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Journal of Power Sources 137 (2004) 239–247
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

LCA of a molten carbonate fuel cell system

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Received 2 December 2003; received in revised form 1 June 2004; accepted 7 June 2004
Available online30 July 2004

Abstract

Fuel cells are recognized by all the scientific community to be ultra low emission energy conversion systems, because the pollutants associated with their operation are very low in concentration, compared to traditional energy systems. On the other hand, fuel cells are mainly fed with hydrogen, a chemical component that is not available as a pure component, but it must be extracted from other compounds. This practice involves energy consumption and emissions related to extraction of fuel, hydrogen conversion, transportation and clean up.

In order to evaluate the environmental impact related to the energy production by the use of a fuel cell it is imperative to consider all the processes related to the fuel cell operation, and not only the FC operation itself.

Life-cycle assessment (LCA) is a unique approach for evaluating the environmental impact related to the whole life of the system, i.e. considering all the processes associated to the system itself, including construction and decommissioning.

In the present study a molten carbonate fuel cell (MCFC) system for electric energy production is considered and the related life-cycle environmental impact is considered. Finally a comparison between traditional energy conversion systems and the MCFC systems is conducted, in order to evaluate which are the advantages and the disadvantages that each supposed scenario can lead to.

Keywords: MCFC; LCA; Energy conversion systems; Environmental impact; Fuel cell; Hydrogen

1. Introduction

Fuel cells are considered to be ultra-clean energy conversion systems because, if hydrogen is used as fuel, they produce water, electric energy and heat, without any other significant pollutants. In order to assess fuel cells' environmental benefits, however, the whole life-cycle has to be considered. In fact, if it is unambiguous that operating life causes very low impact on the environment, on the other hand fuel cell production, disposal and impacts related to hydrogen production and transport probably have a non-negligible burden on the environment. Analyzing the whole life-cycle of the system it is possible to assess which part of the process presents the most relevant environmental load and to find out possible solution for the environmental performance improvements.

The present study is the development of a previous publication of the authors where the MCFC stack's life-cycle is analyzed [1]. Starting from those results, a complete MCFC system will be analyzed in the following sections.

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doi:10.1016/j.jpowsour.2004.06.005

2. LCA in brief

"Life-cycle-assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; and to identify and evaluate opportunities to affect environmental improvements" [2]. The assessment includes all the activities, processes, by-product connected to the system analyzed, including raw material processing, production, maintenance, recycling and disposal.

An LCA study is composed by three main components [3]:

(1) Life-cycle inventory (LCI): an objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste and other environmental releases incurred throughout the life-cycle of a product, process or activity [3].
(2) Life-cycle impact analysis (LCIA): A technical, quantitative, and/or qualitative process to characterize and assess the effects of the environmental loadings identified in the inventory component [3].
(3) Life-cycle improvement: A systematic evaluation of the needs and opportunities to reduce the environmental bur-

Nomenclature

F	Faraday constant (=96487 C/mol)
FC	fuel cell
GT	gas turbine
GW	global warming
I	electric current (A)
J	mean current density (mA/cm^2)
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LHV	lower heating value
MCFC	molten carbonate fuel cell
NG	natural gas
SCV	single cell voltage (V)
SOFC	solid oxide fuel cell
SR	steam reformer
U_f	coefficient of fuel utilization

dens associated with energy and raw materials use and waste emissions throughout the whole life-cycle of a product process, or activity [3].

The three LCA components are not necessary executed in the order given above. It is possible, for example, that during the inventory phase possible improvement conditions are found out, or that the LCA results show the importance of some processes or products, so that a more accurate LCI is required for a specific process/product. For these reasons, the LCA is said to be an iterative process.

3. System description

A typical fuel cell system is composed of a fuel processor, where a rich hydrogen gas is produced, the power section, composed of the fuel cell stacks and finally a power condition section where the dc electric current provided by the FC is converted into ac current, characterized by a desiderated frequency. A schematic representation of the system described is given in Fig. 1.

The fuel considered in the present work is natural gas, processed in a steam reformer (SR). The main chemical

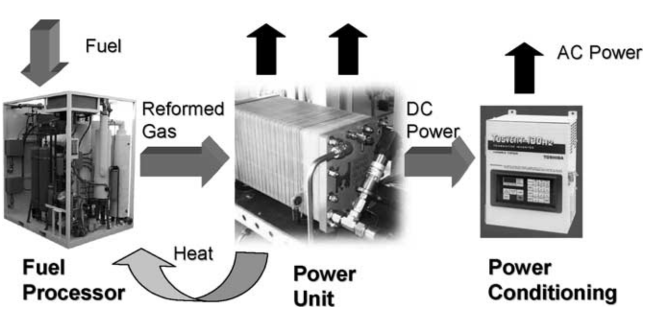

Fig. 1. Schematic representation of the system.

component is methane and the relative reactions that occur for H_2 production are [4]:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \quad (2)$$

The other hydrocarbons reactions are analogous to the previous ones.

