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Life-cycle-assessment of fuel-cells-based landfill-gas energy conversion technologies

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Abstract

Landfill-gas (LFG) is produced as result of the biological reaction of municipal solid waste (MSW). This gas contains about 50% of methane, therefore it cannot be released into the atmosphere as it is because of its greenhouse effect consequences. The high percentage of methane encouraged researchers to find solutions to recover the related energy content for electric energy production. The most common technologies used at the present time are internal combustion reciprocating engines and gas turbines. High conversion efficiency guaranteed by fuel cells (FCs) enable to enhance the energy recovery process and to reduce emissions to air, such as NO_x and CO. In any case, in order to investigate the environmental advantages associated with the electric energy generation using fuel cells, it is imperative to consider the whole "life cycle" of the system, "from cradle-to-grave". In fact, fuel cells are considered to be zero-emission devices, but, for example, emissions associated with their manufacture or for hydrogen production must be considered in order to evaluate all impacts on the environment. In the present work a molten carbonate fuel cell (MCFC) system for LFG recovery is considered and a life cycle assessment (LCA) is conducted for an evaluation of environmental consequences and to provide a guide for further environmental impact reduction.

Keywords: MCFC; LCA; Energy recovery; Environmental issue

1. Introduction

Fuel cells (FCs) are electrochemical devices that allow to obtain electric energy and heat through reaction of a rich hydrogen gas and an oxidant (generally air). The chemical product is water. Since no combustion occurs inside the fuel cell, all the combustion environmental consequences, in terms of NO_x, CO_2, CO and other pollutants are drastically reduced. The use of fuel cell in the automotive sector, for example, seems to be very promising for pollution reduction in urban areas. For stationary applications, fuel cells are interesting because of their high efficiency, low pollutants emissions and the possibility of realizing combined heat and power production (CHP) solutions. Other fuel cells applications are represented by micro-fuel cells for electronic devices, such as cell phones, laptop or military equipment.

Advantages related to energy savings and oil dependence reduction are related to the high energy conversion efficiency, while most of the environmental advantages are related to the absence of the combustion.

In any case, in order to assess the real environmental advantages of fuel cells, it is vital to consider the whole life cycle of the systems, including power plant construction and decommissioning, hydrogen production and electric energy distribution.

In a previous work [1], the authors conducted an LCA of a complete molten carbonate fuel cell (MCFC) power plant, fed by reformed natural gas. The results of the study showed that hydrogen production has a relevant impact on the environment. In fact, while the MCFC section operates with negligible emissions, the SR does not, in particular for what concern CO_2 emissions. Possible improvement in MCFC system can be obtained using renewable energy sources for hydrogen production.

LFG is a gas that is naturally generated during wastes digestion in landfills. This gas presents high methane concentration, and so an interesting CV. The effect of methane released into the atmosphere reflects in an GW increase.

For these reasons, the use of LFG as fuel presents the dual beneficial effect of energy recovery from a renewable sources of energy (in fact wastes can be considered as a renewable sources of energy, since wastes are produced continuously) and greenhouse effect reduction connected to the methane emissions avoiding.

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Nomenclature

CHP	combined heat and power production
CV	calorific value
FC	fuel cell
GW	global warming
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LFG	landfill-gas
MCFC	molten carbonate fuel cell
NG	natural gas
SCV	single cell voltage
SR	steam reformer

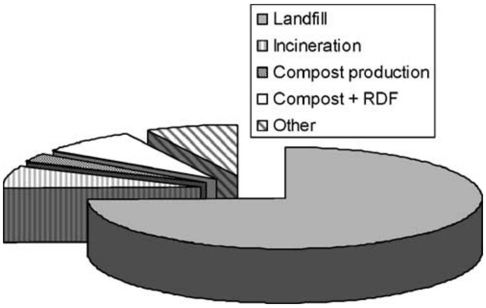

Fig. 1. Italian waste disposal scenario [2].

In Europe, and in particular in Italy, the use of landfills represents the most common practice for waste disposal, as shown in Fig. 1 [2]. For this reason, a complete analysis of the system is conducted.

Results are presented as a comparison between LFG fuelled MCFC, steam reformed natural gas MCFC and traditional energy conversion systems.

