Driven 1 km with Hydrogen and Methanol as Fuel

Fuel cell car (750 kg Base weight)	Hydrogen from natural gas	Methanol from natural gas
Non renewable primary energy (MJ/km)	1.80	2.32
Global emission (mg/km)		
CO_2	97585	119430
CH_4	239	165
N_2O	0.29	0.42
Local regional emission (mg/km)		
SO_2	34	72
CO	32	33
Nox	63	94
NMHC	73	79
Dust and particulates	4	8
NH_3	9.0E-03	3.5E-02
Benzene	2.6E-02	8.2E-02
Benzo(a)pyren	7.6E-05	7.7E-05
Impact categories		
Global warming potential (CO_2 –eq.)	102694	122930
Acidification (SO_2-eq.)	78	138

4.6. Utilization Phase

It is possible to compare the results of the stack production LCA to the environmental impacts during the utilization phase, i.e. the use of the fuel cell car. For this purpose, it was assumed by Pehnt (2000) that the fuel cell car runs with hydrogen or methanol as fuel, the latter with an on-board reformer. In this publication, a number of different production paths were evaluated. In brief, steam reforming of natural gas for hydrogen production and combined reforming of natural gas for methanol production are assumed. The plants are typical for one to be built in the next decade.

The life-cycle emissions of the use (assuming a 160,000 km life) of fuel cell passenger cars (including the production and distribution of the fuel and the emissions of the car) were calculated in the study (Table 3). For comparison, the life-cycle emissions for a future per km gasoline internal combustion engine vehicle with optimized catalyst technology are given in Table 4. This car has the same base weight and a gasoline consumption of 1.62 MJ/km using the same vehicle parameters as for the fuel cell car. The production of the fuel cell stack leads to global warming emissions of 8% to 10% of the emissions emitted due to the utilization of the car (driving 160,000 km) for hydrogen and methanol from natural gas, respectively, and 40% of the acidifying emissions.

Table 4. Life Cycle Environmental Impacts Due to Fuel Cell Stack Production Compared to Impacts Due to the Use Phase of Fuel Cell Cars and Combustion Engines

Impact category	Hydrogen	Methanol	Internal combustion engine
Primary energy (MJ)	270,000	348,000	289,350
Global warming equivalent (CO_2 –eq.) kg	18,349	18,440	20,275
Acidification (SO_2 –eq.) kg	12	21	30

5. Environmental Impact of a Hydrogen Economy on the Stratosphere

The widespread use of hydrogen fuel cells could have unknown environmental impacts due to unintended emissions of hydrogen from stacks, including an increase in the abundance of water vapor in the stratosphere (plausibly by as much as ~1 part per million by volume). H_2 is an important trace constituent [~0.5 part per million by volume (ppmv)] of the atmosphere and participates in atmospheric chemical cycles of H_2O and various pollutants and greenhouse gases. Its modem budget is influenced by anthropogenic emissions (such as car exhaust) but is dominated by photochemical reactions in the atmosphere and uptake in the soil. It is difficult to foresee the magnitude of H_2 emissions associated with a hydrogen fuel cell economy. H_2 added to the troposphere freely moves up and mixes with stratospheric air, and the oxidation of H_2 is a source of stratospheric H_2O. Therefore, increasing the source of H_2 to the atmosphere should moisten the stratosphere (Tromp et al., 2003). This would result in cooling of the lower stratosphere and the disturbance of ozone chemistry, which depends on heterogeneous reactions involving hydrochloric acid and chlorine nitrate on ices of H_2O.