Reactions (1) and (2) can be considered intermediate reactions of the following reaction (3), even thought CO can be present in the reformed final gas.

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \quad (3)$$

The previous reactions are endothermic, and so an external heat source is required. The reaction enthalpy at standard condition of reaction (1) is 206 kJ/mole, while for reaction (3) it is 165 kJ/mole [5]. Generally, additional burners provide the required heat. If the burners are fed by natural gas, the result is a conversion efficiency reduction of the system, in fact part of the natural gas sent to the fuel processor is not converted into hydrogen, but it is just combusted. Moreover this practice means that pollutants related with NG combustion are released into the atmosphere.

The power section is composed of MCFC stacks. The chemical reactions that occur are:

$$H_2 + CO_3{}^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)} \quad (4)$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \quad \text{(anode)} \quad (5)$$

$$CO_2 + \tfrac{1}{2}O_2 + 2e^- \rightarrow CO_3{}^{2-} \quad \text{(cathode)} \quad (6)$$

Giving the following global reaction:

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \quad (7)$$

It is outlying the scope of the present work to assess the operating condition and performances of the MCFC stack. For more details about fuel cells, operation and related technical issues, refer to [4].

Reaction (7) is exothermic, presenting a reaction enthalpy of 285.8 kJ/mole [4]. Obviously, this energy is not total released as heat, but a part is converted into electric energy and the rest into heat.

Considering that for every CH_4 mole, a number between 3 and 4 of H_2 moles are produced (depending on the reaction conditions of (1) and (2)), it is reasonable to suppose that the heat produced by the fuel cell is enough for the steam reforming. The problem is related to the heat transfer from the fuel cell section to the reformer. If high temperature fuel cells are considered, as in the present system configuration, thermal energy can easily be transferred from the outlet anodic and cathodic gases to the reformer section. A plant layout using this technical solution is illustrated in [7]. Another possible solution for heat recycling is the use of the so-called "internal reforming fuel cells". In this case, reactions (1)–(3) occur inside the cell itself, thus solving the heat transfer problem.

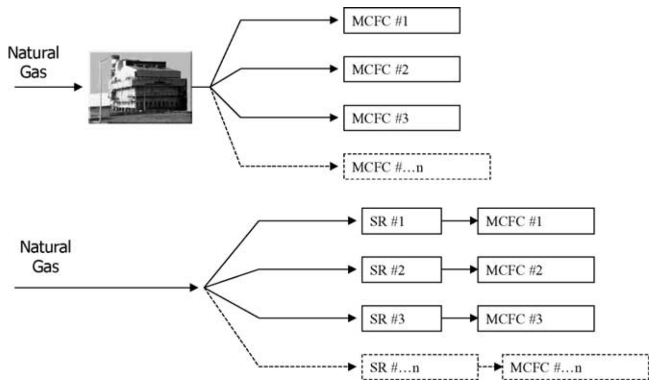

Fig. 2. Schematic representation of the two supposed scenarios.

In the present study, as better explained in the following sections, two hypotheses are made for the hydrogen generation:

(1) Hydrogen is generated in a large size SR industrial plant, and then it is delivered to the MCFC power section. In this case NG burners provide all the heat needed for the process.
(2) Hydrogen is produced recycling the heat produced by the MCFC section. In this second hypothesis, no additional NG is required for fuel processing, but the reformer section must be located near MCFC section, or the MCFC must be able to perform internal reforming. If external reformer MCFC are considered, the SR dimension must be quite smaller than that of the precedent scenario. SRs with reduced dimension are at the present time under development and optimization phase.

Fig. 2 gives a schematic representation of the two scenarios supposed.

4. LCA of the system

4.1. Scope and goal definition

As stated before, the scope of this study is to assess the impact associated to the whole life-cycle of a molten carbonate fuel cell system that uses natural gas as fuel.

The goals are:

- To find out the processes that mostly influence the environmental performance.
- To identify possible improvements for environmental burden reduction.

The functional unit is 1 kW h_e (=3600 kJ) produced by the system.