2. About LFG

Landfills produce the so called landfill-gas (LFG) as by-product of wastes fermentation. The production process can be divided into three main phases. In the first one the presence of oxygen induces aerobic fermentation. Progressively, oxygen is reduced to CO_2 and the second phase takes place. This phase is called “acid fermentation” and it is mostly anaerobic. H_2 and CO_2 reach the highest concentration. During phase three, bacteria digest organic components, thus generating methane. After this third phase, LFG composition is constant along with time.

Table 1 shows typical composition of an Italian LFG located in Rome area [3]. As can be seen, the CH_4 content is quite high; moreover the landfill considered is the largest in Europe, and eventual environmental benefits involved with energy recovery would represent a strong environmental enhancement not only for the area near Rome, but the benefits would be on a national or European level.

Table 1
Reference composition of Italian LFG [3]

Substance	
CH_4 (vol.%)	58.01
CO_2 (vol.%)	41.38
O_2 (vol.%)	0.13
N_2 (vol.%)	0.48
H_2O (vol.%)	0.41
H_2S (mg/m^3)	110
HCl (mg/m^3)	0.26
H_2F (mg/m^3)	<0.1
NH_3 (mg/m^3)	<0.1
Siloxanes (mg/m^3)	12

3. What is LCA?

“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” [4]. The assessment includes all the activities, processes, by-products connected to the system analyzed, including raw material processing, production, maintenance, recycling and disposal.

An LCA study is composed of three main components [5]:

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 [5].
2. Life cycle impact analysis: a technical, quantitative, and/or qualitative process to characterize and assess the effects of the environmental loadings identified in the inventory component [5].
3. Life cycle improvement: a systematic evaluation of the needs and opportunities to reduce the environmental burdens associated with energy and raw materials use and waste emissions throughout the whole life-cycle of a product process, or activity [5].

The definition given above is close to that of the ISO 14040 [6]. The ISO standards provide a series of codes for LCA; these are from ISO 14040 to ISO 14043 [6–9].

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 process or product, so that a more accurate LCI is required for that process/product.

4. System description

The system considered is composed of a LFG collection system, a fuel processor section and a MCFC power section.

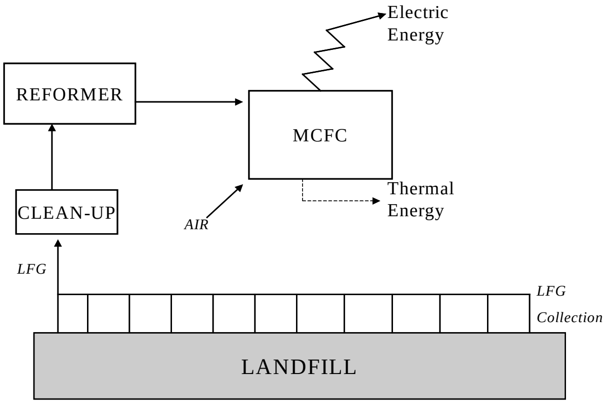

Fig. 2. Schematic representation of an MCFC–LFG system.

Fig. 2 shows a schematic representation of an MCFC–LFG system. Biogas is collected from the landfill and sent to a clean-up system, where substances, like chlorine, sulfur compounds, ammonia and dust are removed to prevent MCFC and SR reduced performance or failure. The "cleaned" gas is then reformed in the SR. A hydrogen rich gas is obtained, ready to be used as anodic gas in the MCFC section. Fig. 3 represents a possible plant solution. LFG coming from the landfill is processed in a clean-up system. This system requires hydrogen for the chemical process and heat to warm the gas. The Hydrogen is received by the reformer section, while the heat is recycled through an heat exchanger, whose hot side is fed with outlet cathodic gas. After the reforming process, the gas is sent to the MCFC anode side. The outlet gas still contains CO and H_2, because fuel utilization is not 100%. These substances are oxidized in a catalytic combustor. The high heat content of the outlet gas is used to provide thermal energy needed for reforming reaction. Before re-entering the stack, gas must be cooled to an adequate temperature depending on the FC operation conditions. This is achieved in an heat exchanger that transfers part of the cathodic heat content to the water that must be sent to the SR. The cathodic outlet gas is instead used to raise air temperature needed for the catalytic combustion and to raise the LFG temperature.

