



## Life Cycle Impact Assessment of a HT-PEM Fuel Cell Powered by Natural Gas Reforming

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### Authors' contributions

This work was carried out in collaboration between the authors. Author SHF designed the study and supervised the data collection and analysis, wrote, interpreted the results and revised the manuscript. Authors ABN and LBCO had a significant share in data collection and analysis. Author JOAP provided valuable suggestions for the study design and revised the manuscript. All authors read and approved the final manuscript.

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### ABSTRACT

This study uses life cycle assessment (LCA) to investigate the environmental impacts, including the cumulative energy demand (CED) and energy payback time (EPBT) of a 20 kWel HT-PEM power plant in Brazil. The power plant investigated is a pilot that uses High Temperature Proton Exchange Membrane (HT-PEM) fuel cell technology and natural gas (NG) reforming to produce energy for the commercial and residential sectors. The scope of the LCA study covered the production and distribution of natural gas in the state of São Paulo, including the phases of construction, installation and maintenance of NG reforming and HT-PEM systems, as well as the production of

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hydrogen and electricity over 40,000 hours of operation. The results indicated that the global warming potential (GWP) is the highest environmental impact of the system. The GWP resulted from the natural gas input into the system (77%). In the hydrogen production phase, 34% of emissions derived from fossil fuels were burnt in the heating process, while 44% originated from the consumption of NG in the reforming process itself. On the other side, both the reuse of hydrogen that has not been consumed in FC as fuel in the heating process and the recovery of waste heat generated in the system can lead to a reduction of up to 20% of the emissions generated in the use phase. In terms of cumulative energy demand, it points towards a reduction of up to 25% of the CED. Under these conditions the EPBT of the system is 10.96 years.

*Keywords: Life cycle assessment; environmental impacts; fuel cell; HT-PEM; natural gas.*

## 1. INTRODUCTION

In recent years, the environmental impact assessment of alternative technologies for electricity production, such as the Fuel Cell (FC), has been the focus of several studies. Considering the various types of FC, which are still being developed, there remain gaps in the field of possible technical solutions to improve environmental performance. Moreover, innovative systems of energy distribution are increasingly receiving attention for providing a high energy utility, with a decentralized and high efficiency heat [1]. These characteristics have played an important role in the reduction of greenhouse gas emissions (GHG) and informed the policies of climate change around the world. Among the different technologies of energy distribution, the type of Fuel Cell (FC) known as the High Temperature Proton Exchange Membrane (HT-PEM) is considered to be an emerging alternative when compared to the usual technologies, including the Low Temperature PEM cell, LT-PEM [2].

Compared to the conventional PEM, the HT-PEM has advantages such as: an operating temperature between 130 and 180°C (~2 atm.), simplified water management, a high tolerance for catalysts for CO, available residual heat for cogeneration, kinetics of electrodes reaction that permit the use of catalysts that are more cost effective than platinum, and a simplified architecture of the system of integration for fuel processing [3,4].

According to National Renewable Energy Laboratory - NREL [5], the HT-PEM operating with natural gas reforming has electrical energy efficiency between 40% and 45% at the beginning operational life – BOL. In this temperature range, the HT-PEM system tolerates a carbon monoxide level of 1% to 2%. The

configuration permits the heat produced to be more easily utilized to generate gas in the system of processing the fuel. Furthermore, unlike what happens in the PEM, it does not require a complex system that considers cleaning reformed gas.

There are different applications of the integrated system of HT-PEM, based on the electricity consumption used by stationary equipment (for commercial and residential use), including the use of hydrogen originating from the natural gas reforming, as an input for the petroleum refining industry, food and as fuel to move electric motors in vehicles, among others.

Although the production of hydrogen by methane reforming emits CO<sub>2</sub>, the transformation of hydrogen into electricity for more efficient technologies, as in the case of FC, contributes to the reduction of the emission coefficient (g CO<sub>2</sub>/kWh), when taking into account the complete cycle of natural gas production to electricity [6].

Recently, environmental problems such as global warming and climate change, in particular, have raised the attention of detrimental effects as a priority in the cost effectiveness of a particular energy source in relation to another [7]. Consequently, there is a constant interest in evaluating the environmental cost of both fuel sources and the power systems through the entire cycle of life.

In fact, many studies of Life Cycle Assessment (LCA) have been conducted on systems related to energy production for diverse reasons [8,9]. The strength of the LCA methodology lies in the ability to consider the entire life cycle of a given product in great depth. This is considering all direct or indirect actions, from the cradle to the grave, that interact and affect the environment.

In this context, this work utilizes LCA to examine emissions and the resulting impacts associated with the steps of extraction, processing and transportation of materials, manufacturing, installation and electrical energy production of a pilot unit of HT-PEM energy production fed by natural gas reforming that has been constructed in Brazil.

The focus of LCA is to identify the stages and the significant impacts from the entire life cycle of the HT-PEM system, besides the cumulative energy demand (CED) and the energy payback time (EPBT). This work was carried out in accordance with ISO 14040 and 14044 [10,11] and the international technical guide HY-FC developed by the Joint Centre Research of Ispra - the European Platform on Life Cycle Assessment [12].