4.2. LCI

The MCFC stack production data were collected during an experimental campaign at the production facility, located in Italy. A complete description of those data can be found in [1].

As stated before, the fuel processor section is supposed to be a natural gas steam reformer. Data used for this process were derived from [7], where an actual SR plant is considered. Referring to Fig. 2, the plant analyzed in [7] reflects the first scenario, where hydrogen is produced in a large SR plant and then distributed to the MCFC location. In this case, the heat needed for reactions (1)–(3) is provided by dedicated burners, fed with natural gas. In the second scenario, the heat needed for the SR is provided by the MCFC itself, as product of reaction (7). This hypothesis is valid for both internal or external reforming fuel cells, even though data collected in [1] are relative to external reforming MCFCs. The main hypothesis is that emissions, energy consumption and resources depletion relative to NG extraction, transport and distribution is the same for both the scenarios. Moreover it is supposed that materials used for small size SR are the same of a large size SR. Efficiency variation, instead, is computed using data relative to a typical effluent gas composition [4].

Other important hypotheses are:

1. SCV = 0.5 V
2. $J = 200\,\text{mA/cm}^2$
3. Single cell area = $1\,\text{m}^2$
4. MCFC life-time = 40000 h
5. U_f=0.7.

The definition of coefficient of fuel utilization used is given in [8]:

$$U_f = \frac{I/2F}{H_2 + CO} \tag{8}$$

In Eq. (8), I represents the electric current provided, F is the Faraday constant, H_2 and CO represent the H_2 and CO inlet flow rates (mol/s).

From hypotheses 2 and 3, current value (I) is computed and coupled with hypothesis 1, the electric power is found to be 1 kW. In order to produce 1 kW h_e, i.e. the functional unit, the fuel cell must operate for 1 h.

The total cell life-time is considered to be 40000 h (assumption 4) and so the results obtained for MCFC stack production in [1] are dived by 40000.

Hypothesis 5 is then used to calculate the total amount of fuel needed by the system.

4.2.1. Scenario 1: one large size SR plant located in a remote area

In this scenario the NG is reformed in a large size SR, located in a remote area. The hydrogen produced is then distributed to the MCFC location.

Large size SR plant can be considered a consolidated technology, since it has been using for decades, and at the present time it represents the most common industrial hydrogen production practice.

Fig. 3 represents the scheme of the SR plant considered. The description of the SR is behind the scope of this work

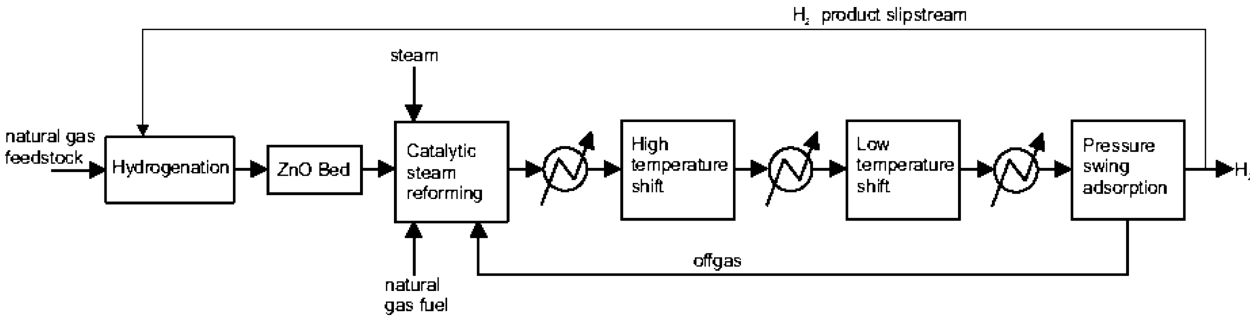

Fig. 3. Steam reforming process.

and can be found in [7]. The natural gas composition, considered for the analysis is reported in Table 1.

The results calculated in [7] for the SR take into account NG extraction, processing and transport; plant construction, operation and decommissioning.

According to [7], the most significant pollutant emitted is CO_2 (about 99% weight) and this quantity is mostly due to plant operation (84%). The major causes of this large amount of CO_2 are related to the reforming process itself, i.e. reactions (1)–(3) and to the NG combustion for heat generation.

The largest part of the emissions, excluding CO_2, is represented by methane. This is mainly related to possible NG fugitive emissions.

As will be better shown in the following sections, this scenario causes a large amount of emissions related to NG combustion and to hydrogen distribution. On the other hand, the advantage is the possibility of locating the SR plant in remote areas, far from the MCFC stack (that is generally located in an urban or commercial areas).

