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Optimization of the design and operation of SOFC-based systems for building sector

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Abstract

The present work, developed in the framework of the ComSos European project, has the aim to demonstrate and evaluate the potential of using a fuel cell-based system in the building sector. In a world that has the duty to look at pollution and climate change with more and more attention, the SOFC-based systems, whit the help of other RES technologies, could be one of the most sustainable and efficient energy solutions thanks to their ability to produce at the same time heat and electricity with almost nil operating pollutants emissions (PM, NOx, SOx, VOC etc.).

The system considered has to satisfy the load of a small hotel situated in Cuneo (Italy). A comparison between the reference case, represented by the supply from the network for electricity and the use of a boiler powered by natural gas for the thermal request, and different case studies based on fuel cell system is presented. The model is based on the hourly electrical and thermal load of the building, the hourly cost of electricity and methane in Italy and the hourly meteorological data of the place during the year. A Mixed-Integer Linear Programming (MILP) model is used to find the optimal configuration for the system minimizing the total cost of the plant during its whole life. The concept of typical days is also implemented to allow the problem to be solved in a reasonable time. In this condition the building examined have a typical annual consumption of 1,128,085.2 kWh_{el} and a thermal request of 277,311.3 $kWh_{th.}$

An analysis from the economic and environmental point of view has been reported in order to analyse the advantages and disadvantages related to SOFC-based cogeneration systems. The results show that the installation of a fuel cell system with the present investment cost and lifetime is still not feasible compared to the traditional systems. However, SOFC-based systems become convenient when reducing the SOFC investment cost up to a commercial target value and improving their lifetime, helping to reduce the total cost of the plant by an 3% to a 10% and the emission by 25 % to 40% with the integration of a RES plant.

Summary

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Nomenclature

INDICATOR	DESCRIPTION	UNIT
FC	Fuel Cell	-
SOFC	Solid Oxide Fuel Cell	
GRID	National electrical grid	-
PV	Photovoltaic system	-
BT	Battery	-
TTS	Thermal tank storage	
SOC	State of Charge	%
MILP	Mixed linear programming	-
GHG	Green gas house	-

1. Introduction

This master thesis wants to demonstrate and evaluate the feasibility of using advanced energy system like fuel cell in the building sector according to the Comsos project. [1] A fuel cell is an electrochemical device that convert the chemical energy of the fuel, hydrogen or natural gas, into electrical one. During this conversion a large amount of heat is developed, and it can be dissipated, stored or used to meet the demands of the building. In this way we are able to satisfy, at the same time, part of the electrical and the thermal load of a building. In this work a Solid Oxide Fuel Cell (SOFC) is analyzed, and its modeling derives from an average of three different fuel cell manufacturers SOLIDpower, Convion and Sunfire.[2] This kind of fuel cell let us to reach a very high electrical efficiency and a good amount of heat thanks to the high operative temperature. Despite this, the SOFCs are less flexible, and they have maximum number of shutdowns for year allowed, so to get the best out of them, activities with a constant base load like hospitals, supermarkets, hotels, office buildings, etc. are preferable.

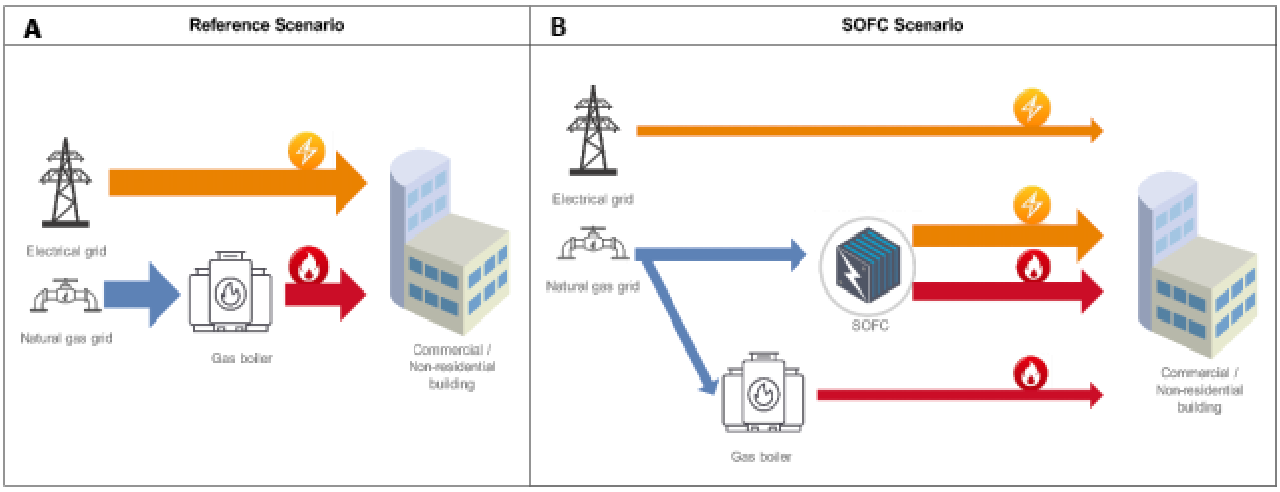


Figure 1 – Reference scenario vs. SOFC scenario.

The work assumes the hourly consumption of electricity and natural gas of a small hotel and perform a comparison between the reference scenario, when the building is completely supplied by the electric and gas network, and the SOFC scenario that implements the fuel cell system in order to reduce the imported energy and environmental emission. To do this a Mixed Integer Linear Programming (MILP) model is implemented in order to find in each scenario the optimal configuration of the systems that satisfy the load and minimize a certain objective function like the total cost of the plant or the total emission produced. At the end, a sensitivity analysis on the most important parameters that influence the problem are done with the aim of studying some possible future scenario.

2. Methodology

2.1 Mixed Integer Linear Programming (MILP)

An integer programming problem is a mathematical optimization model in which some or all of the variables are restricted to be integers. If the objective function and also some constraints are linear the program is called Linear Integer Programming [3], [4]. In this work, the role of the model is to proper select the size of each equipment used to satisfy the thermal and electricity demand of the building minimizing an objective function, like the total cost of the plant. Imposing to each technology appropriated constraints given by their technical data, the algorithm has to be able to find the optimal configuration for each time period and select the units that must be turned on or off and their operative value. For this reason, a Mixed Integer Linear Programming model (MILP) was adopted, that is a linear integer programming in which only some of the variables, are constrained to be integers, while other variables are allowed to be real. The linearization of the problem guarantees the convergence on the solution with a quite good computational time [5], [6].

