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# Comparison of different possibilities for biogas use by Life Cycle Assessment

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## Abstract

This contribution aims at introducing the innovative possibility of biogas use through its upgrading to biomethane and to evaluate this process from an environmental point of view, by applying Life Cycle Assessment (LCA), in comparison with direct use of biogas in energy conversion devices, namely, internal combustion engines and molten carbonate fuel cells.

Due to their high energy conversion efficiency, fuel cell use resulted the solution with the best environmental performances, followed by internal combustion engines and the by biomethane production. However, when thermal energy is not recovered in the case of both fuel cell and internal combustion engine, the differences with respect to the biomethane case are strongly reduced.

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*Keywords:* biogas; biomethane, internal combustion engine; molten carbonate fuel cell; high pressure water scrubbing; life cycle assessment.

## 1. Introduction

Biogas is generated by anaerobic biodegradation of organic materials, thus, it is produced, as major sources, by municipal solid waste landfills, sludge digester in wastewater treatment plants and biogas digester using biowaste, manure and also energy crops. Biogas is mainly composed by methane ($CH_4$) and carbon dioxide ($CO_2$), but it may contain also significant quantities of undesirable compounds such as hydrogen sulfide ($H_2S$), ammonia ($NH_3$) and

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siloxanes, namely depending on the biogas source. Biogas was produced in the European Union for about 12050 ktoe in 2012 [1] and is gaining large interest internationally among renewables.

There are many different biogas utilization pathways [2]: direct use in internal reciprocating combustion engine (ICE), gas turbine, organic Rankine Cycle, fuel cells, or indirect use through preliminary upgrading to biomethane for transport fuel or injection into the public natural gas grid.

As far as direct use is concerned, biogas combustion in ICE is the most widespread alternative at international level, also offering the possibility of Combined Heat and Power (CHP) production. Upgrading to biomethane is quite common in Northern Europe and is gaining increasing interest worldwide, as biomethane – a renewable gas – can substitute natural gas, thus contributing in the future to decrease the strong foreign dependency of several countries from this fossil source. However, in order to obtain biomethane, and to respect the quality standards defined at national level from many European countries – an European standard is not yet available, but the CEN is presently working at this task – several pollutants must be removed from the biogas (sulphur compounds, siloxanes, particulate matter) and, in particular, techniques to remove $CO_2$ must be applied, in order to increase the $CH_4$ content generally over 96% in volume. Obviously, such upgrading processes require the use of energy and materials, whose amount and quality depend on the selected $CO_2$ removal technique. Several processes are commercially available for this purpose, among which physical and chemical absorption, adsorption and membranes. High Pressure Water Scrubbing (HPWS) is the most commonly used, presently, in those plants that perform biogas upgrading.

In this study different possibilities of utilization of biogas were considered, modeled and evaluated from the environmental point of view, by applying a Life Cycle Assessment (LCA) approach.

In the following, the analysis that was carried out is reported and described according to the LCA phases [3]: goal and scope definition, inventory analysis, impact assessment and interpretation and improvement, in term of sensitivity analysis.

## 2. LCA: goal and scope definition

The goal definition is the first phase of the LCA in which the purpose of the study is described. It identifies and defines the object of the assessment.

The purpose of this LCA study is to compare the environmental impacts and resource consumption of three different scenarios using biogas as input. The selected and compared options for biogas use are:

- biogas direct use in ICE for the CHP production (Fig. 1a);
- upgrading of biogas to a gas of the same quality of natural gas, named biomethane, to replace all the purposes where natural gas is used. This is done by HPWS $CO_2$ removal and injection of biomethane into the natural gas grid (Fig. 1c);
- biogas direct use in molten carbonate fuel cell (MCFC) for the CHP production (Fig. 1b).

