Life Cycle Assessment of a metallic type PEM fuel cell

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ABSTRACT

Hydrogen technology is rapidly evolving and many stationary and transportation applications are under the attention of researchers and industries all over the world.

The natural and trendy exploiter of hydrogen is the fuel cell, but how much is the PEM (Polymer Electrolyte Membrane) fuel cell cost in terms of impact to the environment and energy saving?

In the framework of two European Commission financed projects (FUERO and HeliNet) about the effectiveness of a massive introduction of hydrogen fueled vehicles and stratospheric platforms for telecommunication purposes in the present world scenario, Energy Department of the Politecnico di Torino has performed a life cycle study about a PEM fuel cell.

The considered PEM fuel cell was constituted by metallic end and flow field (bipolar) plates. The analysis was performed with the help of the CES (Cambridge Engineering Selector) software and all data where implemented in the Boustead Model to calculate the environmental load for the production of a 1kW fuel cell with a life-cycle perspective. The result of the analysis underlines the importance of the site of production and processing of the metallic parts: if properly chosen, it means a considerable cut of the energy (pollution) cost.

The paper presents the assumptions, the analysis and the results of the study, with some final considerations.

OBJECTIVE

The purpose of this study is to quantify energy and resources consumption and emission of pollutant to the environment resulting from a life cycle analysis of a fuel cell system production for automotive purposes according to the system boundary definition. In detail, the work aims to define the environmental burden related to the production of the PEM – *Proton Exchange Membrane* – cells using the Life Cycle Assessment (LCA) methodology.

INVENTORY ANALYSIS

System boundary and inventory stage

The functional unit of the study is defined as the production of 1 kW of electrical power using a stack constituted by four PEM cells.

The boundaries of the considered industrial system include all the phases from raw materials extraction to the production of a PEM cell. In detail, the system comprehends:

- raw materials extraction and treatments for the materials used in the production of the cell;
- production and distribution of the energy used in the processes;
- transports involved by the system from raw materials extraction to the final production;
- materials production.

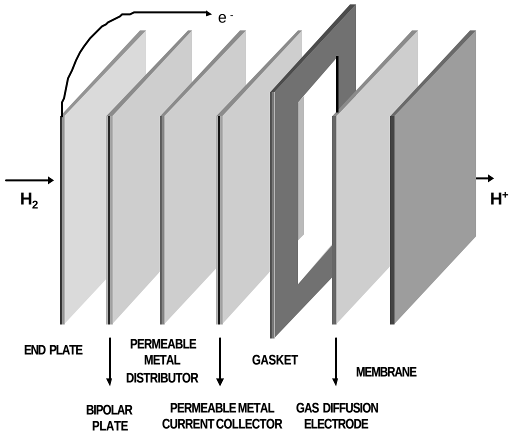

Figure 1. Single cell composition

The considered system does not include the assembling phase and the realization of the stack.

A PEM cell is composed by a series of metallic plates, two porous carbon electrodes (anode and cathode) and an electrolyte that, in this specific case, is a proton exchange membrane pressed between the electrodes that allows the H^+ ions passing from the anode to the cathode but avoid the electrons crossing.

Roughly, in a fuel cell the inputs are a fuel and an oxidant while the outputs are electricity, water and heat. According to the defined functional unit, this work focuses the attention on a system composed by 4 PEM cells in order to have an available power output of about 1 kW.

A schematic view of the stack is shown in Figure 1. while main characteristics of the stack are reported in Table 1.

Methods and data sources

For some of the cited materials, primary LCA data are not available due to lack of information and their confidentiality. To conclude the analysis it was therefore necessary to use secondary data or, in few cases, to adopt alternative and opportune materials for which LCA data were available.

These alternative materials have been selected on the basis of the necessary characteristics and performances. A particular software, the *Cambridge Engineering Selector* (CES), was adopted to assist this phase.

Gasket - Hytrel® is the material indicated for the gasket for its specific properties by the standard configuration of the considered cell. LCA data on Hytrel® are not available. Six main physical characteristics were chosen taking into account the function of the gasket in the fuel cell. An alternative material with similar values for the same properties was defined. In particular, silicone exactly matches Hytrel® elongation, resistivity, tensile strength and water absorption while it presents a higher density and, slightly, a lower tensile modulus. Furthermore, silicone is often used for gaskets in PEM cells. For the LCA study, the silicone is then used as substitute material of Hytrel®.

Membrane - In the standard configuration of the cell, the membrane is made of Nafion® that is not available on the adopted LCA database. According to the results obtained from the CES simulation, no polymers available on LCA databases are good to match all Nafion® characteristics, that is here considered as PTFE. Two are the alternative materials that arose from the analysis and can be adopted for this situation: acrylonitrile (that is commonly used for membranes) and Nylon 66, for which LCA data are complete.