5. Scope and goal definition

The main purpose of the present study is to evaluate environmental impact associated to the whole life-cycle of a LFG energy conversion system based on MCFC. Results obtained allow to understand if the process can really be considered environmental friendly. The final step of the analysis is the comparison with an MCFC fed with steam reformed NG and with traditional energy systems.

The functional unit used in the study is 1 kWh_e produced by the system.

6. LCI

LCI is conducted referring all the input streams and emissions to the functional unit. The LCIA of the MCFC stack production is taken from [10]. The hypotheses for the MCFC stack are the same used in [1], and they are here reported for an ease reading:

1. SCV $= 0.5$ V,
2. $J = 200\,\text{mA/cm}^2$,
3. single cell area $= 1\,\text{m}^2$,
4. MCFC life-time $= 40{,}000$ h,
5. $U_f = 0.7$.

LCA of MCFC stack considers all relevant data for stack construction, operating and decommissioning.

LFG production environmental impact is neglected in this study, because it is considered to be a process that would exist anyway, even when no energy recovery is conducted for LFG. In other words, waste disposal is independent of energy recover, i.e. it is a process that is not conducted for energy conversion, but simply because waste must be disposed. Additionally, as reminded before, methane is a greenhouse gas and so, if no system is used for LFG utilization an GW effect is generated. For this reason, the amount of methane used in the present system is considered as avoided emissions.

As shown in Fig. 3, the heat needed for steam reforming is provided by the cathodic outlet gas and so no additional

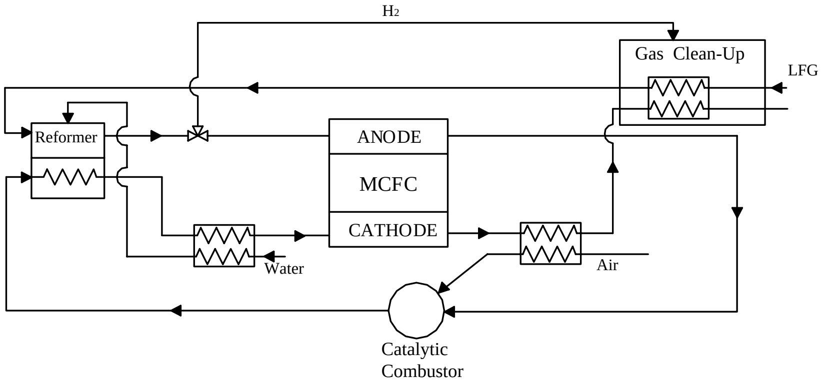

Fig. 3. Possible plant layout.

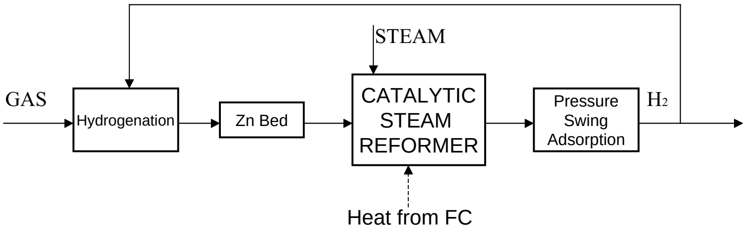

Fig. 4. Steam reforming process.

methane must be burnt for SR. In [1], in fact, it was observed that this practice allows to drastically reduce GW emissions.

Data for SR production and disposal are taken from [11], while emissions and related energy and materials consumption for the operating life are deducting from [12], considering the LFG gas composition of Table 1. A schematic representation of the SR process considered is reported in Fig. 4.

7. LCIA

The data collected during the inventory phase must be grouped and a consequence for the environment must be deducted.

As noted in [13], LCIA presents some limitations. For example, LCIA does not take into account the environment spatial and time variation and emissions, wastes and resources use are combined over time and different places. Moreover, LCIA models are usually based on a linear dependency between the system activities and the environment. Fig. 5 shows the relation between LCI and LCIA [13]. The data collected during the LCI are assigned to different impact categories (classification), like, for example, GW, acidification, eutrophication, etc. According to the methodology chosen for the LCIA, there are different models to quantify the related impact (characterization phase). The final result is an endpoint for each category considered. Much of the controversy over LCIA is in the models definition.