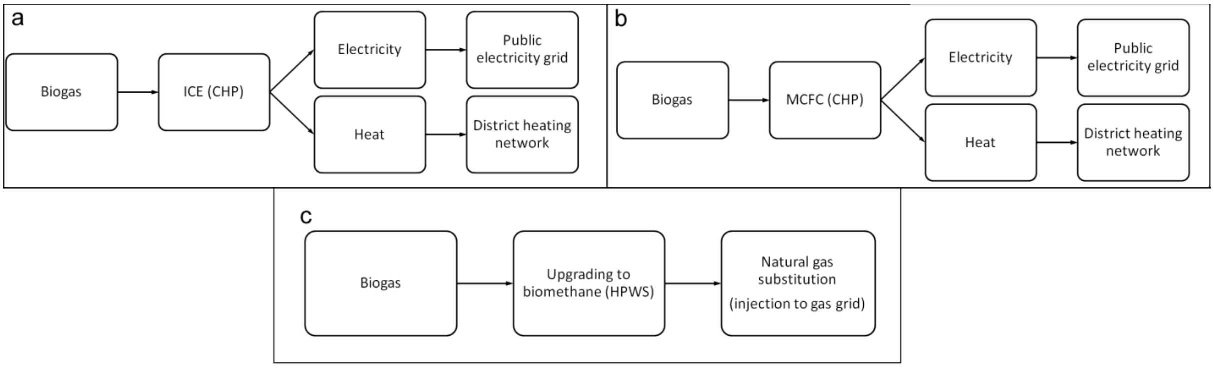

Fig. 1. (a) direct use of biogas in ICE; (b) direct use of biogas in molten carbonate fuel cell; (c) upgrading of biogas.

Even if the MCFC use is not yet so commonly used, this is a quite interesting application, due the typical high conversion efficiency. For this reason this third possibility was also included in the comparison.

According to the goal of the study the selected functional unit of the LCA is 1 Nm$^3$ (at 101325 Pa and 0 °C) of biogas input to the system. The biogas composition chosen for this study is reported in Table 1 and it is kept as a constant input for the three analyzed scenarios, allowing their direct comparison.

Table 1. Assumed biogas composition.

| Component | Unit | Value |
|---|---|---|
| $CO_2$ | vol. % | 38,97 |
| $CH_4$ | vol. % | 60,00 |
| $H_2S$ | vol. % | 0,03 |
| $N_2$ | vol. % | 0,50 |
| $O_2$ | vol. % | 0,50 |

The system boundary includes acquisition of raw materials and emissions for the main processes; transportation; production and use of fuels, electricity and heat; use and maintenance of equipment; disposal of process wastes and products.

Additional assumptions are: the production phase of biogas and impacts related to it were not included; distribution and transportation of biomethane were not included; the impacts related to the use and maintenance of equipment were considered, but not those resulting from their manufacture; desulphurization impacts were not considered; waste disposal processes, such as wastewater and exhausted lubricating oil, were considered; the end of life disposal of equipment was not considered.

## 3. LCA: inventory analysis

In this phase, all the inputs and outputs occurring in the life cycle of the systems previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary either into or out of the system itself.

### *3.1. ICE scenario*

In this scenario the use a co-generation unit with an ICE for electricity and heat generation was assumed. The main parameters assumed for the technical characterization of the ICE are reported in Table 2, as derived from data in Table 3.

Table 2. Technical parameters assumed for the ICE.

| | Vale | Source |
|---|---|---|
| Electrical efficiency | 37% | Average from literature values (Table 3) |
| Parasitic electric consumption | 4% | Average from literature values (Table 3) |
| Thermal efficiency | 50% | Average from literature values (Table 3) |
| Emissions | - | Calculated and retrieved from literature (Figure 2) |
| Maintenance, including lubricating oil | - | ecoinvent |

The inputs to the engine are represented by biogas, lubricating oil and maintenance, while the outputs are divided into products - electricity and heat - emissions and waste (Fig. 2).

The data for the gas engine maintenance were obtained from the ecoinvent database and includes impacts related to: reinforcing steel, burned light fuel oil, electricity, transport.

