Chapter N 082

Life Cycle Assessment and Life Cycle Costing of an unitized regenerative fuel cell stack: a preliminary study

**Abstract**. The unitized regenerative fuel cell (URFC) with polymeric electrolyte membrane (PEM) is an emerging energy storage system that could play an essential role in decarbonizing Europe. Considering that the sustainability of PEM-URFC devices has not been studied in-depth, further analyses are required. In this context, this paper aims to focus on the central main component of a PEM-URFC, the stack, by assessing its potential environmental and economic impacts. Thus, using primary and secondary data, the Life Cycle Assessment (LCA) and Environmental Life Cycle Costing (ELCC) methods are applied, following a cradle-to-gate approach. The analysis shows that the main hotspots of the stack are linked to the membrane electrode assembled (MEAs), which contribute to about 68% of the total cost and more than 76% of all the environmental impact categories. These results are connected to the presence of materials characterized by high or medium critical supplies (e.g., platinum for catalysts, etc.) and high costs due to the early stage of market development. Further, the study highlights the need to have more reliable data on crucial and critical elements used in this type of device and more life cycle thinking studies on URFC to update the current knowledge on hydrogen technologies.

**Keywords.** PEM, Life Cycle Assessment (LCA), Environmental Life Cycle Costing (ELCC), regenerative fuel cell, hydrogen

# Introduction

To achieve carbon neutrality and to reduce external energy dependencies in Europe by 2050 (European Commission, 2019), the unitized regenerative fuel cell (URFC) of type polymeric electrolyte membrane (PEM) seems to be a valid option for improving the power system's stability, given its ability to work both as an electrolyzer - to produce hydrogen fuel - and as a fuel cell - to reconvert it into electricity when required (Regmi et al., 2020). Although several studies are available on this device's electrochemical performances and design (Gabbasa et al., 2014), the potential life cycle environmental and economic impacts of URFC, and of the stack - which represents the heart of this technology - have not still been studied in-depth. To reduce this literature gap, this paper aims to provide a preliminary estimation of the environmental and economic impacts of a small stack of a PEM-URFC. The stack is at the early design stage and has been developed in the context of the project "ELETTRORIGENERA" (PO FESR SICILIA 2014-2020 AVVISO 1.1.5 - PROGETTO ELETTRORIGENERA N. 08ME2899200216). The potential impacts are estimated by combining the Life Cycle Assessment (LCA) (ISO, 2006a, 2006b) and the Environmental Life Cycle Costing (ELCC) (Hunkeler et al., 2008) methods. This analysis allows a global understanding of the contribution of each consumed material and energy and related emissions, as well as environmental externality prices on the PEM-URFC stack's impacts, in order to identify its main critical hotspots.

# Material and methods

## Goal and scope definition

The study combines LCA and ELCC methods in order to: i) evaluate the environmental and economic impacts of a PEM-URFC stack, ii) identify its main environmental hotspots, and iii) calculate the contribution of environmental externality on life cycle costs. The LCA method is applied according to the ISO 14040-44:2006 (ISO, 2006a, 2006b) using Simapro software (PRé Sustainability, 2022). The ELCC is applied according to Hunkeler et al. (2008), using Simapro to estimate externalities' monetization and an MS-Excel worksheet to manage data. According to Masoni & Zamagni, (2011), the functional unit selected is a PEM-URFC stack of 3 and 1 kW of nominal power, respectively in electrolyzer and fuel cell modes. A cradle-to-gate approach is applied, accounting for all energy and material flows linked to the manufacturing phase.

## Life cycle inventory

The inventory data of the stack is modelled by using both primary and secondary data (see Table 1). In particular, the primary data provided by the ELETTRORIGENERA project's partners are weight, number, materials composition and costs of each component (produced and provided by third organizations). While the proxy of working processes (e.g., sintering, thermoforming, etc.) and all materials production processes are selected from the Ecoinvent database (Wernet et al., 2016), except for Nafion and Teflon manufacturing processes estimated according to literature, respectively from Evangelisti et al. (2017) and Simons & Bauer (2015). Due to missing inventory data, Iridium and Ruthenium oxide and Ertalyte manufacturing are assumed from similar materials (Mori & Štern, 2016).