## 2. MATERIALS AND METHODS

### 2.1 The Analysed System

The system studied is a pilot plant for the distributed energy generation, built and tested during the period from October 2012 to

September 2015 by the company Hytron Ltda., located in Campinas (São Paulo/ Brazil). This pilot plant is characterized by the integration of a unit of steam methane reforming (SMR), built by a Brazilian company, with the maximum production capacity of 2 kg/h of H<sub>2</sub>, and a module of a 20 kWh<sub>el</sub> HT-PEM fuel type cell that has been manufactured by the Danish company, Serenergy. Table 1 presents a summary of the technical characteristics of the 20 kW<sub>el</sub> (electrical power) HT-PEM system studied.

In terms of performance, the HT-PEM is similar to the liquid electrolyte of the Phosphoric Acid Fuel Cell – PAFC [5], and specifically in the system studied, the electrolyte is a membrane of polibenzamidazole (PBI) doped with phosphoric acid. The efficiency factors of the HT-PEM system are presented in Table 2.

The HT-PEM system operates at a temperature of 160°C, the pressure of 1.1 bar, and the total hydrogen produced and that necessary for the electrical output of 20 kW<sub>el</sub> comes out to 1.31 kg/h. Table 3 presents the energy required to operate the FC, including the consumption of hydrogen and natural gas.

**Table 1. Technical characteristics of HT-PEM system studied**

<b>Fuel use &amp; reforming</b>	<b>Value</b>	<b>Unit</b>
Type of fuel	Methane	
Fuel consumption	1.27E-03	kg/s
Hydrogen consumption (excluding preheating)	3.65E-04	kgH <sub>2</sub> /s
Energy used by reforming	7.5	kW
<b>Fuel cell operating conditions &amp; theoretical Gibbs energy</b>		
Temperature	160	°C
Pressure	1.1	bar
Gibbs energy	-38.4	kW
Open circuit cell voltage	1.090	V
<b>Operating characteristics &amp; efficiencies</b>		
Constant voltage & fuel flow proportional to the current		
Operating cell voltage (DC)	0.700	V
Voltage efficiency	64.2%	
Operating cell current	60.00	A
Current density	5702.58	A/m <sup>2</sup>
Current or fuel utilization efficiency	96.3%	
<b>Electrical power and heat output</b>		
Electrical power output (AC)	20.0	kW
Electrical generation efficiency	29.8%	
Usable heat gain	10.6	kW
Overall heat and power efficiency	43.4%	
Heat to power ratio	0.528	
<b>Fuel cell stack configuration</b>		
Number of cells	360	
Volume of stack	0.0456	m <sup>3</sup>
Operating stack voltage	84	V
Operating stack current	282.28	A

**Table 2. Efficiency factors for 20 kW<sub>el</sub> HT-PEM system**

Efficiency factors	Value
Theoretical efficiency	87.0%
Voltage efficiency	64.2%
Fuel utilization / current efficiency	96.3%
Practical fuel cell efficiency	53.8%
Reformer efficiency (fuel consumed by reforming)	57.0%
DC / AC converter efficiency	97.0%
Electrical generation efficiency (electricity out / fuel in)	29.8%
Heat efficiency (usable heat gain / fuel in)	13.6%
Overall efficiency (heat and power)	43.4%

**Table 3. Energy requirements, hydrogen and fuel consumption for a 20 kW<sub>el</sub> HT-PEM system**

Power required from the fuel cell stack	Value	Unit
Net power required from the fuel cell system	20	kW
Total ancillary loads referred to AC output	3	kW
Total AC power required from the system	23	kW
Converter efficiency	97.0%	
DC power required from the fuel cell stack	23.71	kW
<b>Voltage constant with current</b>		
Cell voltage	0.700	V
Sum of currents through all cells in the stack	3.39E+04	A
<b>Fuel flow proportional to current, or constant utilization</b>		
Hydrogen utilised in the stack	3.51E-04	kgH <sub>2</sub> /s
Current efficiency or ratio of fuel utilization	96.3%	
Hydrogen supplied to the stack (without recirculation)	3.65E-04	kgH <sub>2</sub> /s
Fuel (NG) supplied to the reformer (excluding recirculated & preheat fuel)	7.25E-04	kg/s
Fuel (NG) used for preheating the reformer (excluding recirculation)	5.47E-04	kg/s
Total fuel consumption	1.27E-03	kg/s

As noted in Table 3, the pilot plant for HT-PEM electricity production was configured for the reuse of hydrogen that was not consumed in the HT-PEM, as fuel in the reforming furnaces (internal heating) and for the reuse of heat (exhaust gases) generated in the process of reforming natural gas in its own reformer.

## 2.2 The LCA Approach

The LCA is a methodology that assesses the environmental loads associated with a product, process or activity through the means of identifying and quantifying the materials and energy flows and its emissions to the environment. This technique is considered one of the most appropriate methods to respond to the challenges for the development of energy systems that meet the demands of sustainability.

In this context, the LCA study of the HT-PEM system was conducted in accordance with international technical standards ISO 14040 [10] and the recommendations of the Hy-FC guide developed by the Joint Research Centre of Ispra [12] for performing LCA on fuel cells and hydrogen technologies. The following paragraphs

detail the application of the study as stated by the standards and the guide mentioned above.

### 2.2.1 Goal and scope

The objective of this LCA is to identify the more significant stages and impacts of the HT-PEM system life cycle, from the natural gas production to the electricity generation. This is a non-comparative study, that is, no other system of production of electrical energy, via FC technology and hydrogen production, was evaluated in order to compare performance. The results obtained in this study aims at assisting both the establishment of guidelines for decision-makers, and as developing technologies of low-impact energy production, fuelled by natural gas.