4.2.2. Scenario 2: small size SR located near the stacks

In this second scenario, the hydrogen reforming is conducted in a fuel processing section, located near the power section. The heat needed for the reforming reactions, is provided by reaction (7). The heat recovery is obtainable through a direct heat transfer (i.e. conduction and convention) from the fuel cell section to the fuel processing section, or cooling the outlet gases from anode and cathode. The first practice is achievable only if the SR operating temperature is lower than that of the power section. Modern reformers, in order to achieve a satisfactory efficiency, generally operate in a temperature range between 700 and 1100 °C, while MCFCs operate at about 650 °C [4]. For this reason, in order to obtain direct heat transfer, the reformer operating temperature must be lowered. Research on new materials are undergoing to achieve high efficiency steam reforming at low temperature. The second heat recovery solution, i.e. through the outlet gas cooling, is easily achievable because MCFC outlet gases temperature is generally quite enough. An example of a possible plant solution is given in [6].

Table 1
Natural gas composition

Component	% mole
Methane	94.5
Ethane	2.7
Propane	1.5
N_2S	0.8
CO_2	0.5

Table 2
Reformed gas composition [4]

Gas components	Reformer effluent (%)
H_2	46.3
CO	7.1
CO_2	6.4
CH_4	2.4
N_2	0.8
H_2O	37.0
Total	100

Whatever the technology solution considered is, this scenario allows to eliminate the problems (technical and environmental) related to the hydrogen processing for transportation (like compression or liquefaction) and it allows to reduce the CO_2 production, since no combustion occurs for hydrogen generation.

In order to compute the emissions related to this scenario, the operating emissions of the SR plant considered in the previous scenario have been replaced with emissions related to small size SRs. Table 2 reports the reformed gas composition considered [4]. Considering 0.7 as coefficient of fuel utilization (hypothesis 4 of the previous section), it is possible to compute the emissions related to this second scenario, considering the same impact due to construction, decommissioning for the SR of the previous scenario.

5. Results

In the following sections, results obtained for the two hypothesized scenarios are illustrated and compared. During the inventory phase, it is supposed that electric energy is provided by the Italian national grid.

During LCIA, data collected during the LCI phase are associated with category impacts. The methodology is quantitative and/or qualitative. “Impact assessment is presently under development and has, as yet, no commonly agreed-to methodologies” [2]. For this reason, in the present study, the authors decided to use a very easy approach, used by several authors, as for example [9]. On the other hand, using this approach most of the pollutants collected during the LCI are not considered. Almost all the detailed data collected during the inventory phase are instead considered using the Eco-Indicator-99 methodology [10]. This approach, however, is more complex and is much more subjective.

Following the approach of [9], the impact categories considered for the classification and characterization phases [2], are:

- Energy resources
- Global warming
- Acidification.

The first category is quantified, computing the energy requirement for the whole system life-cycle. The system related global warming (GW) is computed through CO_2-eq, while the acidification (A), through SO_2-eq.

In Table 3, the weight used for the definitions of CO_2-eq and SO_2-eq are reported.

5.1. Results for scenario 1

Fig. 4 shows the results obtained for scenario 1. As can be noted, the hydrogen production phase presents a relevant impact for both energy requirements and global warming. This result emphasizes the importance of evaluating the whole life-cycle system and related operations, in fact, if only the MCFC operation is considered, no relevant CO_2 emissions can be appreciated.

The high impact of H_2 production on energy resources is due to the energy requirements of the SR Plant; [7] reports an energy consumption of 1 MJ from fossil energy (on LHV basis) for every 0.66 MJ of hydrogen produced.

Analogous conclusions can be deducted for GW, in fact the CO_2 emissions for SR is 10.621 g_{CO_2}/g_{H_2}.