The general form of MILP can be represented by [4]:

$$\begin{gathered} \min f(x, i) \\ Ax, i = b \\ l \le x \le u \\ x, i \in Z \quad \forall \mathrm{i} \in I \end{gathered} \tag{1}$$

Where *f(x,i)* are the objective functions and the *x,i* are the decision variables, that are the variables that have to be optimized limited to an upper u and lower bound l. The matrix A and B represent respectively the Constrain matrix and the constraint known term. As we will see in the following chapter the formulation of the MILP problem involves also some different variables, like binary variables, introduced to model in order to simulate the on and off of the technology and auxiliary variable.

All the algorithms have been writing in MATLAB® ambient and solved by CPLEX® solver.

2.2 Typical days: K-means clustering

The computational time required to solve the linear programming depends on the variable and constraints involved. According to [7], *"Optimizing an energy system model is a very computationally-demanding task due to the high number of the data considered and demand time series."* In order to reduce as much as possible, the computational resources, the time series aggregation and the typical days concept are implemented.

The aim of time series aggregation is to merge a set of periods into groups such that the group members are similar as possible [7]. Each group is then represented by a single period. To the single period created is possible to modify or add some 'extreme periods', for example same characteristic peak of the load, in order to achieve a more feasible system.

In the figure 2a,2b,2c all the steps are represented in graphical view.

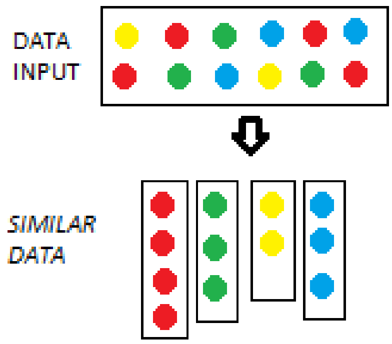


Figure 2a – Merge of similar data in groups

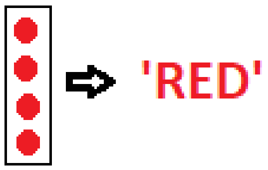


Figure 2b – Representation by single period

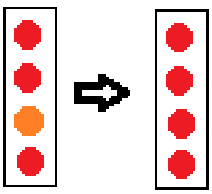


Figure 2c – Add extreme periods

We can summarize the process used in this work to create the groups in four simple steps described below [7], [8].

1. Normalization of Data Input

   Assuming *X* a vector with the data to aggregate, *X_norm* is the normalized vector calculated following the equation:

$$X\_norm = \frac{X - \min(X)}{\max(X) - \min(X)} \qquad (2)$$

   The process of normalization is fundamental to do an analysis on time series with the same scale.

2. Aggregation in Groups

   The aggregation is done by the 'K-means clustering' Matlab-embedded algorithm. The K-means program create groups called 'Cluster' in order to minimize the Squared error between the empirical mean values and all the values of the cluster itself. In our case the squared error equal to the Euclidean Distance:

$$d = |\sqrt{x^2 + y^2}| \qquad (3)$$

   Summing the algorithm up, it consists in

- Randomly select an initial number of cluster (*k*) and the mean value of them ("Centre")
- For each initial data the Euclidian distance with these centres is calculated, and the value is assigned to the cluster that minimize it.
- Re-calculate centre of new cluster obtained
- If the new centre coincides with the previous one, we can go on else we return on the second step.

As result we obtain a sequence of *k* different cluster identifiable with the centre.

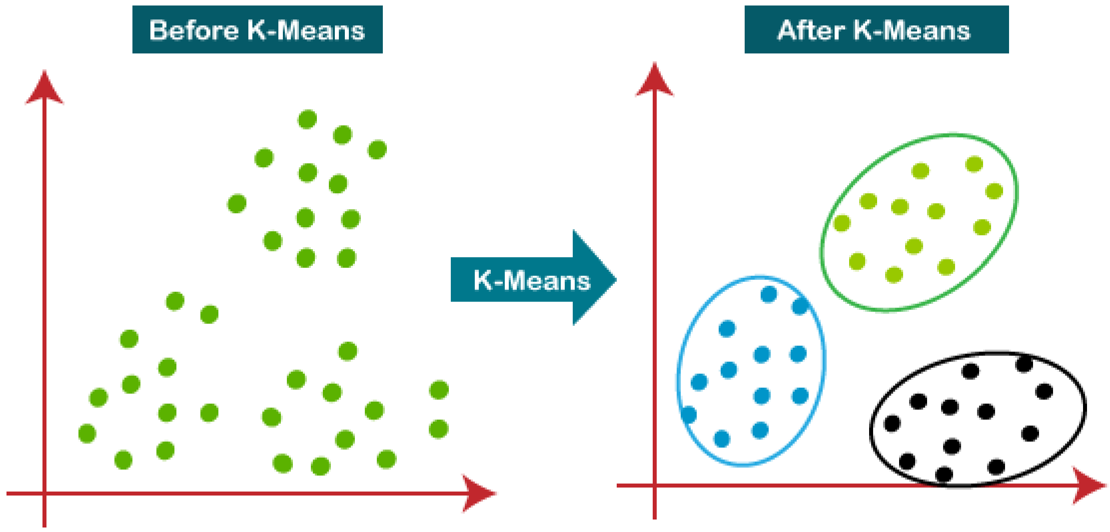


Figure 3 – K-means Clustering result [9]

3. Extreme Periods

As explained before, these periods are important in order to reproduce in as much accurate as possible manner the system under analysing. In fact, is possible that some periods, that are maybe occasional periods, are cut off by the groups because considered not representative. Especially in energy system model these data can be relevant.

We can add the extreme periods in different way:

- Add it as new cluster centre
- Add manually this data after the algorithm in the final cluster
- Modifying or substituting the data contained in the final cluster

4. Scaling back

The original time series have extreme values that we cannot exceed. To avoid this, we scale back the aggregated series to the original scale. If in the final cluster same values are bigger the one, they are putted equal to 1 and re-scaled with the other values.