#### 2.2.1.1 Functional unit and system boundaries

The HT-PEM system is a pilot unit of a 20 kW<sub>el</sub> stationary energy supply and its main function is the electrical energy production. Although this system can be used as an energy supply source in remote locations, where there is no connection to the distribution network, in this case it is necessary to have an availability of constant

supply of natural gas. The main applications for the use of this system are a stationary source of prime power energy or a standby in both commercial and residential areas.

The functional unit established for this study is 1 MJ<sub>el</sub> (net calorific value). The equivalent in electrical energy is 0.28 kWh<sub>el</sub> and the reference flow is 1 MJ<sub>el</sub> (net calorific value). Even if the HT-PEM system offers, additionally, the option of recovering heat and, therefore, may be operated as a combined heat and power (CHP) system, this study did not examine the multifunctionality of the hydrogen by-product produced in the reforming system as an input chemical in other productive chains and the heat produced in the whole system for cogeneration.

The life cycle of electricity production via HT-PEM system consists of three major production processes. The first refers to the production of natural gas, which is used as a raw material for the production of hydrogen. This energy vector, in turn, is used as fuel by the HT-PEM system to generate electricity and heat. The stages of the system's life cycle measured by the assessment were:

- a) The construction of the floating vessel platform - Floating Production Storage and Offloading-FPSO, production, processing and distribution of natural gas, specifically in the state of São Paulo.
- b) The construction of the reforming equipment, the materials transportation, installation, maintenance and hydrogen production (Fig. 1).
- c) The manufacture of the stack components (5 kW<sub>el</sub>), the HT-PEM module (20 kW<sub>el</sub>), and the accessory equipment (balance of system), transportation, installation, manufacturing and electricity production (Fig. 2).

The study's focus was mainly on the stages related to the step of hydrogen production and the electricity generation by the HT-PEM.

The geographical boundaries represented at each stage of the life cycle were defined in accordance with the primary data, the geographic location of each production plan evaluated and/or the data of global production available in the commercial database.

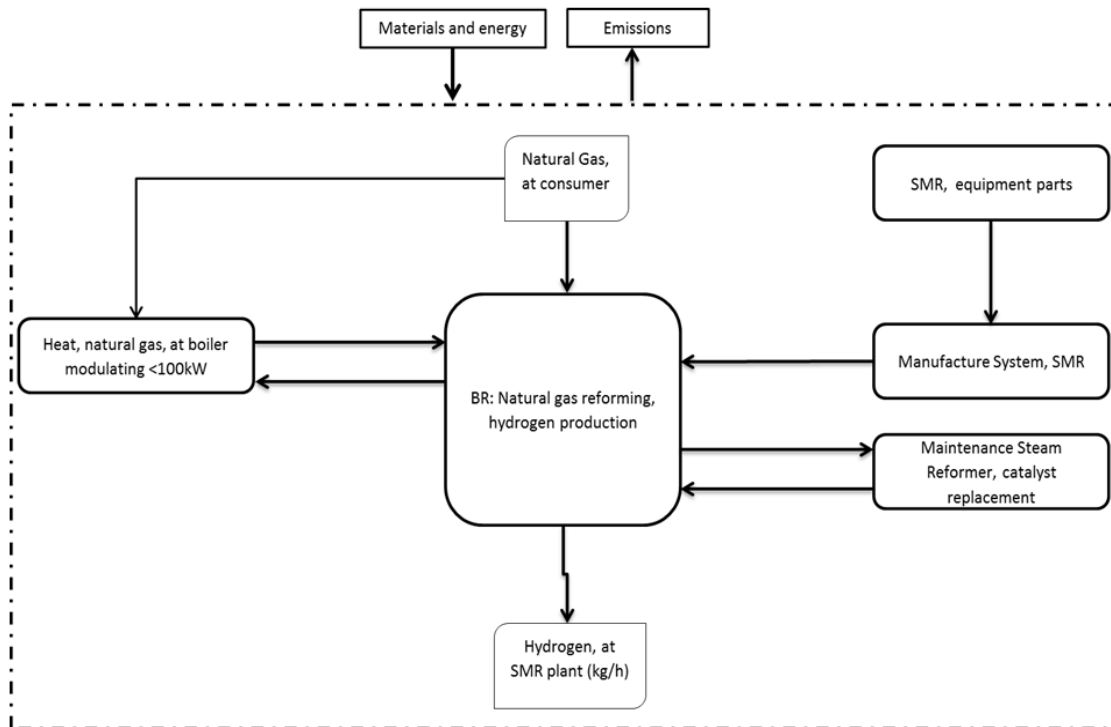
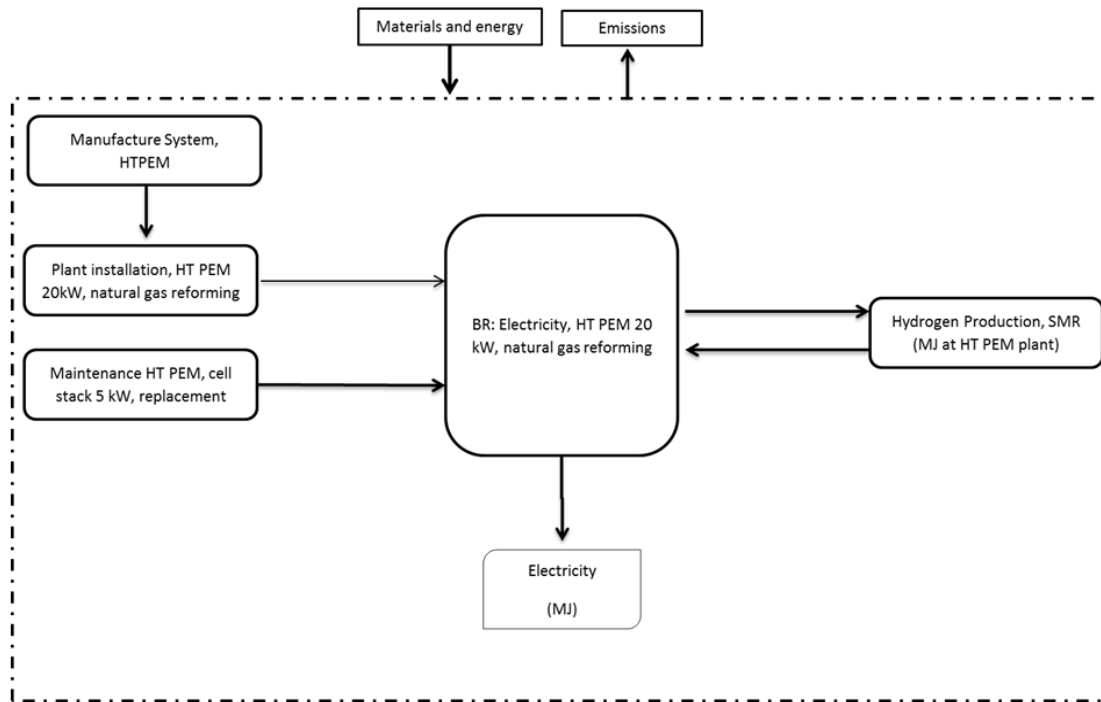