Table 3
Weighting factors for CO_2-eq and SO_2-eq

Substance	Factor
CH_4	21
N_2O	310
CO_2	1
$kg_{CO_2\text{-eq}} = 21 \times kg_{CH_4} + 310 \times kg_{N_2O} + kg_{CO_2}$	
SO_2	1
NO_x	0.7
H_2S	1.88
HCl	0.88
HF	1.6
$kg_{SO_2\text{-eq}} = kg_{SO_2} + 0.7 \times kg_{NO_x} + 1.88 \times kg_{H_2S} + 0.88 \times kg_{HCl} + 1.6 \times kg_{HF}$	

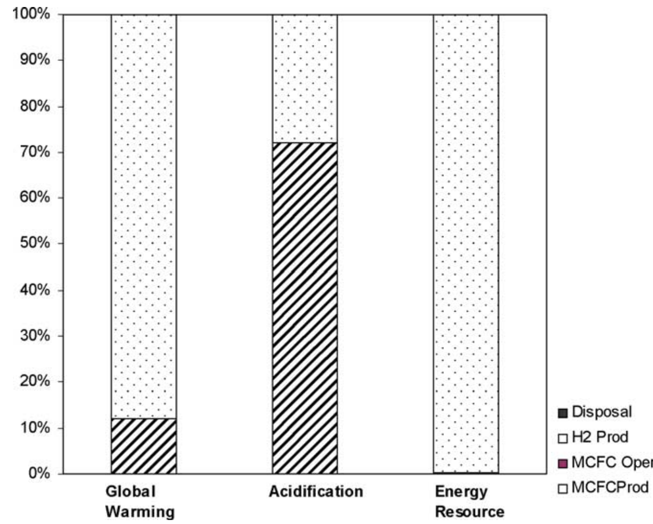

Fig. 4. Scenario 1 results.

The acidification, instead, is mainly due to the MCFC production phase. No significant contribution is given by the MCFC operation.

The pollutants related to the life-cycle of the considered MCFC system are very low in concentration, with the exception of CO_2. Considering that large size SR plant can be considered a consolidated technology [7], it is quite difficult to imagine future efficiency and environmental performance improvement. This means that other hydrogen production systems must be evaluated for achieving global CO_2 emissions reduction and high life-cycle conversion efficiency.

5.2. Results for scenario 2 and comparisons

In this second scenario, as stated in Section 3, no additional NG is burnt for providing the heat need for the NG reforming. The thermal energy required for reactions (1)–(3), in fact, is provided by the fuel cell reaction itself. As a result, less energy is needed and less CO_2 emissions are released. The burnt NG is evaluated in [7] to be 9.88% of the total NG. This quantity, along with the CO_2 emissions associated with the combustion, has been subtracted to the data of the previous scenario. Results, shown in Fig. 5, allow observing a sensible reduction of the hydrogen production GW related effect. The energy requirements reduction for H_2 production is about 28%, but it is still relevant against MCFC production and disposal energy requirements.

6. Comments and considerations

The results shown in the previous sections allow to assess the influence of all the process and sub-system related to the MCFC operation itself. In particular, Figs. 4 and 5 show the high environmental impact of hydrogen production via natural gas steam reforming. In the second scenario, i.e.

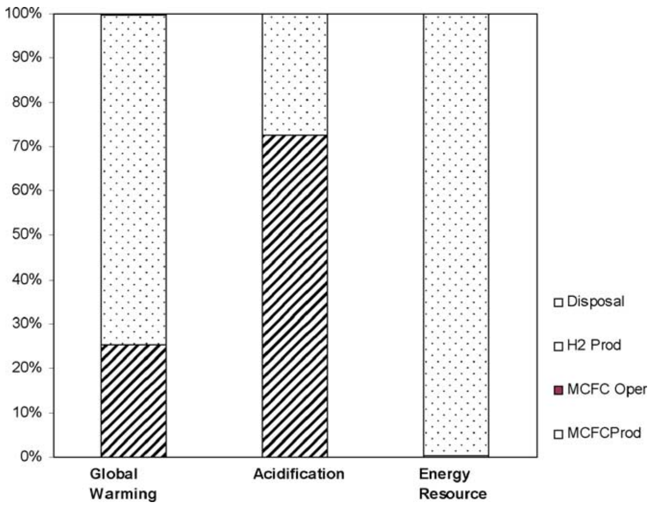

Fig. 5. Scenario 2 results.

when a reformer is located near the MCFC stack, it is possible to recover the heat released by the power section for the reforming process, thus avoiding CO_2 emissions related to NG combustion for thermal energy providing. Moreover, in this case, NG saving is achieved.

Scenario 2, in a life-cycle point of view, allows CO_2 emissions reducing, but, at the same time, it must be considered that the life-cycle analysis does not allow to consider logistic, political and social issues. Scenario 1, in fact, produces more pollutants, but it allows to locate the SR plant in a remote and ventilated area, where pollutants dispersion consequences on human health can be reduced. The scenario 2 related emissions, instead, even if are lower in concentration than those of scenario 1, are released near the power section. In a distributed energy scenario this means that the pollutants related to the hydrogen production are released in an area characterized by a human activity.