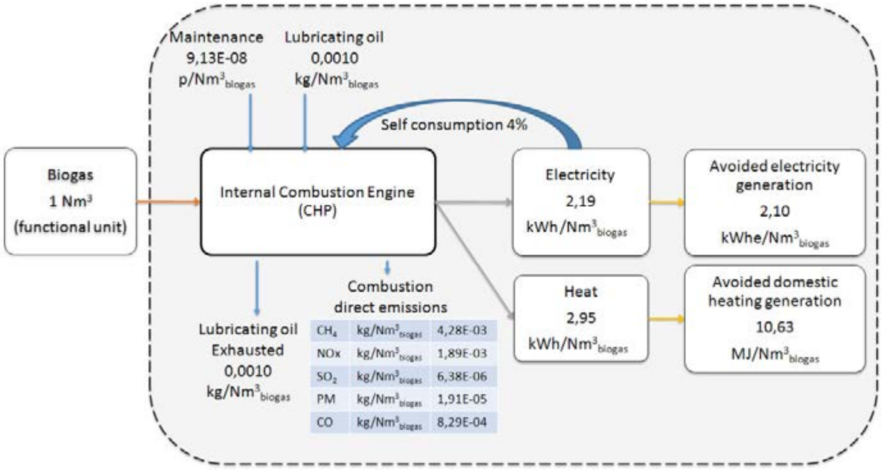

Fig. 2. Main input and output streams for scenario based on ICE.

Table 3. Literature data for ICE performances.

| | [4] | [5] | [6] | [7] | [8] | [9] | Average |
|---|---|---|---|---|---|---|---|
| Electrical efficiency (%) | 39 | 43 | 33-40 | 33 | 32 | 40 | 36,9 |
| Thermal efficiency (%) | 46 | | 48-50 | 54 | 50 | 33 | 50,4 |
| Parasitic electric consumption (%) | | | 2-4,5 | | | | 3,75 |

Main atmospheric emissions from ICE were considered. While $CO_2$ and $CH_4$ emissions were calculated from the biogas composition ($CO_2$ emission were calculated but then not considered as contribution to the greenhouse effect, since of biogenic origin), assuming $CH_4$ losses from the engine at 1%, the emissions of $SO_2$, NOx, CO and particulate matter (PM) were calculated according to literature [13].

Produced electricity was accounted for the avoided effects due to the electricity produced from the Italian electric mix, while for the cogenerated heat, the replacement of the heat used for civil use (domestic heating) was assumed.

### *3.2. MCFC scenario*

In this scenario the use of a MCFC in co-generation mode was assumed. The main parameters assumed for the technical characterization of the fuel cell, are reported in Table 4, as derived from data in Table 5.

The inputs to the fuel cell are represented by biogas, and maintenance, while the outputs are divided into products - electricity and heat – and emissions (Fig. 3).

Maintenance includes: reinforcing steel, chromium steel, zinc, stack fuel cell, transport. Fuel cells' atmospheric emissions are very low and reported in Fig. 3, as assumed from ecoinvent.

Regards to the indirect emissions avoided by the use of electricity and heat produced in this scenario, the same assumptions set out for scenario 1 were used.

Table 4. Technical parameters assumed for the fuel cell.

| | Value | Source |
|---|---|---|
| Electrical efficiency | 50% | Average from literature values (Table 5) |
| Parasitic electric consumption | 2% | Average from literature values (Table 5) |
| Thermal efficiency | 37% | Average from literature values (Table 5) |
| Emissions | - | ecoinvent |
| Maintenance | - | ecoinvent |

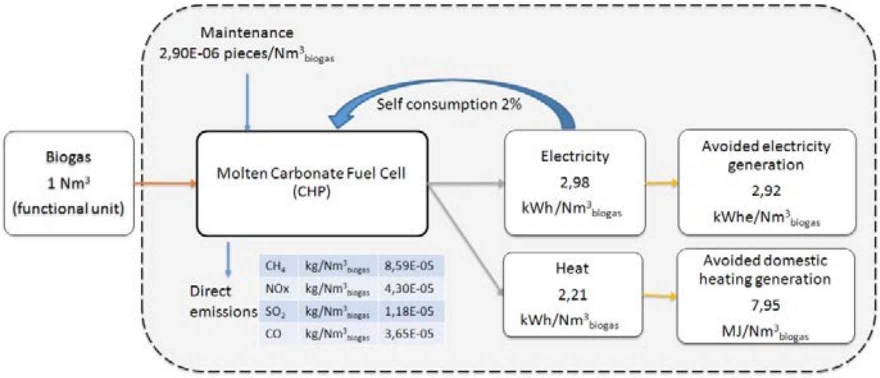

Fig. 3. Main input and output streams for scenario based on MCFC.