Fig. 1. Boundaries for the hydrogen life cycle stage



**Fig. 2. Boundaries for the HT-PEM system product**

**2.2.2 Life cycle inventory**

Given the goal and scope established of the study, the main processes assessed within the limits of the system life cycle are the natural gas and hydrogen production and electricity generation via HT-PEM. Therefore, the manufacture of the equipment, fuel and energy vector production, materials and components transportation, maintenance, installation and the pilot plant operation have been weighed. The end of the system’s life cycle, that is, the decommissioning and final disposal, was not included in this analysis.

For the evaluation of natural gas production, the inventory data presented in the study by Schori & Frischknecht [13] on the production of NG, including infrastructure, transportation and the distribution network, have been calibrated and recalculated for the Brazilian context. To the fullest extent possible, the process units with a global geographical location were used in place of those specifically related to the European conditions.

The offshore inventory platform and the FPSO of the city of Sao Paulo were considered as similar regarding the use of materials and energy

necessary for their construction, except for the use of the concrete. In this case, it was assumed that the FPSO is constructed mostly of steel. Thus, the volume of concrete present in the offshore platform from the commercial database was not accounted for.

In the stage of natural gas transportation and distribution across long distances and high and low pressure; the data were adjusted in accordance with the transport conditions as shown in Table 4. It was adopted that the loss of natural gas during the process of transportation and distribution via pipelines, estimated in the database, are the same as in Brazil.

In the stage of the SMR manufacturing, all of the main materials used in this system were evaluated. However, data deemed sensitive that are related to the reformer’s operational control system were not included in this evaluation.

Given the characteristics of the study, in which the majority of the components are manufactured by suppliers, only the energy consumption related to the raw materials extraction and processing and materials transportation used in the SMR and corresponding emissions were measured.

**Table 4. Pipeline and transport distances used in this study**

<b>Transport</b>	<b>Distance (km)</b>
<b>Long distance</b>	<b>406</b>
Bacia -> ETGCA (1) Caraguatatuba (offshore)	310
ETGCA (1) -> EP (2) Taubaté (onshore - Gastau)	96
<b>High pressure</b>	<b>155</b>
EP (2) Taubaté -> Term. Guararema (Gaspal (3))	61
Term. Guararema -> ECGM (4) Mauá (Gaspal II)	55
ECGM (4) Mauá -> ESB São Bernardo (Gasal II)	39
<b>Low pressure (Distribution network COMGAS)</b>	<b>11.618</b>
(1) ETGCA: Caraguatatuba gas treatment unit	
(2) Pressuring station	
(3) Estimated route	
(4) ECGM: Gas control station	

Additionally, the consumption of energy and materials used for the commercial construction (infrastructure) and equipment needed in the manufacturing process was not evaluated here. Nevertheless, it was undertaken that the efficiency of the SMR manufacturing process is the efficiency of the manufacturing materials used in the reformer.

In the stage of the HT-PEM technology manufacturing it is deliberated that the main auxiliary components are the same as the PAFC technology of the inventory elaborated in the study developed by Rooijen [14].

The infrastructure required for manufacturing the HT-PEM was also assumed similar to those presented in the inventory of Report 20 of the Ecoinvent 2.2 on the technology LT-PEM. In this sense, data related to the HT-PEM manufacturing, infrastructure, energy consumption and maintenance were parameterized according to the lifetime and power, established in the HT-PEM system studied.