Gas diffusion electrode - In the considered cell configuration, this component is realised by brushing an opportune hydro-alcoholic solution (water, alcohol, polymer, carbon and platinum) directly onto the membrane. Concerning the polymer, Nafion® is used in the solution thus the same considerations explained for the membrane are applicable also in this case, for which acrylonitrile was adopted.

Table 1. Materials of the cell components

Component	Material	Origin	Main shaping treatments	Material form
End plate	Stainless steel	Secondary	Hot rolling – cutting	Shaped sheet
Bipolar Plate	Aluminium alloy	Secondary	Hot rolling – scalping	Shaped sheet
Distributor	Stainless steel	Secondary	Hot rolling – cutting	Shaped sheet
Current Collector	Stainless steel	Secondary	Hot rolling – cutting	Shaped sheet
Gasket	Silicone	Virgin	General moulding	Granu-lated + shaping
Gas diffusion electrode	Water content	-	-	Liquid
	Methanol	Synthetic	-	Liquid
	Acrylo-nitrile	Virgin	None	Granulate

	Carbon black	Virgin	-	Granulate
	Platinum	Cu by-product	-	Solid
Membrane	Acrylo-nitrile	Virgin	General moulding	Granu-lated or powder + shaping
	Nylon 66			

Platinum catalyst - The proton exchange membrane cell needs a platinum catalyst, that is prepared depositing metal particles of about 10 atoms diameter (the smallest dimension that it's possible to obtain with current technology) on a surface of little carbon particles. The platinum for the gas diffusion electrode has to be brushed in a quantity of 2 g per m^2. About platinum extraction, LCA data refer to primary copper production system in which platinum is a by-product.

INVENTORY DATA

According to previously described analysis, the final configuration of the cell is described in Table 1.

Before describing each component by material, it is important to underline the importance of the technology used to produce a material and the country where the production sequence takes place.

In the case of metals, for instance, it is important to know if the process refers to a primary or secondary material. In this study, it is assumed that all metals come from a secondary metallurgy. In detail, the importance of a specific technology and energy mix have been estimated only for the most important materials that are used for the cell production.

About energy mix, four different scenarios were considered:

- France: most of the electricity is produced from nuclear plants;
- Italy: electricity production is mainly from thermoelectric power plants;
- Sweden: electricity production is balanced among nuclear, hydro and, slightly, thermal;
- Europe: consists in a European average energy mix updated on 1998 situation.

With regards to metals production, a proper energy mix is set for each operation involved from the material production to the final machining. About ancillary materials, taking into account the increased uncertainty on their provenience and the scarce importance in terms of quantity and energy consumption, no specific assumption for the energy mix is made and the UK energy mix is used as default.

Steel - For this work, steel is considered to be made with the electric arc furnace technology in which the main raw material is constituted by steel scraps and the main energy carrier is the electricity. The product is a steel wire rod that is then shaped in order to provide the most opportune component for the cell.

Aluminum - It is supposed that the components produced with cast aluminum are completely made from secondary metal. The saline scoria treatment for the recovery of sodium chloride and aluminum is included in the calculations, too. All the energy necessary both for production and shaping activities of aluminum ingots is considered. Data on aluminum production come from two Italian plants, while data for shaping are from the Boustead database.

Polymers - Concerning polymers production (apart from silicone production), the environmental information come from the Boustead Model Database that has been defined in conformity with the *Association of Plastics Manufacturers in Europe* (APME).

Other materials - Other main materials such as carbon, platinum and water, according to their low importance in terms of quantity and energy consumption, have not been characterised with a specific energy mix.

Life cycle inventory results

The results were grouped in two principal categories: **Energy Results**, which correspond to the energy associated to the functional unit; **Environmental Results**, which deal with the resources depletion, air emissions, water emissions, solid waste production, always related to the functional unit.

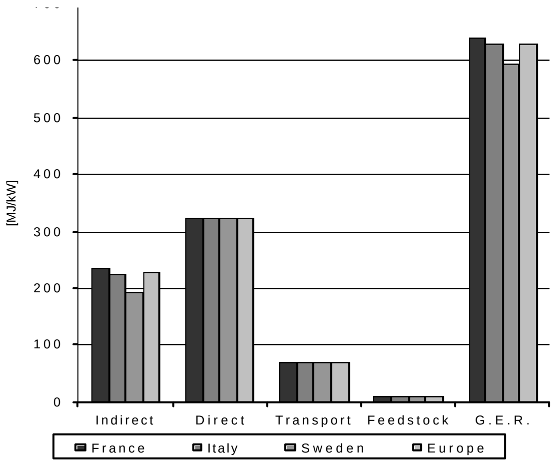

Figure 2. Energy consumption - Comparison of different scenarios (GER = Gross Energy Requirement)

Table 2. Details of the GER for PEM cell materials production - average European energy mix (data in MJ per 1 kW).