In the present work, data collected are implemented in a commercial software, *Sima-Pro*. The LCIA methodology adopted is the Eco-Indicator 99 technique (EI-99) [14]. This methodology presents different subjective elements, especially for the characterization. On the other hand, the EI-99 takes into account a huge variety of impact categories, and so most of the emissions, waste and resource related to the life-cycle are taken into account.

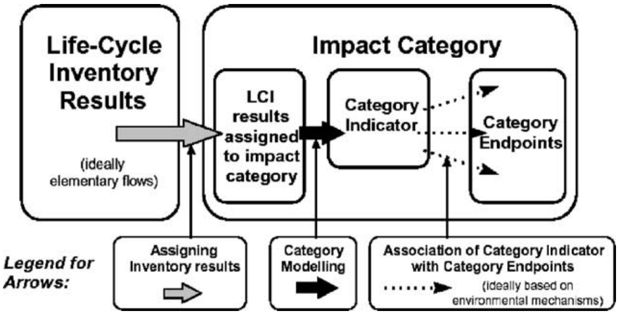

Fig. 5. Relation between LCI and LCIA [13].

In order to have more objective instruments for LCIA, together with the EI-99, LCI data are connected to impact assessment using another, very easy and objective technique. $CO_{2\text{-equivalent}}$ and $SO_{2\text{-equivalent}}$ along with the total energy requirements are computed. The airborne emissions considered, along with the weight considered to calculate these two parameters are shown in Table 2. The objective of this approach is conversely paid by the fact that only three environmental consequences are considered and quantified (GW, acidification and energy requirements). The two approaches chosen can be considered both useful for life-cycle impact evaluation and so both the results are reported, according to the specific case analyzed.

Fig. 6 shows the LCIA results obtained when $CO_{2\text{equivalent}}$ and $SO_{2\text{equivalent}}$ are used to quantify the GW and the acidification effects. As can be noted, the CH_4 emissions avoided recovering LFG have a benefit effect that is much larger than the direct GW emissions related to the steam reforming, so that the steam reforming process presents a negative impact value (i.e. the benefits related to the avoided emissions are more evident than the direct emissions consequences). This result, as will be better explained in the following section, makes LFG a very interesting fuel for fuel cells, considering that the largest impact for GW category is represented by the H_2 production phase [1]. As far as acidification is concerned, hydrogen production contributes with about 35% of the total life-cycle impact, while the most significant contribution is due to MCFC production phase. Finally the energy

Table 2
Weight used for the $CO_{2\text{equivalent}}$ and $SO_{2\text{equivalent}}$ definitions

Substance	Factor
CH_4	21
N_2O	310
CO_2	1
$\text{kg}_{CO_2\text{equivalent}} = 21\text{kg}_{CH_4} + 310\text{kg}_{N_2O} + \text{kg}_{CO_2}$	
SO_2	1
NO_x	0.7
H_2S	1.88
HCl	0.88
HF	1.6
$\text{kg}_{SO_2\text{equivalent}} = \text{kg}_{SO_2} + 0.7\text{kg}_{NO_x} + 1.88\text{kg}_{H_2S} + 0.88\text{kg}_{HCl} + 1.6\text{kg}_{HF}$	

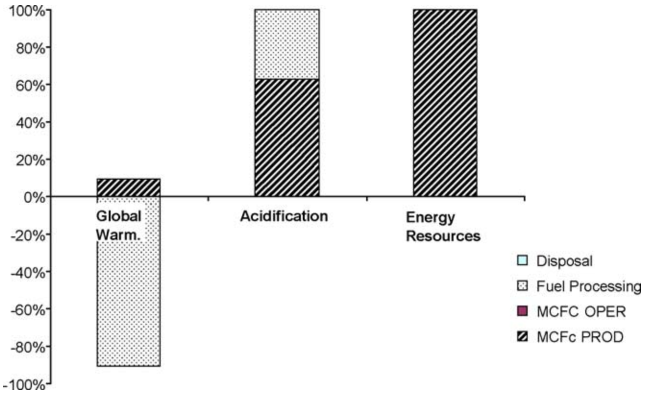

Fig. 6. LCIA results using $CO_{2equivalent}$ and $SO_{2equivalent}$.

required for the systems is almost totally due to the MCFC production phase, in fact no resource is consumed for LFG production and the energy requirement for the system operating is significantly less than that required for the stack production.