Due to the similarities in the operating conditions of HT-PEM system to the PAFC system, the calculations of fuel consumption and the efficiencies were based on technical characteristics of PAFC operation. It must be noted that the manufacturing of the fuel cell type HT-PEM and its integration with the system of reforming natural gas are still in development. For that reason, the environmental effects of future mass production of equipment can now only be assessed on the basis of the pilot plant production and with consideration of the assumptions.

Data from the electricity production matrix in Brazil were taken into account in the processes of the distribution network and the transport of

natural gas, manufacturing and reformer installation, while the HT-PEM's production used the data from electricity generated in Denmark.

#### 2.2.2.1 Data collection and data quality

The implementation period of the data collection procedure and processing occurred during the months from January 2013 through June 2014, totaling 18 months, including the construction of a pedigree matrix, distribution definition and standard deviation, useful for analyzing uncertainties. Data from the manufacturing and operation of the equipment of reforming and HT-PEM were obtained by means of questionnaires, technical visits and interviews.

The gaps that exist in relation to the whole system were supplemented from the collaboration of specialists at Hytron and the Center of Fuel Cell and Hydrogen (CCCH) - Nuclear and Energy Research Institute (IPEN), besides estimates based on the literature.

The HT-PEM pilot plant powered by hydrogen via natural gas reforming is a product system in which all major components were manufactured by external suppliers. Since obtaining the necessary information from each of the suppliers is a complex task and requires a vast amount of time, the priority was to obtain the data from Hytron, the Brazilian company responsible for the construction and integration of the reforming system.

That is to say, the majority of primary data used in the evaluation were provided by Hytron and, to a lesser extent, by the Danish manufacturer of HT-PEM technology. Hence, in constructing the HT-PEM inventory, data from the life cycle of the LT-PEM and PAFC technology available in the literature were used, when relevant, along with that based in Ecoinvent 2.02.

Thus, the transportation of materials and equipment to the premises of the suppliers are excluded from the evaluation, as well as emissions from manufacturing and waste from external suppliers that are not accounted for in the database from the production processes of SimaPro.

For the system of natural gas production, the data used were based on Ecoinvent 2.02, where the information on transportation and distribution of GN were adjusted according to the conditions encountered in the state of São Paulo. The data on the network of distribution of natural gas were obtained in technical reports that were publicly available through the National Petroleum Agency (ANP) and the Ministry of Energy of the State of São Paulo. The main secondary sources of data used in this study are:

- a) Data from Ecoinvent 2.02 included in the SimaPro Software: inventory of the life cycle of production of natural gas [13]; electrical energy and heat used in the SMR system and the infrastructure for the manufacturing of HT-PEM (Report 20).
- b) Data from other sources not included in the SimaPro Software: materials and transport, the distribution network for natural gas in the state of São Paulo [15,16,17].
- c) Data available in scientific platforms: Production module and the technological cell of the HT-PEM fuel cells [3,4,18,19] methane gas reforming [20,21].

All results were calculated using the SimaPro Analyst 8.02 software. Additionally, Excel was also used to quantify the inputs and outputs of the system of manufacturing the equipment of HT-PEM reforming and the data of fuel consumption as a function of the technical characteristics of the HT-PEM. In the software, the product system was modeled and calibrated as a function of the goal and scope established for this study. The software has allowed the analysis of the inventory and potential environmental impacts.

### **2.2.3 Life cycle impact assessment**

The CML method 2.05 baseline 2001 was selected as the most appropriate to calculate the contribution of potential environmental impacts of the HT-PEM system. The investigated midpoints categories for the environmental and energy demand evaluation were:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Ozone layer Depletion Potential (ODP)
- Cumulative Energy Demand, Non-Renewable (CED NR)
- Cumulative Energy Demand, Renewable (CED R)

These categories were defined according to the recommendation of the FC-Hy guide (JRC, 2011) and include almost 100% of the potential impacts of the HT-PEM system. The total contributions of the potential impacts to the EP and ODP were calculated according to the formulas pertaining to each of the categories established by the CML, utilizing the applicable impact factors and in relation to flows of input and output accounted for in the entire system.

The method of assessing the endpoints impact categories was not examined in this study. In relation to the CED, the calculation procedure follows in accordance with the method given by Frischknecht et al. [22].

This study also evaluated the energy payback time (EPBT), defined as the ratio of the total energy input during the system's life cycle as compared to the yearly production during system operation. EPBT was calculated according to the following equation:

$$EPBT = LCE \text{ input (MJ)} / AEO \text{ (MJ/year)} \quad (1)$$

In the equation above, the LCE input is the life cycle primary energy input (total CED) and AEO is the annual energy output or energy yield in their primary energy equivalent. EPBT refers to the years required to recover the primary energy consumption throughout its life cycle by its own energy.

## **3. RESULTS AND DISCUSSION**

### **3.1 Impact Assessment**

The global warming potential (GWP 100 years) is the most significant impact of the entire system, at 99.6%. Table 5 presents the absolute values of the contribution for each category of impact under study, which highlights the environmental load of the production process of H<sub>2</sub> in relation to the GWP (1.25 E-02 kg CO<sub>2</sub> eq) in the life cycle of the pilot unit HT-PEM.



Nearly all of the emissions from the GWP are related to the step of hydrogen production (84%) (Fig. 3). Since the HT-PEM pilot unit is primarily a system that uses non-renewable resources to generate electricity; the phase of operation of the reformer is without a doubt the stage that presents a greater environmental impact.