Fuel type	Indirect energy	Direct energy	Transport energy	Feed-stock energy	TOTAL energy
Elect-ricity	208,1	95,7	1,7	0	305,4
Oil fuel	7,1	14,6	65,7	2,7	90,1
Other fuels	12,8	213,9	1,8	6,2	234,8
Totals	227,9	324,2	69,2	8,9	630,3

It is necessary to highlight how the electricity production impacts are strongly dependent on the energy mix. In detail, different energy mixes lead to different efficiencies (that can be roughly measured by the Indirect – Direct energy ratio) and also to the use of different fuels that can be recognized in Table 2. Moreover, CO_2 emissions are mostly due to combustion in the electricity production activities, hence their value significantly depend on the local mix.

Table 3. Main non-energy raw materials for PEM cell materials production. Data are expressed in g per kW and materials under 100 g/kW are here omitted

Raw material	Quantity
Sodium chloride	350
Sand	210
Limestone	530
Aluminium scrap	8.300
Iron/steel scrap	7.400

The environmental results report the raw material consumption (Table 3), the air and water emissions, the quantity and quality of waste generated. The results refer to different steps of the life cycle: *fuel production*, *fuel use*, *transport*, and so on.

INTERPRETATION

The analysis was performed to evaluate the contributions to the final results of the main components of PEM cells stack. (Table 4).

Table 4. Contributions of used materials to the GER (data in MJ per 1 kW). *GDE = gas diffusion electrode; G = gasket; M = membrane; D = distributor; EP = end plate; CC = current collector; BP = bipolar plate.*

	France	Italy	Sweden	Europe
Black carbon (GDE)	0,3	0,3	0,3	0,3
Acrylonitrile (GDE)	0,02	0,02	0,02	0,02
Platinum (GDE)	0,3	0,3	0,3	0,3
Water (GDE)	< 0,01	< 0,01	< 0,01	< 0,01
Methanol (GDE)	0,01	0,01	0,01	0,01
Silicone (G)	56,9	54,8	48,6	55,5
Acrylonitrile (M)	19,0	18,1	15,0	18,4
Steel (D)	3,5	3,4	3,1	3,5
Steel (EP)	206,8	200,2	178,9	201,8
Steel (CC)	2,3	2,2	2,0	2,2
Aluminium (BP)	348,9	348,1	345,7	348,4

Since different country location is considered for plants, it is important to highlight the environmental loads ratio that depends on the energy mix for which the materials production activities are not directly (but indirectly) responsible. In order to perform this evaluation, two impact categories (both energy and environmental) had been defined:

- *direct responsible impact*: that includes the operations for which the materials production is directly responsible. For the energy assessment this category includes the total of direct, transport and feedstock energy, while for the environmental assessment it includes the fuel use, process and transport emission;

- *indirect responsible impact*: that includes the energy and environmental impacts generated by using local mix. For the energy assessment, this category includes the indirect energy while only the fuel production emissions are considered to perform the environmental assessment.

In order to show contributors to air emission values and to quantify the influence of a specific energy mix, air emissions are characterized as reported in Figure 3.

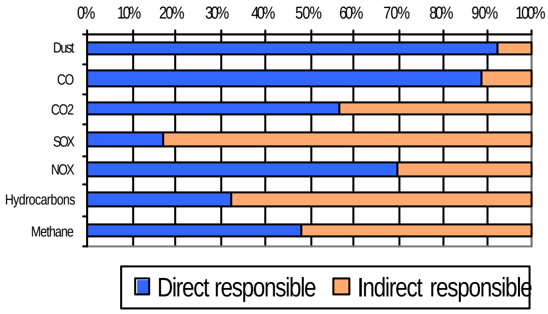

Figure 3. Contributions to each substance emission for European scenario

CONCLUSIONS

The environmental load for a stack of four fuel cells can be resumed in the GER figure (630 MJ for 1 kW in the European energy mix scenario) and in the Global Warming Potential (36 kg of CO_2 equivalents for 1 kW in the European energy mix scenario).

Different energy mixes lead to slight difference on total results, both energy and environmental. Some differences are also due to the use of nylon membrane instead of acrylonitrile one. Most of the energy consumption and hence most of the environmental burdens are due to the production of aluminum bipolar plate and steel end plate. Thus improvement actions for eco-efficiency target should be mainly focused on these components and on the site of production.

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