At the end of the process, we have obtained a sequence of *k* representative days (Cluster) scaled to original time scales. In other words, we always obtain a year of 365 days, but the 365 days of the post-processed year aren't anymore 365 unique and different days. At each day in original year is assigned a specific day of the k representative cluster. [10]

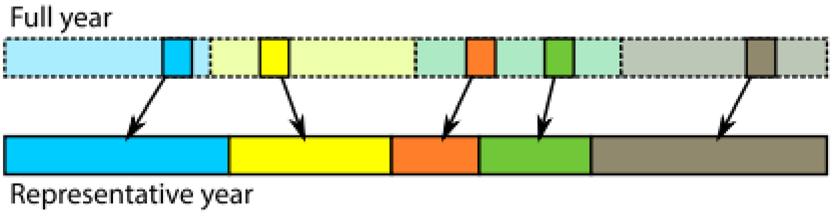


Figure 4 – Representation of typical year

All the data and variable operative are so calculated only for these typical days and the result obtained are multiply for the number that these days are repeated in the typical year reducing significantly the time computational of our process.

2.3 Input data

In this sub-chapter all the data used in the model are explained. In addition to the environmental and statistical data, all the component of the systems, analysed in the future sections, are analysed from the technical and economic point of view.

2.3.1 Building characterization

In order to find the hourly electrical and thermal consumption requested to the MILP some considerations are done. First of all, since no data of building for the location chosen (Cuneo, Italy) are been available, a climatic approximation are made. From the Open Data Catalog of the U.S. Department of Energy [11], is possible to take the hourly load profiles of some hotels located in established USA zone climate and using them as reference for other hotels located in the similar zones in the world. According to [12], the climatic zone is influenced by different parameters, in particular the latitude and altitude are direct influence on the temperature and so indirectly on the thermal request of the building. Analysing the geographical data of Cuneo, we have choice to select the Marshfield city (WI, U.S.A) as reference.

Figure 5 – Location of the cities of Marshifield and Cuneo.

Table 1 - Geographical data of the two locations.

	Cuneo	Marshfield
Latitude	44.38 N	44.66 N
Altitude	534	392

The data of the load are available in the Appendix A1.

2.3.2 Technical Data

PHOTOVOLTAIC SYSTEM

The data used in order to model the photovoltaic system (PV) were obtained from the PVgis website [13] using the "solar radiation tool" by selecting the most recent hourly data (2016) and considering the ideal position and orientation (check the box "Optimize slope and Azimuth") positioning in the city of Cuneo, Italy.

The data obtained are the external ambient temperature [° C] and the solar irradiation [W / m^2] of our site.

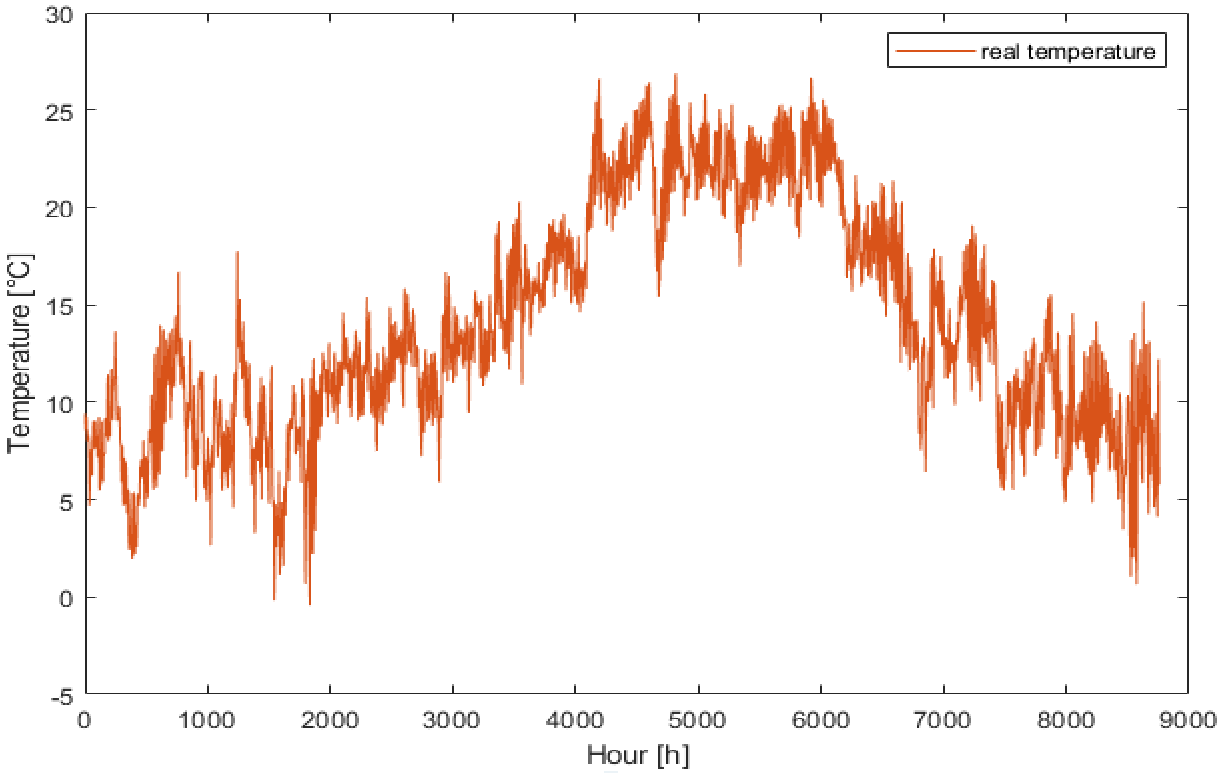


Figure 6 – External Ambient Temperature for the city of Cuneo.