In analyzing the stage of hydrogen production, the impacts related to the emissions of greenhouse gases (GWP) mainly occur due to the consumption of natural gas used in the reforming process itself (44%) and in the burning of this fuel for producing heat (34%) throughout the 40,000 hours of operation of the HT-PEM system (Fig. 4).

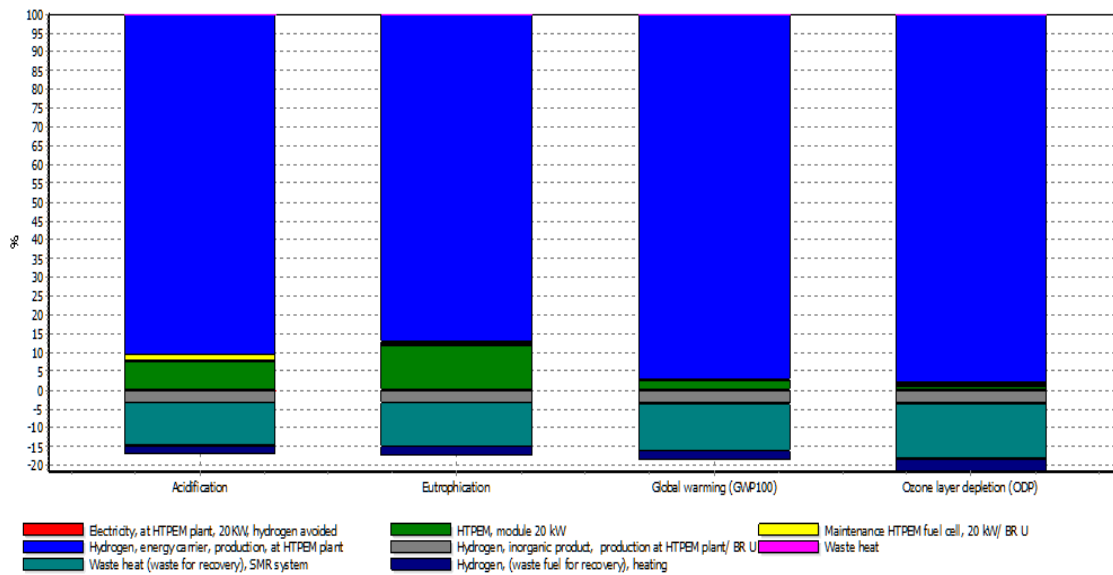
Table 6 display the absolute values of the contribution of the gas reforming processes itself (6.81 E-01 kg CO<sub>2</sub> eq), and the consumption of natural gas in the furnace of the reformer (5.60 E-01 kg CO<sub>2</sub> eq) to the global warming potential in the stage of hydrogen production.

In the analysis of the hydrogen production processes, it was found that approximately 50% of the contribution to the GWP associated with the consumption of natural gas, refers, in fact, to the environmental load of the fossil fuel production steps, at which the production of NG at low pressure and high pressure corresponds to 27.6% and 9.4%, respectively (Fig. 5).

Furthermore, the drying of NG, the burning of sweet gas in the flare and the use of NG in the gas turbine for the compression station are the processes that, together, collaborate to make up 8.75% of GWP emissions. Whereas, the sum of the contribution of materials and equipment necessary for the construction of the infrastructure of transport and distribution of natural gas (processes of the production of cast iron and the use of equipment for digging) corresponds to 8.69%.

**Table 5. Absolute values of the contribution of the HT-PEM system in each impact category**

Category of impact	AP kg SO <sub>2</sub> eq	EP kg PO <sub>4</sub> <sup>3-</sup> eq	GWP100 kg CO <sub>2</sub> eq	ODP kg CFC-11 eq
HT-PEM operation	Absolute value	Absolute value	Absolute value	Absolute value
Electricity, at plant, HT-PEM	<0	<0	<0	<0
Module HT-PEM	5.33E-06	3.50E-06	7.18E-04	4.31E-11
Maintenance HT-PEM	1.15E-06	1.81E-07	7.43E-02	8.51E-05
Hydrogen, production at plant	2.90E-05	1.16 E-06	1.25E-02	1.54E-09
Waste heat recovery	-7.93E-06	-3.41E-06	-3.52E-03	-5.07E-10
Residual H <sub>2</sub> recovery	-1.64E-06	-7.08E-07	-7.30E-04	-1.05E-10