7. Effects of the electric scenario on the MCFC stack production phase impact

Since the electric energy required for the stack production is consistent [1], and traditional energy conversion systems present high environmental impact, it is useful to evaluate the environmental impact associated with the electric energy consumption for the stack production, if a part of the electric energy, instead of being provided by the national grid, is provided by MCFC systems itself. In other words, this section considers a future scenario, where part of the electric energy for the stack production is provided by the MCFC system itself, once in operation. The LCA conducted in [1] is recalculated, substituting the actual scenario for energy conversion in Italy with a future one, where 50% of the total energy is generated by the system previously analyzed. The obtained results show that, for these processes, small differences could be appreciated if the hydrogen is produced

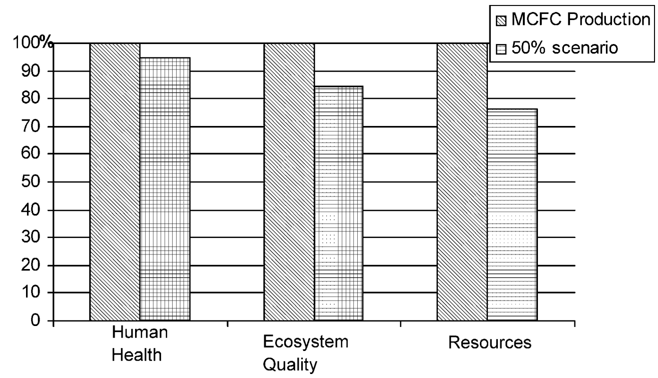

Fig. 6. Comparison between the current and possible future MCFC stack production.

according to the scenario 1 or the scenario 2, supposed in Sections 4.2.1 and 4.2.2. For this reason, in Fig. 6, it is reported only the results obtained for scenario 1, compared with the current situation for the MCFC stack production. The LCIA methodology used fort this analysis is the EI-99. The impact categories considered are human health, ecosystem quality and resources. In Fig. 6, the left boxes refer to the actual situation, while the right ones, refer to the improved scenario, where part of the electricity is generated by the MCFC systems ("50% scenario" in Fig. 6).

For all the considered categories a reasonable improvement is achievable considering the hypothetical future scenario, particularly in the resource category, due to the high electric conversion efficiency of the MCFC system, and, consequently, low fuel consumption.

8. Comparisons with traditional energy systems

The final step is comparing MCFC based energy systems with traditional ones. The comparison is performed between the two MCFC scenarios proposed in Section 4, a GT system and the actual electricity production scenario in Italy. Both the LCA models for the GT system and the Italian present power production have been developed by the Swiss Federal Institute of Technology, Zurich (ETH), and they are

Table 4
Comparison between the supposed scenarios

Substance	Italy mix	MCFC 1	MCFC 2	GT
Methane (g)	1.01	6.35	6.35	1.32
N_2O (μg)	12.00	0.48	0.48	5.63
CO_2 (g)	767.07	1150.61	528.43	1323.91
g CO_2-eq	788.28	1284.10	661.93	1353.37
SO_2 (g)	4.90	1.57	1.57	0.18
NO_x (g)	1.69	1.34	1.24	2.51
H_2S (μg)	0.86	0.01	0.01	4.07
HCl (μg)	23.30	0.34	0.34	0.63
HF (μg)	5.67	0.08	0.08	0.08
g SO_2-eq	6.11	2.50	2.43	1.94

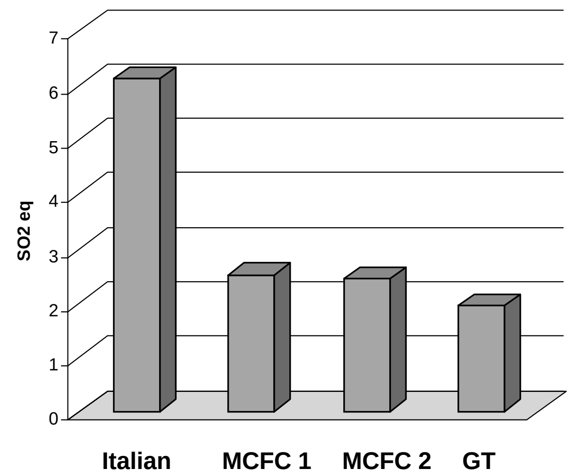

Fig. 7. Acidification effect comparison between the supposed scenarios.