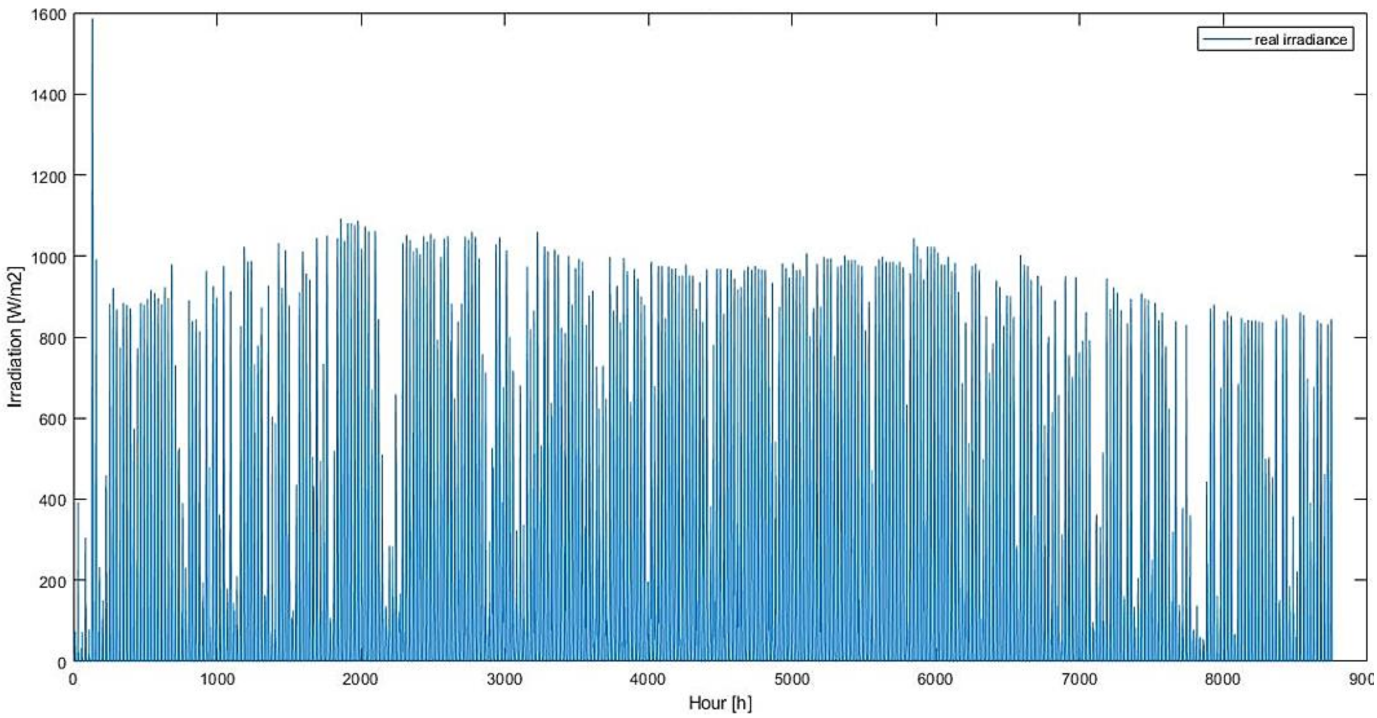


Figure 7 – Irradiation data for the city of Cuneo.

As we can see, around the 250th hour, we have a data that seems anomalous considering the trend of the variable taken into consideration, this can be caused by a simple transcription error. By acting on the input data, it is possible to reduce or eliminate the 'spikes' directly. In our case it has therefore been replaced with an average value considered over the whole sampling as reported in figure 8.

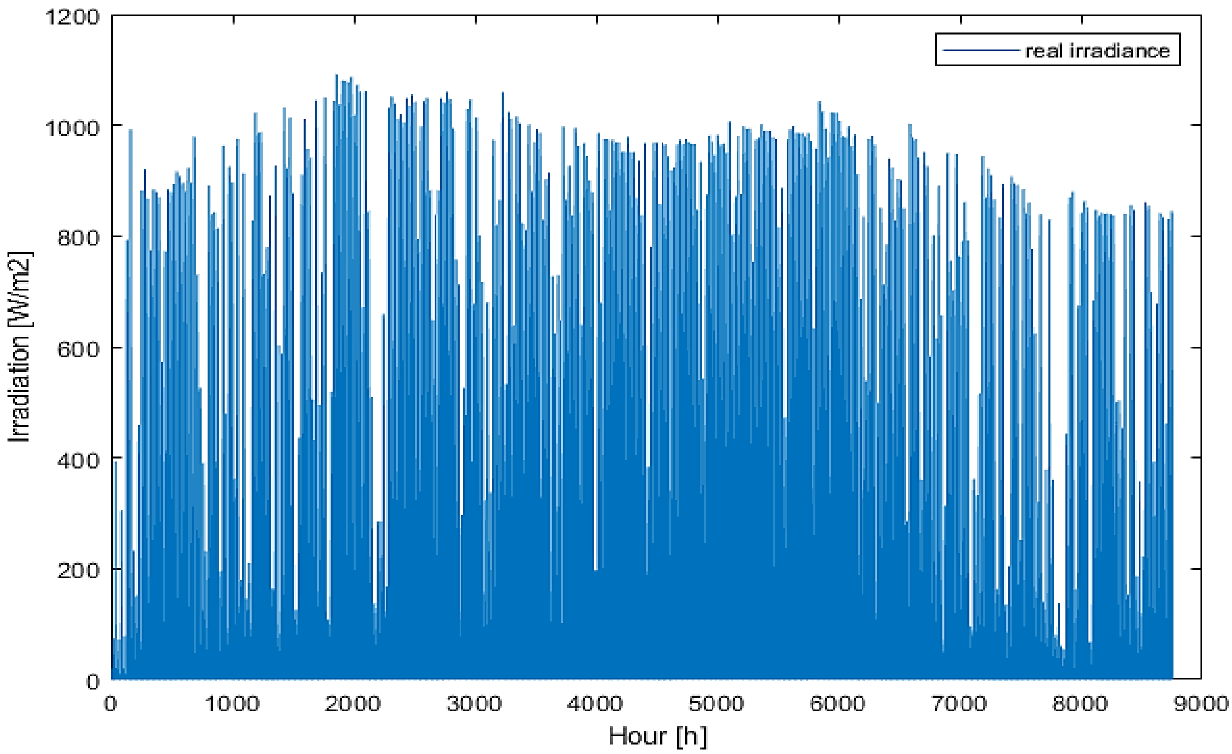


Figure 8 –Correct Irradiation data for the city of Cuneo.