**Fig. 3. Impacts of the entire life cycle of the HT-PEM system**

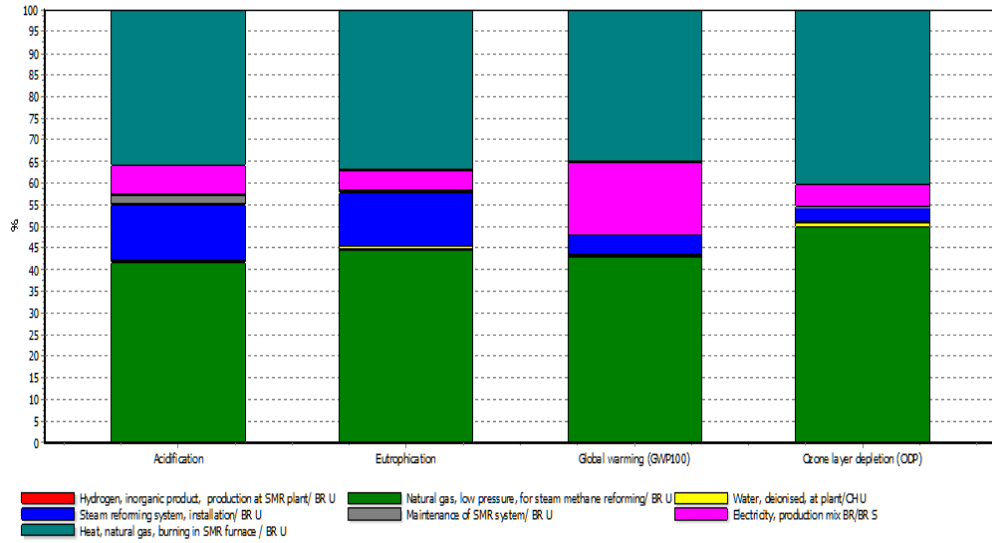


Fig. 4. Impacts of the life cycle stages of the hydrogen production

Table 6. Absolute values of the contribution of hydrogen production through all the impact categories

Impact categories	AP kg SO <sub>2</sub> eq	EP kg PO <sub>4</sub> <sup>3-</sup> eq	GWP100 kg CO <sub>2</sub> eq	ODP kg CFC-11 eq
SMR operation	Absolute value	Absolute value	Absolute value	Absolute value
NG, low pressure, reforming	1.53E-03	6.61E-04	6.81E-01	9.82E-08
Tap water, at plant	1.66E-05	1.04E-05	3.54E-03	2.68E-09
Installation/assembly, SMR	4.71E-04	1.83E-04	7.43E-02	6.67E-09
Maintenance SMR <sup>(1)</sup>	8.85E-05	5.69E-06	8.41E-04	1.62E-10
Electricity, production mix/ BR	2.50E-04	7.14E-05	2.66E-01	1.00E-08
Heat, NG, burnt in SMR furnace	1.33E-03	5.48E-04	5.60E-01	8.00E-08

(1) Maintenance SMR: replacement of catalyst, after each 40,000 hours of operation.

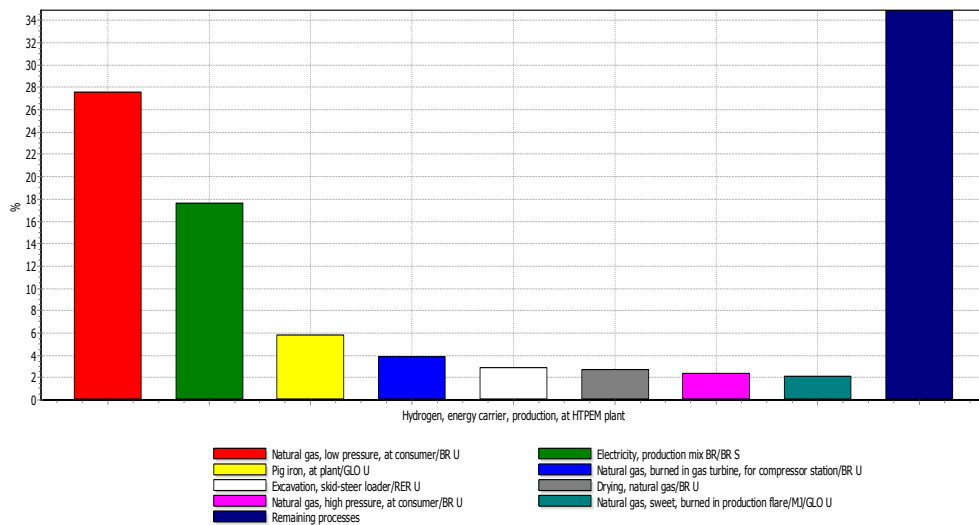


Fig. 5. Relative contribution of the global warming potential of the natural gas production process in the H2 production stage

In the general framework, the phases of equipment manufacturing, maintenance and installation of the HT-PEM unit have little or no significant contribution when examining the entire system. Only when they are assessed separately, that is, within each stage of the life cycle, a more significant participation is observed from the materials and processes of manufacturing.

### 3.2 Cumulative Energy Demand and Energy Payback Time

It was observed that the CED is mostly non-renewable due to the consumption of the natural gas in the production of hydrogen. Table 7 shows the absolute values of the contributions to the CED, both renewable and non-renewable.

On a life cycle basis, for one MJ of primary energy consumed by the system, 0.42 MJ of electricity is produced, that is more energy is used by the HT-PEM system than is produced. The total sum of non-renewable and renewable cumulative energy demand over the 40,000 hours of HT-PEM lifetime operation was 6.91E06 MJ. This value also accounts for the upstream energy process used in producing and distributing the natural gas and in producing the hydrogen required to operate the HT-PEM plant.

The energy produced over one year by the HT-PEM system was 6.31E05 MJ. Under these operating conditions, the energy payback time is estimated at 10.96 years.

On the other hand, it was found that the reuse of residual hydrogen (not consumed in the HT-PEM) and the heat recovery within the system reforming itself can produce positive effects with regards to the environmental performance of the system (Fig. 6). Such benefits can provide a reduction of up to 20% of emissions generated and at most 25% of the CED of the entire life cycle.