Table . Number, weight and price of components included in one URFC stack

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | N. | Main materials [% on weight] | Total Weight [kg] | Price [€]\*\* |
| Membrane Electrode Assembly(MEA)\* | 30 | * Catalyst-coating membrane (CCM):
	+ Membrane (Nafion (**a)** 3.39%)
	+ Electrocatalysts (Iridium Ruthenium oxide (**b)** 0.05%, Platinum black 0.07%, Platinum on Carbon 0.05%)
	+ Ink preparation (Carbon black 0.25%, Methanol 0.18%, Nafion (**a)** 2.03%).
* Gas diffusion layers:
	+ Mesh (Titanium 42.13%)
	+ Felt (Porous Titanium 51.92%)
 | 5.72 | 29,183 |
| Frame\* | 60 | * Ertalyte (**c)** (100%)
 | 1.99 | 9,000 |
| Gasket hole\* | 60 | * Polytetrafluoroethylene (**d)** (Teflon) (100%)
 | 0.33 | 16 |
| Bipolar plate\* | 30 | * Titanium (100%)
 | 1.59 | 3,600 |
| Current collection plate (CCP) | 2 | * Copper (100%)
 | 0.22 | 150 |
| Gasket final | 2 | * Polytetrafluoroethylene (**d)** (Teflon) (100%)
 | 0.02 | 1 |
| Tie rods, spring | 20, 300 | * Iron (100%)
 | 0.71 | 270 |
| Endplates | 2 | * Aluminum (100%)
 | 3.86 | 936 |
| \* components of the cells; \*\* prices comprehensive of materials acquired and manufacturing costs at laboratory scale (a) manufacturing process assumed by Evangelisti et al. (2017); (b) manufacturing process assumed as palladium by Mori & Štern (2016); (c) manufacturing process assumed as PET; (d) manufacturing process assumed by Simon and Bauer (2015). |

## Life cycle impacts assessment

For environmental impacts calculation, the CML-IA baseline (CML, 2016) method is applied to evaluate abiotic depletion potential (ADP), acidification potential (AP), global warming potential (GWP), eutrophication potential (EP), and photochemical oxidation formation (POF)[[1]](#footnote-2). In addition to these, using the Cumulative Energy Demand (CED) method (Frischknecht et al., 2015), renewable (CEDr) and non-renewable primary energy (CEDnr) consumed is calculated. The ELCC is calculated as equation 1 by summarising two values: 1) the life cycle costs (*LCC)*of each component and 2) the environmental price (*EP)*.

|  |  |
| --- | --- |
|  | (1) |

The first is based on primary data provided by the ELETTRORIGENERA project's partners, including materials and manufacturing costs; the latter is calculated by applying the Environmental prices method (De Bruyn et al., 2018), which includes the average European prices for the social cost of pollution expressed in Euros per kilogram of pollutant.

# Results and discussion

The environmental, energy and economic results are reported in Table 2.

Table . Environmental, energy and economic impacts of the PEM-URFC stack

|  |  |  |
| --- | --- | --- |
| Impact categories | Units | Values |
| *Emvironmental impacts* | **ADP**  | kg Sb eq | 2.63E-02 |
| **AP**  | kg SO2 eq | 3.00E+01 |
| **GWP**  | kg CO2 eq | 6.19E+02 |
| **NP**  | kg PO43- eq | 3.02E+00 |
| **POF**  | kg C2H4 eq | 1.12E+00 |
| *Energy impacts* | **CEDnr**  | MJ | 8.74E+03 |
| **CEDr**  | MJ | 3.87E+02 |
| **CED** | MJ | 9.12E+03 |
| *Economic impacts* | **LCC**  | € | 4.22E+04 |
| **EP**  | € | 6.75E+02 |
| **ELCC**  | € | 4.29E+04 |

Concerning the environmental impacts, during the manufacturing phase, the stack could emit about 0.026 kg Sbeq in ADP, 30 kg SO2eq in AP, 619 kg CO2eq in GWP, 3.02 kg PO43-eq in NP and 1.12 kg C2H4eq in POF. Focusing on CED, the primary energy consumed for components manufacturing is 912 MJ, of which 96% is produced from non-renewable energy sources.