Table 5. Literature data for fuel cell performances.

| | [5] | [6] | [10] | [11] | [12] | Average |
|---|---|---|---|---|---|---|
| Electrical efficiency (%) | up to 60 | 45-50 | about 50 | 50 | 50 | 50,78 |
| Thermal efficiency (%) | | up to 40 | | 30 | 40 | 36,67 |
| Parasitic electric consumption (%) | | | | | 2 | 2 |

### *3.3. Scenario biomethane*

In this scenario biogas upgrading was considered, according to HPWS method, in order to produce biomethane to be injected into the natural gas grid (Fig. 4).

The HPWS method is used to remove $CO_2$ from the raw biogas (therefore increasing the methane content) and is also effective at removing $H_2S$. The method relies on the basic principle that $CO_2$ (and $H_2S$) are more soluble in water than $CH_4$. Any condensed moisture or particulates present within the raw gas stream need to be removed prior to water scrubbing. The raw gas is then pressurized (to 10 bar) and introduced to the bottom of the scrubbing tower whilst water is flushed into the top of the tower. The scrubbing tower is packed with a high surface area media (e.g. pall rings) to provide a high contact area between gas and water. As the raw biogas moves up the column against the flow of water, $CO_2$ and $H_2S$ become dissolved within the liquid stream [5]. Upgraded gas leaves the top of the column. Any methane dissolved within the water is captured by depressurizing the water to 4 bar within the flash tank. Gases released are then returned to the bottom of the column. Upgraded gas is then available for drying and compression for storage.

The HPWS process was modeled by using Aspen Plus, in order to calculate devoted inventory for the assumed specific biogas composition: the model results were validated according to [14]. Then minor modifications were applied as increasing the flash tank pressure from up to 4 bar, in order to ensure higher removal efficiency of $CO_2$ and higher purity for biomethane. Fig. 4 shows the layout of the Aspen Plus simulation, while Table 6 reports the main technical parameters for the HPWS.

The inputs to the biogas upgrading plant are represented by biogas, electricity and water, while the outputs are divided into products - biomethane - emissions and waste (Fig. 5).

Specific electricity and water consumption were compared with literature data [14] and resulted within the range of 0,16 – 0,43 kWh per $Nm^3$ of biogas, for the electricity consumption, and within the range of 1,5 – 4,5 kg per $Nm^3$ of biogas for the water consumption.

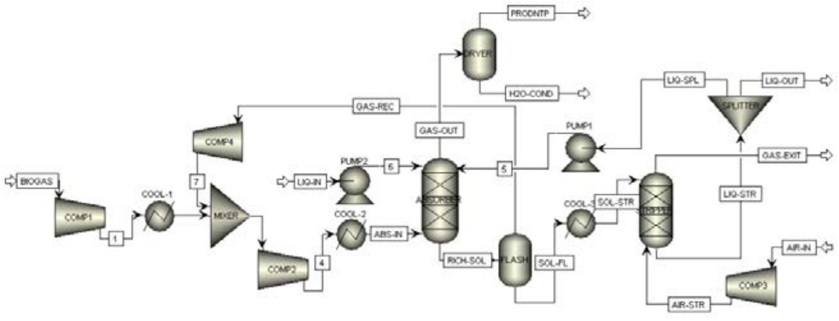

Fig. 4. Layout of the simulation of the HPWS in Aspen Plus.

Table 6. Technical parameters calculated for HPWS process.

| | Unit | Value |
|---|---|---|
| $CO_2$ removal efficiency | % | 99,36 |
| $CH_4$ recovered | % | 98,80 |
| $CH_4$ biomethane purity | % | 97,38 |
| Methane losses (CH4 slip) | % | 1,20 |
| Specific biomethane production | $Nm^3$ of biomethane/$Nm^3$biogas | 0,596 |
| Specific electricity consumption | kWh/$Nm^3$biogas | 0,34 |
| Specific electricity consumption | kWh/$Nm^3$biomethane | 0,57 |
| Specific water consumption | kg/$Nm^3$biogas | 4,00 |
| Specific wastewater production | $m^3$/$Nm^3$biogas | 0,00396 |
| $CO_2$ removal efficiency | % | 99,36 |