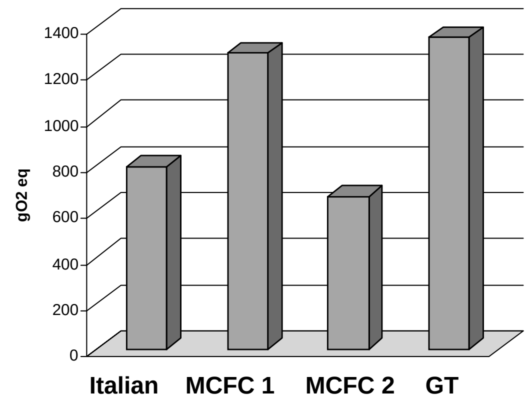

Fig. 8. Global warming effect comparison between the supposed scenarios.

embedded in the Sima-Pro Software database. These studies take into account the construction of power plants and all the other infrastructure connected to the life-cycle (i.e. grid connection, pipelines and so on), the operation of the power plants, the flue gases treatment and, finally, the waste management.

The comparison results are presented in Table 4 and Figs. 7 and 8.

Fig. 7 shows the SO_2-eq emitted by the three systems considered. As can be noted, the MCFC system usage can lead to a relevant SO_2-eq reduction in Italy. Compared to actual GT power plants, instead, the total amount of SO_2-eq is not reduced, even if less SO_2 is released. This is because of the high concentration of acidification effect gases during the MCFC production phase and during the steam reforming, as shown in Fig. 4. Further environmental improvements and analyses should focus on these two crucial life-cycle phases.