8. Comparison with MCFC fueled by NG steam reformed

In the present section, results obtained in the previous section are compared to that obtained for a MCFC system using steam reformed NG [1].

Fig. 7 shows the comparison for all the pollutants considered for the GW, i.e. CH_4, N_2O and CO_2 and finally the relative $CO_{2equivalent}$.

As can be expected, the methane emissions are drastically reduced, in fact for the LFG recovery system methane avoided emissions are taken into consideration, thus obtaining negative CH_4 emissions. N_2O are almost the same, while CO_2 emissions are reduced of about one third. The result is a drastically reduction in $CO_{2equivalent}$ emissions.

Table 3
Italian electricity production scenario

Power plant type	Energy supplied (%)
Oil fed	49
Gas fed	18.6
Coal fed	10.4
Hydropower	20.5
Storage hydropower	1.5

As far as acidification is concerned, results are presented in analog way in Fig. 8. In this case, most of the benefits are mainly related to the NO_x emission reduction. Finally, it is useful to compare the two MCFC scenarios to the traditional energy conversion systems for electricity production. The scenario considered for the traditional energy conversion systems is that relative to the Italian energy production situation. Table 3 illustrates the Italian power plant types used in the study. The Swiss Federal Institute of Technology-Zurich (ETH) developed the model for LCA of traditional energy systems and this model is embedded in the Sima-Pro database. Results obtained are presented in Fig. 9, using the EI-99 methodology for LCIA. Results are presented in the “damage assessment” form [14], i.e. the referred to the system with the highest impact. Categories considered for LCIA are “human health”, “ecosystem quality” and “resources”, each of those composed by sub-categories, as shown in Table 4. Fig. 9 shows clearly the advantage of LFG use in an MCFC systems compared to NG external steam reforming MCFC system and to the current Italian situation. It is interesting to note that, even if two different LCIA methodologies have been used for NG-reforming and LFG MCFC systems, the results obtained are in prefect accordance (Figs. 7–9).

Once again, in fact, the results demonstrate the environmental benefits related to fuel cells. These advantages are much more tangible if LFG is used as fuel.

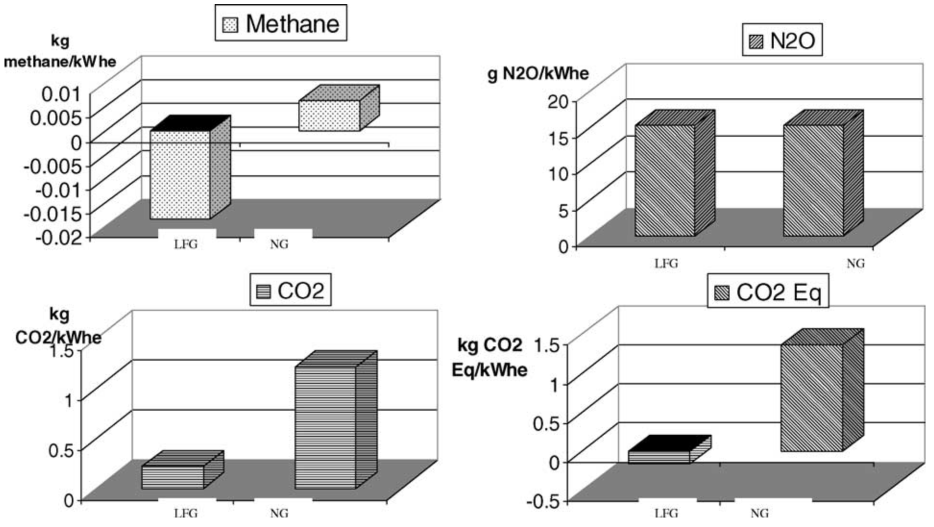

Fig. 7. Global warming emissions comparison between LFG–MCFC and NG–MCFC systems.