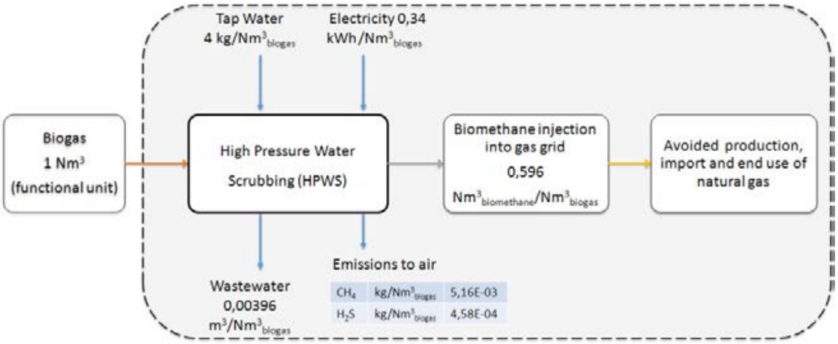

Fig. 5. Main input and output streams for scenario based on HPWS.

## 4. Results – Impact assessment

Results are presented according to Life Cycle Impact Assessment, which examines the mass and energy inventory input and output data for a product system to translate these data to better identify their possible environmental relevance and significance. This translation uses, where possible, numerical indicators for specific subjects or categories that reflect in some manner the system environmental loading or resources depletion for that category. These indicators then constitute an environmental loading and resources depletion profile for a system. This profile with possible further analysis and weighting is intended to provide an additional useful perspective on the possible environmental significance in one or more general areas of resources, natural environment and human health.

In this study, environmental indicators according to the Eco-indicator '95 method was used [15]. Eco-indicator ’95 method uses nine environmental effect indicators greenhouse effect; ozone depletion; acidification; eutrophication; heavy metals; carcinogens; winter smog; summer smog; pesticides, to which two additional ones – primary energy consumption and solid waste - are usually added.

The Eco-indicator’95 effects can be normalized and weighted to obtain a single indicator score in eco-points [15].

The results presented in this paragraph, about the global warming potential, do not include $CO_2$ emissions of biogenic origin, but only $CO_2$ emissions of fossil origin. In fact, $CO_2$ biogenic emissions, generated during the biogas treatment, can be considered as a neutral contribution.

No impacts for the pesticides and solid waste categories were obtained.

### *4.1. ICE scenario*

The impact assessment results for this scenario are reported splitting the overall amount of each indicator into the contributions given by several sub-processes, as reported in Table 7.

The contribution to each impact category from each sub process is reported as percentage of total value in Fig. 6.

Table 7. Sub-processes considered in the ICE scenario.

| Sub-processes | Description |
|---|---|
| Lubricating oil | Necessary for the engine operation |
| Maintenance | Required for proper engine operation over time |
| Direct emissions | Resulting from the biogas combustion in ICE |
| Lubricating oil disposal | Exhausted lubricating oil |
| Avoided Electricity production | Non-production of electricity from the Italian electricity mix |
| Avoided Heat production | Non-production of heat from the Italian domestic heating mix |

Values of the indicators for this scenario are predominantly negative and this is due to the ICE electricity and heat production and the corresponding avoided effects.

All the other sub-processes of the scenario, such as lubricating oil - production and disposal - maintenance and direct emissions, represent the positive impacts, which are nearly always negligible with respect to the magnitude of the negative ones.