Tromp et al. (2003) reports the results of models of atmospheric chemistry and transport that estimate the effects that an increase in H_2 emissions would have on stratospheric temperatures and on concentrations of stratospheric H_2O and ozone. They examine the atmospheric chemistry of H_2 using the Caltech/JPL 2-D model. This model solves the continuity equation for all important long-lived species and includes all the chemistry recommended by NASA for stratospheric modeling. To assess the potential impact of an increase of H_2 in the atmosphere, model was run for two cases: (a) concentrations of H_2 and CH_4 are assumed to equal their approximate current global annual means at Earth's surface; and (b), the same as (a), except that the concentration of H_2 at Earth's surface is raised to 2.3 ppmv (about four times the current global annual mean). In the model described by Tromp et al. (2003), predictions suggest that anthropogenic emissions of H_2 could substantially delay the recovery of the ozone layer that is expected to result from the regulation of chlorofluorocarbons. However, lower levels of chlorofluorocarbons expected several decades in the future should lead to less destruction of stratospheric ozone for a given amount of stratospheric moistening and cooling. Thus, the real consequences of a hydrogen economy will depend, in part, on whether it develops within about 20 years, when chlorofluorocarbon levels remain high; or more than 60 years in the future, when chlorofluorocarbon levels have substantially decreased. The results suggested that a fourfold rise in surface H_2 concentrations, which might occur because of large rises in anthropogenic emissions, will lead to substantial moistening and cooling of the lower stratosphere and substantial decreases in stratospheric O_3. Figure 8 shows the magnitude of these effects for smaller and larger changes in H_2O concentration in the lower stratosphere. Cases (a) and (b) correspond to one and four times the current H_2 concentration, respectively. This would cause stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone, an increase in noctilucent clouds, and changes in tropospheric chemistry and atmosphere-biosphere interactions.

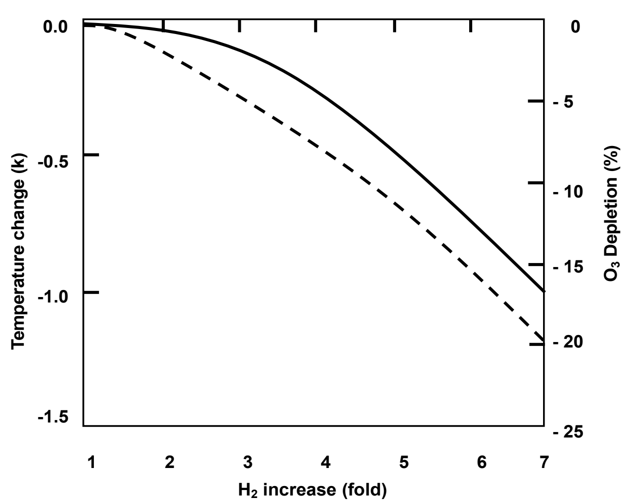

Figure 8. The temperature changes at 74 °N in the lower stratosphere (solid line) and the resulting maximum ozone depletion in the northern polar vortex (dashed line) caused by the increase of H_2O.

6. Conclusions

LCA of fuel cells is a challenging approach that examines various environmental issues and deals with huge amount of uncertain data and unreliable future views. Environmental informatics support this knowledge intensive engineering tasks. There are numerous life cycle inventory models available for this purpose, which include GREET, Simapro, etc. The current review includes both vehicle cycle and fuel cycle stages of fuel cell technology to understand the environmental burdens caused by them. The following observations have been made:

The review shows that production of fuel cell stacks leads to environmental impacts when compared to the utilization of the stacks in a vehicle. These impacts are mainly caused by the materials used for the catalyst and materials and energy for the flow field plates. Recycling of these materials can be a significant and economic requirement for future stack generations.

A review on comparison of life cycle assessment on hydrogen-fuelled PEMFC vehicles to traditional internal combustion engine vehicles operating on gasoline has also been carried out. Energy efficiencies and greenhouse gas emissions have been analyzed from different hydrogen production methods: natural gas reformation, wind and solar electricity generation, hydrogen production through water electrolysis. The economic attractiveness of renewable energy technology depends significantly on the ratio in costs for hydrogen and natural gas. Since all the other beneficial environmental aspects associated with fuel cells, are confirmed, further improvement must be made for the hydrogen generation practice. Low emissions hydrogen generation processes such as biomass or waste gasification can be considered.

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