In this sense, if on the one hand, currently, the process of steam methane is still recognized as an inevitable option for the economic viability of the HT-PEM system, then the environmental impacts caused by the natural gas consumption and the emissions of the reforming process can be reduced through the processes development that permit a greater reuse of the heat of residual gases. This combined with other technological advances and developments, such as the use of the organic Rankine cycle, or even the capture of CO<sub>2</sub>, may provide a reduction in the consumption of the fossil fuel and consequently the resulting impacts from its use.

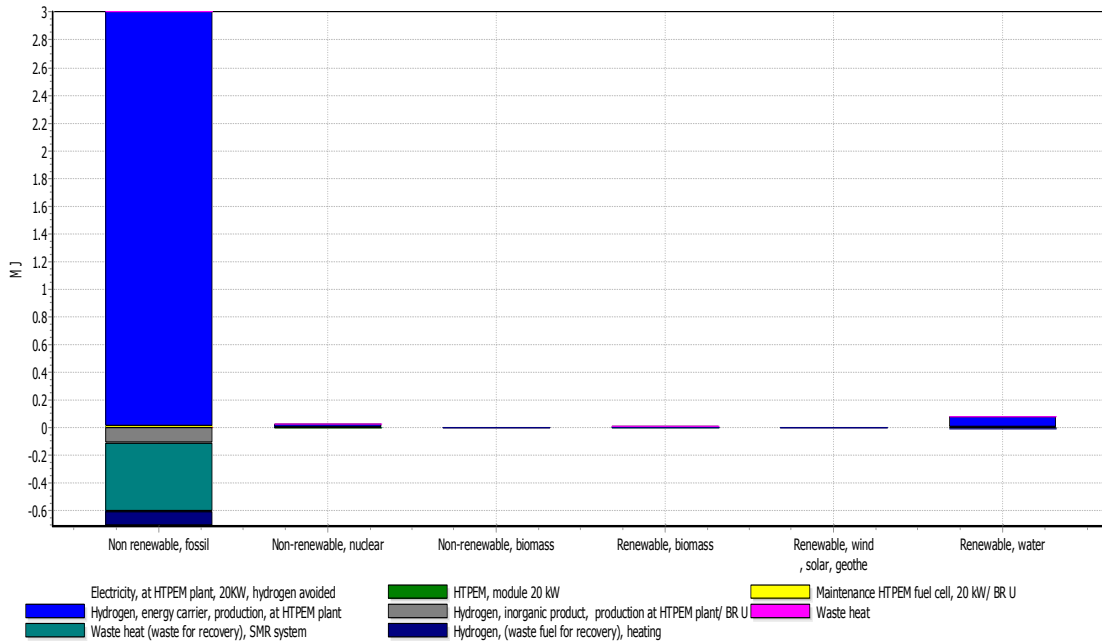


Fig. 6. Cumulative energy demand of the entire life cycle of the HT-PEM system

**Table 7. Absolute values of the contribution to the cumulative energy demand from the entire life cycle of the HT-PEM system**

Cumulative energy demand	Non-renewable (MJ)				Renewable (MJ)	
	Fossil	Nuclear	Biomass	Biomass	Wind, solar & geothermal	Water
Electricity, at HTPEM plant, 20KW, hydrogen avoided	<0	<0	<0	<0	<0	<0
HTPEM, module 20 kW	8.41E-03	1.62E-03	2.19E-08	1.34E-04	2.76E-05	3.20E-04
Maintenance HTPEM fuel cell, 20 kW/ BR U	1.53E-03	2.58E-04	9.03E-10	2.39E-05	4.24E-06	4.04E-05
Hydrogen, energy carrier, production, at HTPEM plant	2.99E+00	2.72E-02	3.39E-05	6.67E-03	2.85E-04	8.03E-02
Hydrogen, inorganic, production at HTPEM plant	-1.14E-01	-1.03E-03	-1.29E-06	-2.53E-04	-1.08E-05	-3.05E-03
Waste heat	<0	<0	<0	<0	<0	<0
Waste heat (waste for recovery), SMR system	-4.95E-01	-2.65E-03	-5.20E-06	-4.59E-04	-4.59E-04	-1.16E-03
Hydrogen, (waste fuel for recovery), heating	-1.03E-01	-5.50E-04	-1.08E-06	-9.53E-05	-6.91E-06	-2.41E-04

#### 4. CONCLUSION

Clearly, in the stage of hydrogen production, it was observed that the greatest contribution in all impact categories was associated with the use of natural gas in the reforming process itself and the fuel combustion in the furnace of the reformer. As a result, the use of this fossil fuel is also the largest contributor in the cumulative energy demand, characterizing in this way, the CED of the system as predominantly non-renewable. The steps associated with the operation of NG production, such as the NG production and transportation at high pressure, are the processes that have a higher environmental burden at this life cycle stage of the system.

It should be pointed out that the impacts associated with the greenhouse emissions gases, including eutrophication and acidification, are directly related with the energy consumption, specifically of natural gas in the reforming processes and the NG production, and indirectly due to the other fossil fuels consumption, both in the electrical energy production, as well as in raw material extraction and the materials processing and transportation.

Therefore, the development of processes that allow a better reuse of heat and residual gases and technologies such as the capture of CO<sub>2</sub>, for example, can provide a reduction in the consumption of the fossil fuel and wherefore the impacts resulting from its use.

#### CONSENT

All authors declare that written, informed consent was obtained from the other approved parties for the publication of this case report and accompanying images.

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#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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