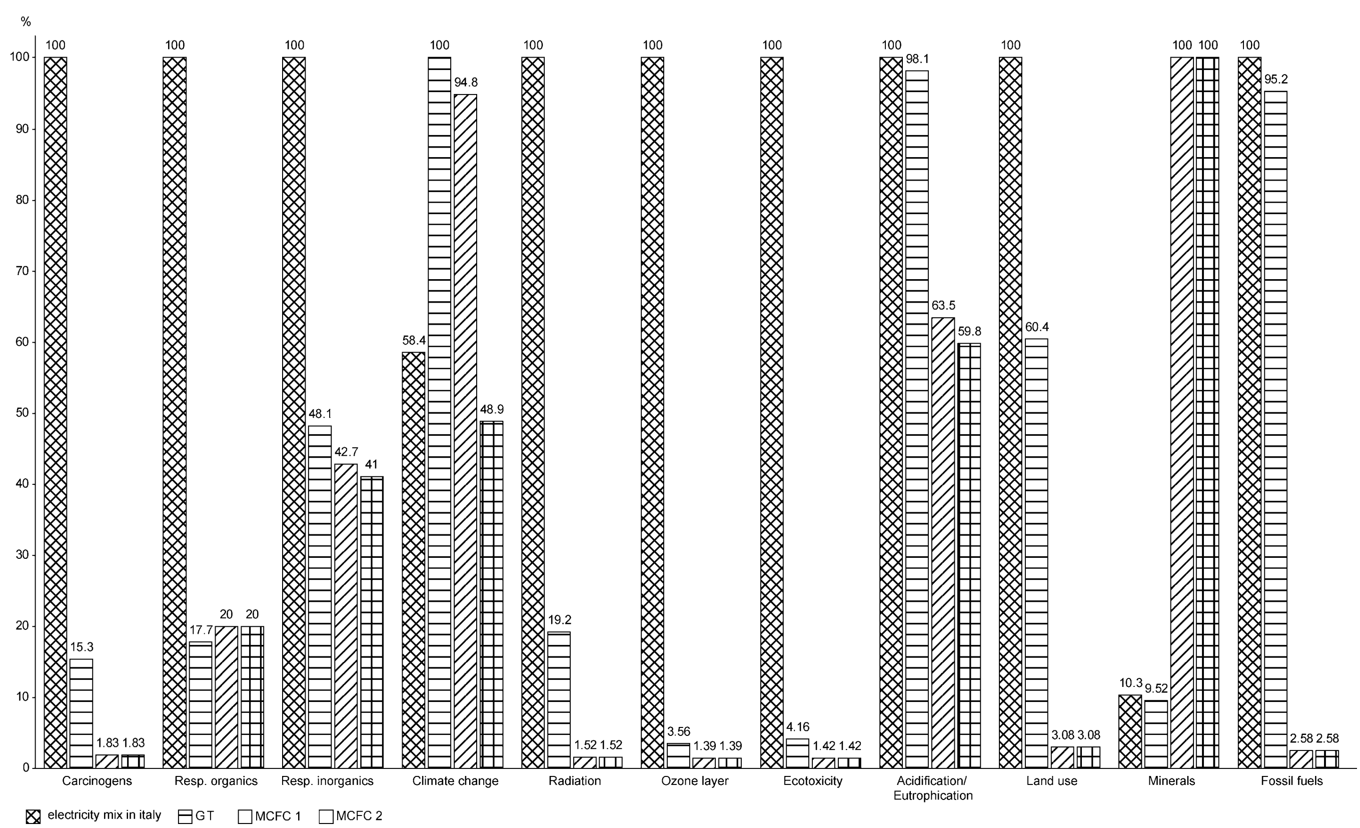

Fig. 9. Comparison between the supposed scenarios, according to the EI-99 methodology.

For what concern GW gases, and in particular CO_2, Fig. 8 and Table 4 show how the hydrogen production phase for the entire life-cycle environmental performance is important. If H_2 is produced in a large size SR plant, in fact, the total amount of GW gases would increase in Italy, rather than diminishing. This result is of particular importance, since fuel cells are generally considered very important instruments for GW gases reduction just because their operational activity releases few or zero CO_2. Adopting a SR with energy recovery from the FC power section itself, instead, the CO_2 and the GW gases are reduced. In any case the steam reforming of NG must be considered as a transitional practice for hydrogen generation, since at the present time this can be considered a mature technology and it is difficult to imagine significant improvements in future years. High environmental performance can be predicted for renewable energy hydrogen generation systems coupled with FCs, like for example biomass or waste gasification. Nevertheless, the NG steam reforming can play a significant role during the "switching" phase, from a fossil fuel based economy to a hydrogen economy, since it requires low investment costs and the present NG facility can be used for fuel delivering.

Figs. 7 and 8, however, show LCI results of just some kinds of pollutants. In Fig. 9 it is possible to observe results obtained with the EI-99 methodology. Comparing Fig. 7 with Fig. 9, it is evident that different results are obtained with EI-99 methodology for acidification, while results obtained for climate change in Fig. 8 are comparable with those of Fig. 9, confirming the necessity of finding alternative hydrogen production systems. Fig. 9 also shows the low fuel requirements associated with MCFC systems, due to their high-energy conversion efficiency, while mineral consumption is still high due to the fact that at the present time no nickel is recycled for MCFC stack production. The EI-99 presents a further weighting phase, by which it is possible to group all the results and to obtain a unique single score. This step is very subjective [10], but can give a global score associated to the life-cycle of each considered scenario. The results of this further step are reported in Fig. 10; the measure unit is mPt, developed and described in [10].

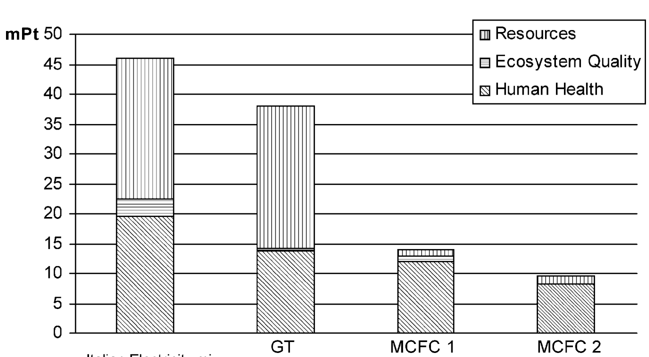

Fig. 10. Weighting phase results, according to the EI-99 methodology for the supposed scenarios.

9. Conclusion

In the present study two different MCFC system scenarios fed with steam reformed natural gas were considered. In the first case, hydrogen is produced in a large SR plant and then delivered to a MCFC system. In the second one, SR is performed near the MCFC power section, so that the heat recovery for SR is feasible. Results showed that, even if MCFC operating life presents quasi-zero emissions, a crucial role is played by the hydrogen production. If SR is conducted according to the first scenario, the CO_2 emissions increase, while a reduction can be achieved through the second scenario.

Since all the other beneficial environmental aspects associated with MCFC, and in general with FC, are confirmed, further improvement must be made for the hydrogen generation practice, considering low emissions hydrogen generation processes, like for example biomass or waste gasification. This practice is, moreover, in agreement with the European and American political decision of reducing the total oil demand.

Acknowledgements

The Authors would like to thank Francesco Zepparelli for the contribution given during his MS. Thesis preparation.

Very important was also the kind collaboration of Dr. Giovanni Pasquale and Dr. Cristina Amelio during the LCI phase.

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