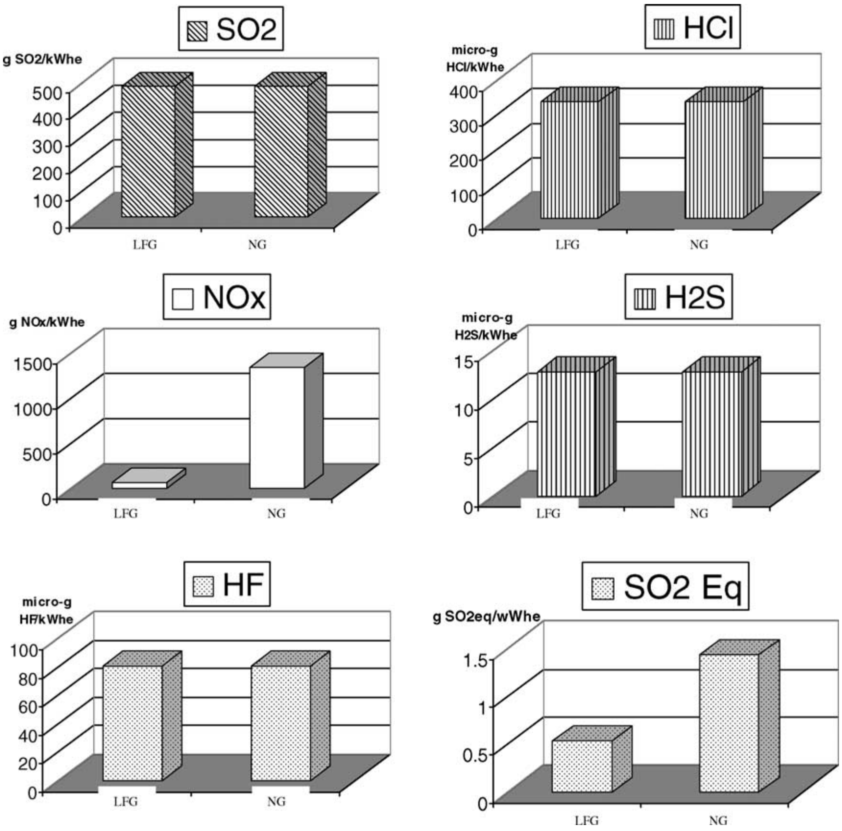

Fig. 8. Acidification emissions comparison between LFG–MCFC and NG–MCFC systems.

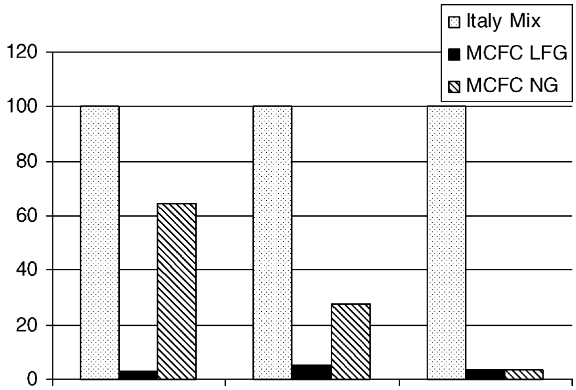

Fig. 9. Eco-Indicator 99 results.

Table 4
EI-99 categories and sub-categories

Impact categories	Sub-categories
Human health (HH)	Carcinogen effects, respiratory effects (organic), respiratory effects (inorganic), climate change, radiation, ozone depletion
Ecosystem quality (EQ)	Ecotoxicity, acidification/eutrophication, land use
Resources (R)	Minerals, fossil fuels

Nevertheless, it must be noted that even if LFG use allows to drastically reducing environmental burden, it is not possible to think to replace all the energy resources with LFG. What is feasible, instead, is to replace part of the current energy from fossil fuels with LFG, in order to obtain emissions reduction and a decrease in resources consumption.

9. Conclusion

An LCA of LFG–MCFC system was conducted and the results were presented using different LCIA methodologies. Even if the two methodologies considered are structurally different, the results obtained are comparable. Both of them, in fact, show a dramatic improvement obtainable using LFG as fuel. These benefits are mostly due to methane emissions avoiding and MCFC's high efficiency.

Compared to a MCFC system fuelled with steam reformed NG, the MCFC–LFG system allows to us obtain a relevant reduction in GW gases and NO_x reduction. Finally, the comparison with traditional systems shows impressive environmental benefits. Although it is not possible to replace all the energy resources with LFG or to replace all the energy systems with fuel cells, a partial substitution would bring substantial emissions reduction and a decrease in resources consumption.

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