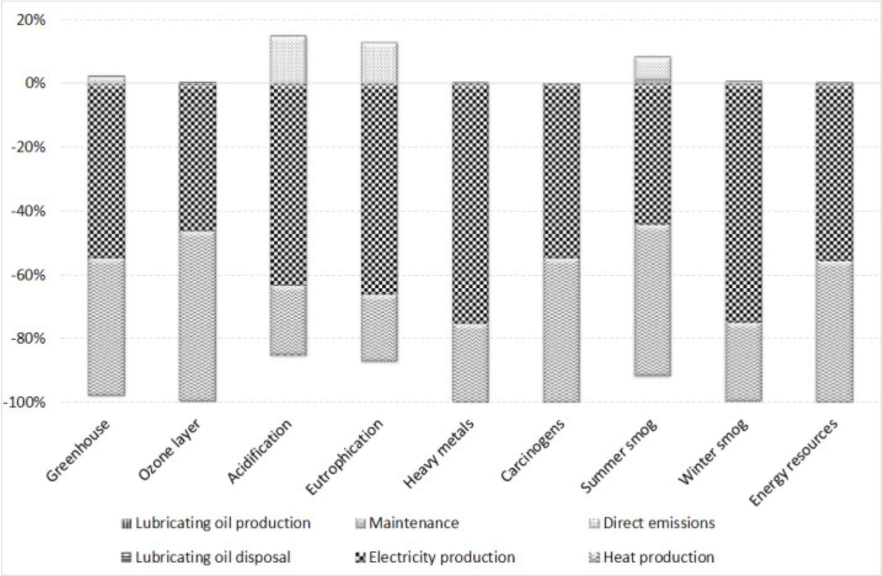

Fig. 6. Contribution for each indicator from the sub-process of the system. ICE scenario.

The most important positive impacts come from direct emissions from the ICE, which mostly affect the acidification, eutrophication and summer smog indicators, with percentages of 21%, 17% and 9% of each total value, respectively.

The losses of methane, which are included in the calculation of the direct emissions, have a very limited impact on the greenhouse effect total impacts, with a percentage of 2%.

In general, it is possible to highlight how the avoided impacts related to the electricity production are bigger than the avoided impacts linked to heat production.

### *4.2. MCFC scenario*

The impact assessment results for this scenario are reported splitting the overall amount of each indicator into the contributions given by several sub-processes, as reported in Table 8.

The contribution to each impact category from each sub-process is reported as percentage of total value in Fig. 7.

Fig. 7 shows that in this scenario there are almost exclusively negative impacts. This is due to insignificant direct emissions from fuel cells; whereas benefits, in terms of negative impacts that occur from the avoided production of electricity and heat are very high. In addition, maintenance seems not to affect the overall indicator values.

Table 8. Sub-processes considered in the MCFC scenario.

| Sub-processes | Description |
|---|---|
| Maintenance | Required for proper fuel cell operation over time |
| Direct emissions | Resulting from the biogas reforming in fuel cell |
| Avoided Electricity production | Non-production of electricity from the Italian electricity mix |
| Avoided Heat production | Non-production of heat from the Italian domestic heating mix |

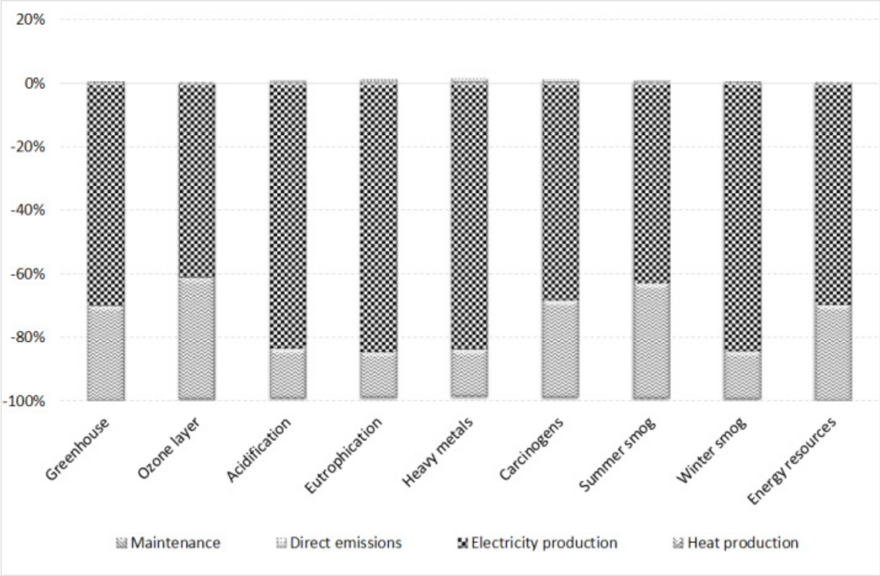

Fig. 7. Contribution for each indicator from the sub-process of the system. MCFC scenario.