From these data, the specific power [kW / kWp] referred to 1 kW of peak power was obtained using the formula [14]:

$$Specif\ Power\ PV\ = f_{PV} \frac{G}{G_{stc}} * (1 + \gamma * (Tcell - Tcell_{STC}) \qquad (4)$$

Where:

f_{PV} = the PV derating factor [%]

The photovoltaic (PV) derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated. [7]

G = the solar radiation incident on the PV array in the current time step [kW/m^2]

Gstc = the incident radiation at standard test conditions [1 kW/m^2]

γ = the temperature coefficient of power [%/°C]

Tcell = the PV cell temperature in the current time step [°C] calculated by the following equation

$$Tcell = T + \frac{G}{800} * (NOCT - 20) \quad (5)$$

$Tcell_{STC}$ = the PV cell temperature under standard test conditions [25°C]

The result is available in the Appendix A1. The table *2* summarizes the data used for the PV model.

Table 2 - Technical data for PV system.

Technical information		Value	Unit
Nominal Operating Cell Temperature NOCT	*NOCT*	44	°C
Derating factor	*f_PV*	0.86	%
Temperature coefficient	*γ*	-0.003	%
Incident radiation at Standard Test Condition (STC)	*G_stc*	1000	W/m^2
PV cell temperature at Standard Test Conditions (STC)	*Tcell_STC*	25	°C

FUEL CELL

A Solid Oxide Fuel Cell (SOFC) is an energy conversion device that produces electricity by electrochemically combining a fuel and an oxidant across an ionic conducting oxide electrolyte. It is composed by an electrolyte between two porous electrodes anode and cathode. Fuel, fed to the anode, undergoes to an oxidation reaction releasing electrons to the external circuit. Oxidant is fed to the cathode, accepts electrons from the external circuit, and undergoes a reduction reaction. [2]. The electron flow in the external circuit from the anode to the cathode produces direct-current electricity. In figure 9, a schematic representation of the SOFC's operation cell is proposed.

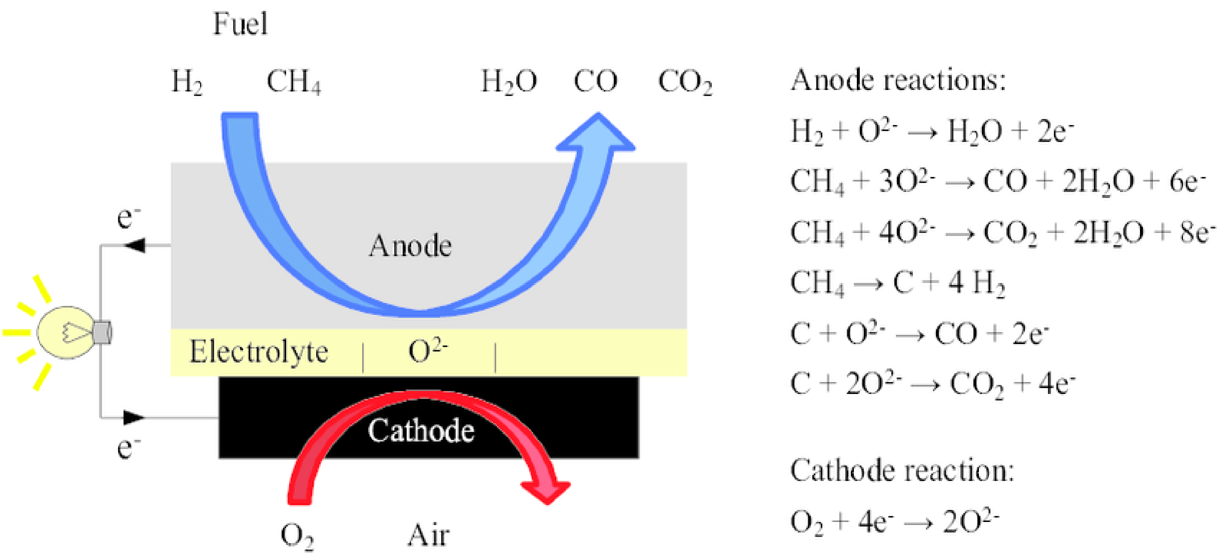


Figure 9 – SOFC reduction and oxidation reaction [15]

In order to favour the ionic conduction in the ceramic materials the temperature has to be quite high (650 – 700 °C). So, other the high electrical efficiency, the SOFC cell are interesting also under the point of view of CHP application thanks to the amount of heat at high temperature released during it operation. The data for the model are obtained from confidential information on 3 different manufacturers (SUNFIRE, SOLIDPOWER, CONVION) joining the Comsos project. Data obtained as an average between the products of the 3 manufacturers are represented in table 3. [1].

Table 3 - SOFC technical Data

Technical information	Values	Units
SOFC system nominal size	25	kW
Electrical efficiency @ nominal size	55	%
Thermal efficiency @ nominal size	27	%
Total efficiency	82	%
Modulation range	30-100	(min-max) %
Current stack technical lifetime	5	y
NOx emission	35	mg/kWh

GAS BOILER

The gas boiler (GB) considered in the model is a condensing gas boiler. Data taken from a Ferrioli technical data sheet for a boiler with an "industrial" power of 125 kW (Model ENERGY TOP W 125). [16] are illustrated in Table 4.

Table 4 - Gas Boiler Technical data

Technical information	Values	Units
Gas boiler system nominal size	125	kW
Thermal efficiency	98	%
Max Power	113.7	kW
Min Power	24.6	kW
Modulation range	17-95	(min-max) %
Current stack technical lifetime	20	y
NOx emission	45	mg/kWh

As regards the data on NOx emissions, it was obtained from the average between that reported on the technical data sheet of the gas boiler and a guided British study [17] on the exhaust gases of a group of residential boilers which confirm the validity of the statements made by the manufacturers in the technical data sheets.