The life cycle costs of stack increase as one moves from conventional LCC (43,155.98 € per unit) to environmental LCC (43,830.55 € per unit), reflecting the inclusion of the "environmental externalities". Considering that costs of components refer to a device not still commercialized, the LCC is relatively higher than similar mature technologies, and environmental prices contribute to about 1.5% of economic impacts globally.

Plotting the overall contributions in percentages allows for identifying the main hotspots linked to stack manufacturing for each impact category and visualizing the substantial differents and analogies among them (Figure 1).

Figure . Contribution analysis and hotspot identification for PEM-URFC stack manufacturing

The main environmental and energy impact contribution in the manufacturing phase comes from the MEA, responsible for more than 76% (GWP) of all the impacts. These high values are linked to electrocatalysts responsible for more than 88.7% of impacts of MEA, except for CEDr, in which catalysts are responsible for at least 62.39%. The rest of the elements are responsible for 37.61% in CEDr, 11.30% in GWP and 8.74% in CEDnr, while in the other categories, they contribute to less than 2% of MEA impacts. On the contrary, the lowest impact of the stack is related to the tie rods contributing less than 0.16% in all environmental categories.

Focusing on the economic impacts, it could be observed that the highest manufacturing costs are related to MEAs that contribute 68.05% in LCC and 95.14% in EP, reflecting the environmental emissions linked to the mining of platinum. Although the monetization of impacts increases the global economic impacts by less than 2%, essential differences exist among components, for which it is calculated that the EP increases LCC from 0.01% in the frames to 18.04% for gaskets.

Comparing environmental and economic impacts, Figure 1 shows that, while the hotspots are similar for MEA and bipolar plates among the ELCC and GWP and CED scores, differences exist in other components and impact categories. For example, while the frame contributes approximately less than 2% in all impact categories, its cost has a much more significant economic impact (20.54% of ELCC). The contrary is for gaskets: the cost has a minor significant percentage (0.05%) than the GWP score (6.72%). The highest discrepancies could be associated with the fact that the technologies are not still commercialized, and the particular shapes required for some components are affected by treatment and machinery prices. However, in this preliminary study, considering that third organizations provide the components, it was impossible providing an estimation of the influential contributions for each material, energy, and operating cost due to missing data for both LCA and ELCC, especially on crucial and critical elements such as catalysts.

# Conclusions

This paper aimed to evaluate the environmental and economic impacts of a PEM-URFC stack in order to identify its main hotspots. The LCA and ELCC of a small PEM-URFC stack were carried out to reach the study's scope, and a contribution analysis was conducted to identify critical issues. The life cycle study included primary data on each stack component's weight, materials, and costs. Instead, the working processes proxies, materials production datasets and environmental prices are taken from the Ecoinvent database and literature studies. The analysis shows that the highest potential impacts are associated with MEA, which includes catalysts and materials (such as Palladium, Platinum, Titanium, and Nafion) characterized by a high or medium critical supply chain that affects both the economic (LCC) and environmental (LCA) pillars of sustainability. Despite the similarities between LCA and ELCC hotspots, some discrepancies were noticed for frame and gasket components. However, considering that most of the data refer to emerging technology at early stage design and laboratory scale, the sustainability of the device has to be evaluated considering different parameters for both economic and environmental models and market scenarios. In addition, future studies may be focused on evaluating, e.g., the whole life cycle of URFC systems from manufacturing to end-of-life, calculating the uncertainty linked to catalysts production processes and the relative effects on results and estimating the potential benefits of technologies if compared with alternative energy storages.

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1. These choices were performed according Masoni & Zamagni ( 2011), where these impact categories are considered essential in LCA studies of fuel cells and electrolysers. [↑](#footnote-ref-2)