### *4.3. Biomethane scenario*

The impact assessment results for this scenario are reported splitting the overall amount of each indicator into the contributions given by several sub-processes, as reported in Table 9.

The contribution to each impact category from each sub-process is reported as percentage of total value in Fig. 8.

Fig. 8 shows that in this scenario the negative impacts are solely represented by the biomethane production – avoiding natural gas production - and from avoided CO2 emissions, obtained by biomethane end-use in place of natural gas.

The main positive impacts are represented by: electricity consumption, required for the HPWS operation; wastewater treatment and direct emissions.

The electricity consumption greatly affects the acidification, eutrophication, heavy metals, carcinogens and winter smog categories. For acidification and summer smog, these positive impacts are almost completely balanced by the negative impacts related to the biomethane production. While this is not the case for eutrophication, heavy metals and carcinogens.

Table 9. Sub-processes considered in the biomethane scenario.

| Sub-processes | Description |
|---|---|
| Electricity | Necessary for HWPS operation |
| Water | Required for biogas cleaning |
| Biomethane production | Results in avoided natural gas production |
| Avoided $CO_2$ emissions | From biomethane end-use in place of natural gas |
| Direct emissions | Resulting from the gaseous waste HPWS stream |
| Wastewater treatment | Treatment of the liquid waste HPWS stream |

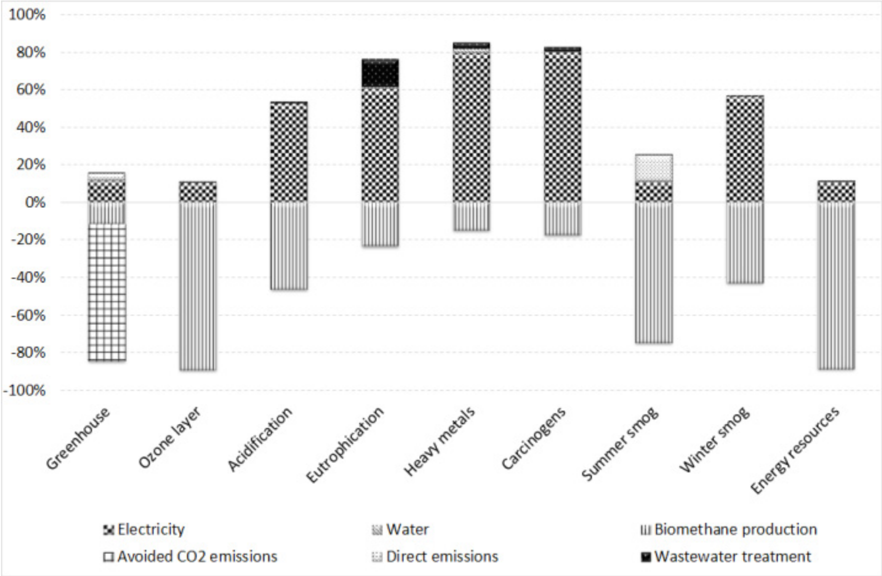

Fig. 8. Contribution for each indicator from the sub-process of the system. Biomethane scenario.

### 4.4. Comparison

Table 10 shows the direct comparison of the indicator total values calculated for each scenario. The last raw also reports the value of the synthetic Eco-indicator’95. MCFC scenario clearly emerges as the best-case scenario for all the impact categories, followed by ICE scenario and then by biomethane scenario.

Table 10. Results comparison for the different scenarios.

| Impact category | Unit | ICE | MCFC | Biomethane |
|---|---|---|---|---|
| Greenhouse | kg $CO_2$ | -2,07E+00 | -2,35E+00 | -1,10E+00 |
| Ozone layer | kg CFC11 | -2,04E-07 | -2,13E-07 | -1,10E-07 |
| Acidification | kg $SO_2$ | -6,33E-03 | -9,32E-03 | 1,31E-04 |
| Eutrophication | kg $PO_4$ | -1,43E-03 | -2,06E-03 | 1,81E-04 |
| Heavy metals | kg Pb | -3,02E-05 | -3,69E-05 | 3,26E-06 |
| Carcinogens | kg B(a)P | -1,29E-07 | -1,41E-07 | 9,35E-09 |
| Pesticides | kg act.subst | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Summer smog | kg $C_2H_4$ | -3,48E-04 | -4,03E-04 | -1,28E-04 |
| Winter smog | kg SPM | -5,44E-03 | -6,71E-03 | 1,70E-04 |
| Energy resources | MJ LHV | -3,65E+01 | -4,04E+01 | -2,23E+01 |
| Solid waste | kg | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Eco-indicator’95 | Eco-point | -4,40E-03 | -5,50E-03 | 1,13E-04 |