LI-ION BATTERY

In recent years, batteries have had an important development in renewable energy systems. Thanks to the clean energy stored, when it is available, is possible to increase the self-consumption, and avoid balance problems. In the following table the main characteristic of a Li-ion battery and the data used in the model are reported according to Makibar & Narvarte [18].

Table 5 - Li-ion Technical data

Technical information	Values	Units
Charging converter efficiency	93	%
Discharging converter efficiency	95.5	%
Charging efficiency	95	%
Discharging efficiency	95	%
SOC range	0.2-1	(min-max) %
SOC initial	0.5	%
Current stack technical lifetime	10	y

The self-discharge coefficient hourly is considered null.

THERMAL STORAGE TANK

The most common Thermal Store Tank (TTS) is the hot water storage. The concept is very simple and usually it consists in an insulated cylinder able to store water, successively used for space heating or domestic use. There are several type of TTS available on the market, in our model the hypothesis on the perfect stratified tank is used in order to analyse the component in terms of State of charge (SOC) [10].

Table 6 - TTS technical data

Technical information	Values	Units
Self-discharge coefficient hourly	-0.1	%
SOC range	0 - 1	(min-max) %
SOC initial	0.4	%
Current stack technical lifetime	Life of the plant	y

2.3.3 Economic data

The hourly price of electricity and methane are taken from the database of GME [19] for the 2019 year. The choice of not using the most update data of the last two years falls on having a scenario that has not been influenced by the Covid-19 period, which has altered costs due to a reduction in requests and lockdown periods in most part of the world. The electrical and thermal request of the building under examination are classified as industrial load so to the free-market price the correspond various fees have been added.

HOURLY COST OF ELECTRICAL ENERGY

According to the request load, the following extra costs are added to the electrical cost [20]:

- Fixed Cost (*Cf*): fixed system charges and annual fixed distribution and transmission costs:
- Variable Cost (*Cv*): Variable system charges and annual variable distribution and transmission costs;
- Excise (*Ca*): Excise duty is a tax paid to the state for the production and sale of consumer goods. it is calculated on the quantity and not on the value or price of the product.
- Power cost (*Cp*): It is a fixed price, which depends precisely on the power of the system and it does not vary with consumption

The final cost of electricity is obtained adding the Italian VAT (22%).

Table 7- Cost of electricity: extra costs to be summed to the pure energy price.

Fixed Cost	Cf	629.66 €/year
Variable Cost	Cv	0.0503 €/kWh
Excise (Ca)	Ca	0.0125 €/kWh
Power cost (Cp)	Cp	5858.12 €/kW/year

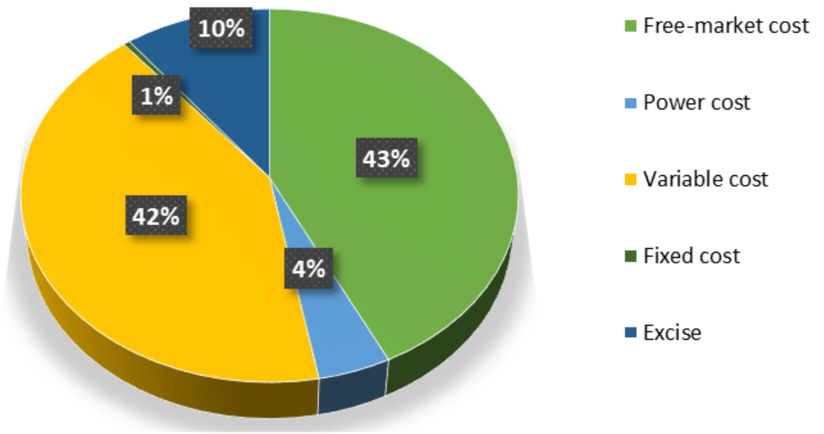


Figure 10 – Focus on electrical cost.

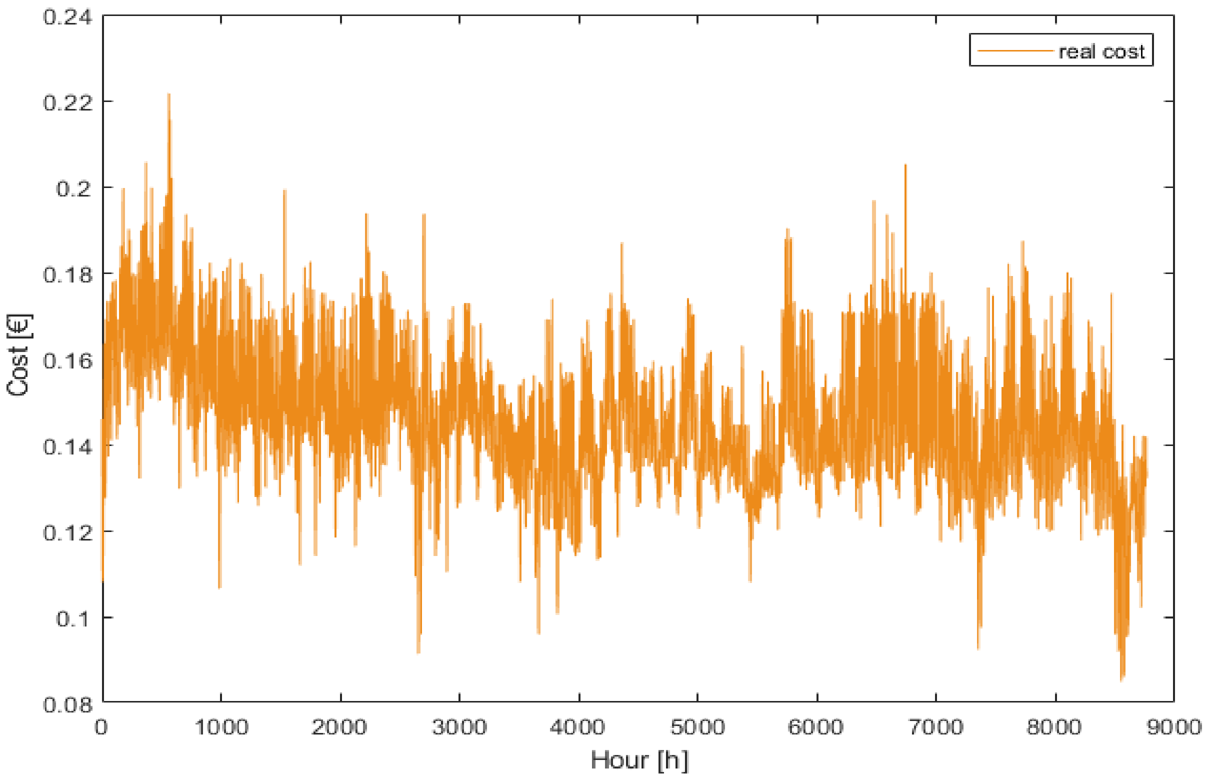


Figure 11 – Electrical energy cost from the Italian Grid.