### 4.5. Sensitivity analysis

In order to highlight the quite important contribution that comes from the heat recovery in ICE and MCFC scenarios, a modification to the inventory data was made, excluding such recovery of heat.

Table 11 presents the results when the heat recovery is excluded. In this condition the gaps between the ICE and MCFC scenarios are reduced with respect to the biomethane one.

Table 11. Results comparison for the different scenarios in the case of excluding the heat recovery for ICE and MCFC scenarios.

| Impact category | Unit | ICE | MCFC | Biomethane |
|---|---|---|---|---|
| Greenhouse | kg $CO_2$ | -1,14E+00 | -1,65E+00 | -1,10E+00 |
| Ozone layer | kg CFC11 | -9,37E-08 | -1,31E-07 | -1,10E-07 |
| Acidification | kg $SO_2$ | -4,35E-03 | -7,84E-03 | 1,31E-04 |
| Eutrophication | kg $PO_4$ | -1,03E-03 | -1,76E-03 | 1,81E-04 |
| Heavy metals | kg Pb | -2,27E-05 | -3,13E-05 | 3,26E-06 |
| Carcinogens | kg B(a)P | -7,07E-08 | -9,72E-08 | 9,35E-09 |
| Pesticides | kg act.subst | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Summer smog | kg $C_2H_4$ | -1,50E-04 | -2,55E-04 | -1,28E-04 |
| Winter smog | kg SPM | -4,08E-03 | -5,69E-03 | 1,70E-04 |
| Energy resources | MJ LHV | -2,03E+01 | -2,83E+01 | -2,23E+01 |
| Solid waste | kg | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Eco-indicator’95 | Eco-point | -3,14E-03 | -4,56E-03 | 1,13E-04 |

## 5. Conclusions

This study allowed the evaluation of the environmental impacts related to three different biogas utilization scenarios, applying the Life Cycle Assessment (LCA) methodology.

The selected functional unit, common to the three scenarios, is one normal cubic meter of biogas input to the system. A fixed composition for the biogas was chosen, with 60% in volume of methane and 38.97% in volume of carbon dioxide.

The scenarios based on the use of internal combustion engine (ICE) and molten carbonate fuel cell (MCFC) are assumed to have as output both electricity and heat, avoiding the environmental impacts linked to the conventional production of electricity and heat from fossil fuels. The biomethane scenario is concerned with the biogas upgrading through a High Pressure Water Scrubbing (HPWS). A HPWS model was specifically designed using the software Aspen Plus, that allowed determining the yield, the direct emissions and the energy consumption of the system.

Biomethane can substitute natural gas in all its uses; this was considered by accounting the impacts in terms of avoided $CO_2$ emission – for the avoided combustion of natural gas - and in terms of avoided natural gas production.

The results obtained from the impact assessment phase, carried out according to the Eco-indicator’95 method, clearly show that MCFC scenario is the best-case scenario, with the highest avoided effects in all the impact categories. Also ICE scenario records very favorable impacts in all the impact categories, but cannot compete with the MCFC’s higher electrical efficiency and lower direct emissions.

Biomethane scenario shows avoided impacts only for greenhouse effect, ozone layer depletion, summer smog and energy resources categories. The effective impacts are mostly due to the HPWS energy consumption, then to the wastewater treatment and, to a lesser extent, to the process methane losses.

However, the avoided impacts recorded for the greenhouse effect category of biomethane scenario, are still very important and this is mainly due to the avoided emissions of fossil $CO_2$ substituting biomethane to natural gas.

When the heat recovery is excluded in the ICE and MCFC scenarios, the gaps between the ICE and MCFC scenarios are reduced with respect to the biomethane one.

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