In this way the cost of electrical energy from the grid fluctuates between a minimum value of 0.09 €/kWh and a maximum value of 0.22 €/kWh, with an average of 0.15 €/kWh. Also the revenue of the injected energy into the grid is considered as indicated in table A2.4 in Appendix A2.

HOURLY COST OF METHANE

According to Arera [21] the only fee added to the free market price of gas withdrawn to the grid is the excise. Taking the consumption of the building and assuming a heating value of 10.5 kWh/smc, it is possible find the right duty that we have to consider (as shown in the Appendix A4).

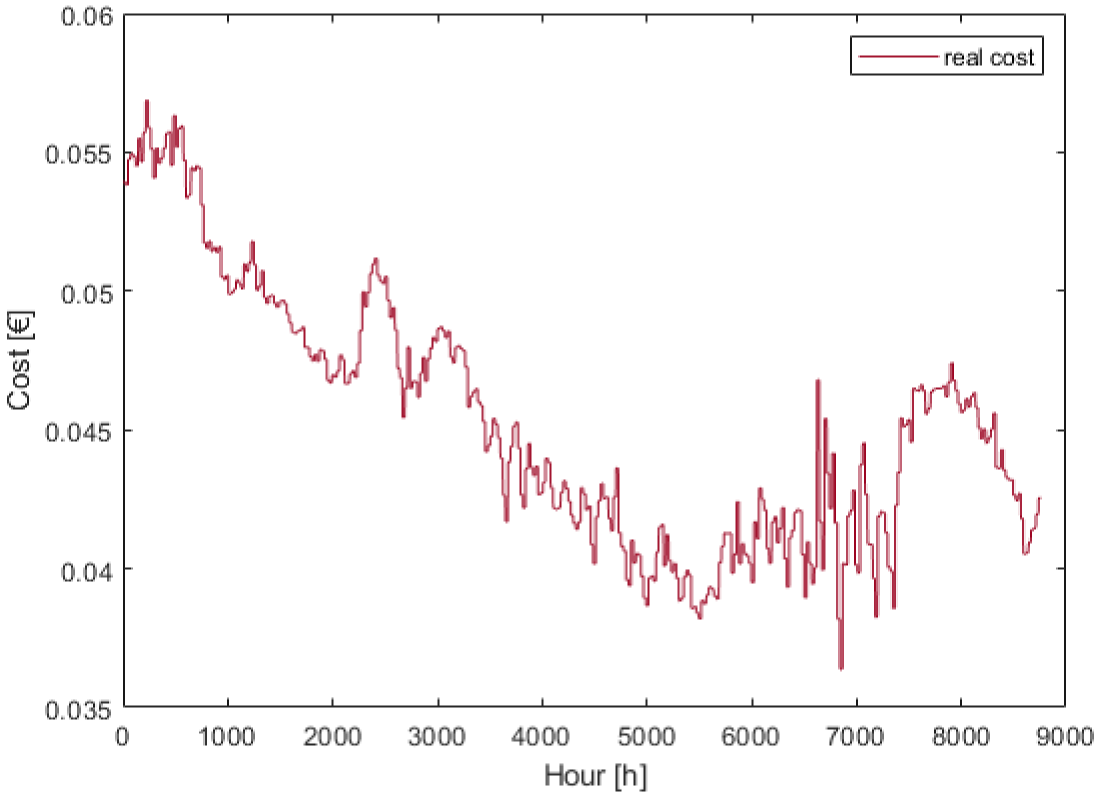


Figure 12–Methane cost from the Italian Grid

Considering VAT at 22%, the cost of methane gas is included between a minimum value of 0.036 €/kWh and a maximum of 0.057 €/kWh with an average cost of 0.045 €/kWh

COMPONENT AND OPERATIVE COST

For all the components of the system, the data economic implemented in the model are available in the Appendix A2.

3. Scenario's settings

In this section all the design variables and the main constraints of the MILP model are explained. The simplest problem that we can go to analyse can be summarized in the Figure 13 and represent our reference scenario.

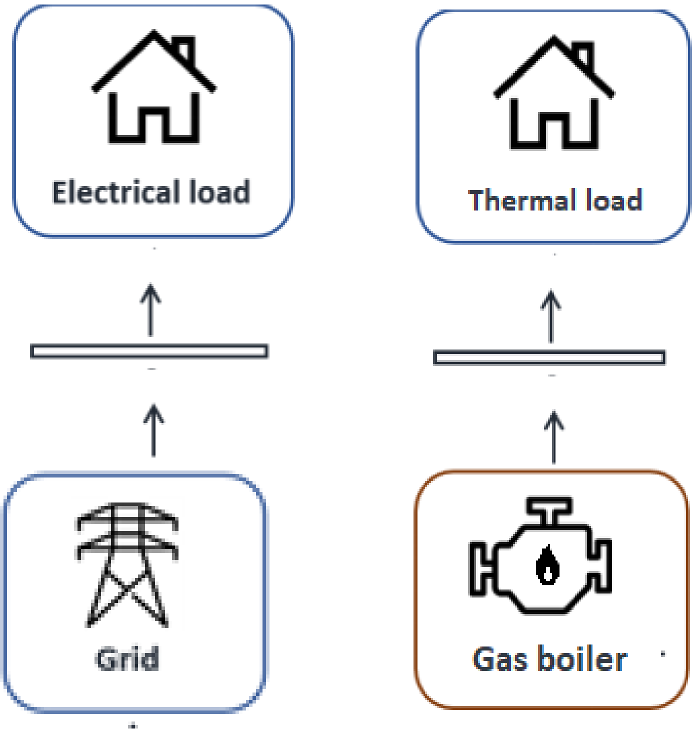


Figure 13 – schematic representation of the reference case

First of all the problem is subdivide in the electric and the thermal one. Therefore, to each sub-system, the power balance at each time step *t* is performed:

$$PGRID(t) = PLD,EL(t) \tag{6}$$

$$QGB(t) = PLD,TH(t) \tag{7}$$

PGRID is the power withdrawn by the grid, PLD,EL is the electrical load power to be satisfied, QGB is the gas boiler outlet power and PLD,EL is the thermal request that has to be satisfied.

These equations are the main equalities constraints that our MILP problem has to respect, satisfying this equation, the optimal value of each variable involved in them are calculated in order to minimize the objective function.

A more general system, divided into its electrical and thermal subproblem, is now descripted in order to explain the mathematical model behind each component that will makes up our systems in the future chapters [8].

3.1 Electrical energy balance

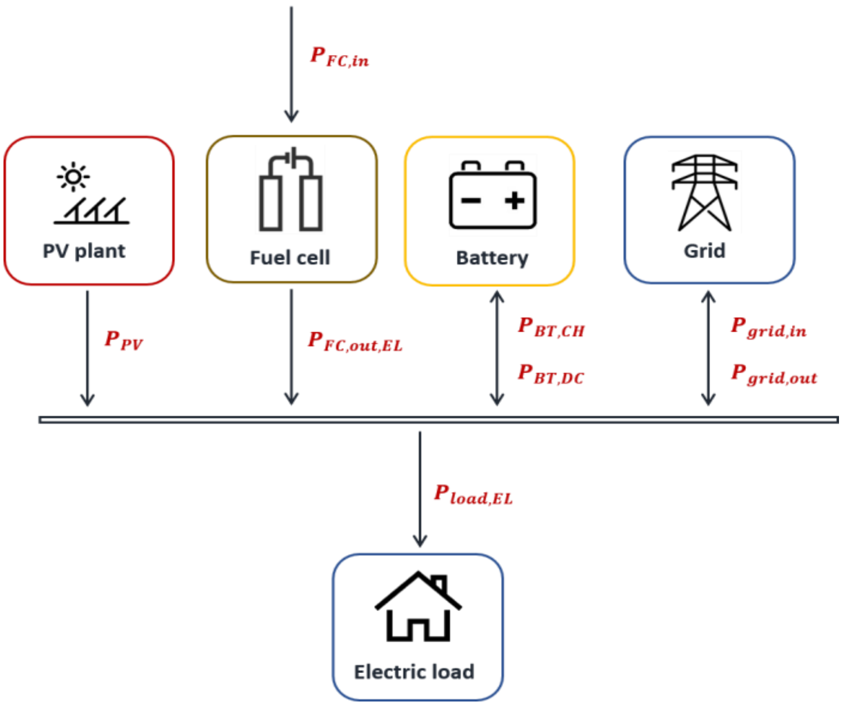


Figure 14 – schematic representation of the electrical side of general case

The power balance of the current electric sub-system is:

$$P_{PV}(t)+P_{BT,dc}(t)+P_{FC}(t)+P_{\mathrm{GRID,out}}(t)=P_{LD}(t)+P_{BT,ch}(t)+P_{\mathrm{GRID,\,in}}(t) \tag{8}$$

For each unit of the system, design variable, operative variable and their constraints are set.

<u>GRID</u>

The $P_{\mathrm{GRID,out}}$ and $P_{\mathrm{GRID,\,in}}$ are the only operative variables assigned to grid. They represent respectively the electrical power withdrawn and sold to the national electrical grid.

PHOTOVOLTAIC

The photovoltaic system is designed by its size in kWp (*PVrated*). $P_{PV}(t)$ is the power outlet of the RES plant and it is calculated by multiplying the optimized design variable for the specific power, explained in the sub-chapter 1.3.2, at each time steps *t.*

$$P_{PV}(t) = PVrated * SpecifPower_{PV}(t) \tag{9}$$

BATTERY

The Li-ion Battery has the role to store energy in excess. At each time step, the energy within the battery can be defined as:

$$\mathrm{E_{BT}(t)} = \mathrm{E_{BT}(t-1)} \cdot (1 - \sigma_{\mathrm{BT}}) + \mathrm{P_{BT,\,ch}(t-1)} \cdot \Delta \mathrm{t} \cdot \eta_{\mathrm{BT,\,ch}} \cdot \eta_{\mathrm{BT,\,conv}} - \frac{\mathrm{P_{BT,ch}(t-1)} \cdot \Delta \mathrm{t}}{\eta_{\mathrm{BT,dh}} \cdot \eta_{\mathrm{BT,conv}}} \tag{10}$$

Where σ_{BT} is the battery self-discharge rate, the $P_{BT,ch}(t)$ is the power stored at each time t and the analogous $P_{BT,dc}(t)$ on other side is the hourly discharged power.

By defining the following constants:

$$a = \Delta t \cdot \eta_{BT,ch} \cdot \eta_{BT,conv} \tag{11}$$

$$b = \frac{\Delta \mathrm{t}}{\eta_{\mathrm{BT,\,dc}} \cdot \eta_{\mathrm{BT,\,con}}} \tag{12}$$

The battery energy can be thus rearranged as (∀ t ≠ 1):

$$E_{BT}(t) = E_{BT}(t-1) \cdot (1-\sigma_{BT}) + \mathrm{a} \cdot P_{\mathrm{BT},ch}(t-1) - \mathrm{b} \cdot P_{BT,dc}(t-1) \tag{13}$$

At the first time step the initial boundary condition is set:

$$E_{BT}(t_{in}) = Cap_{BT} \cdot SOC_{in} \tag{14}$$

Where SOC_{in} corresponds to the SOC at the beginning of the simulation and Cap_{BT} (in kWh) is the battery rated capacity, the design variable.
According to Gabrinelli et [[8]], the storage units can be considered as seasonal storage system and so at the end of the year (t = 8640 h) we have to implement a self-sufficiency constraint:

$$E_{BT}(t_{end})=E_{BT}(t_{in}) \tag{15}$$

<u>FUEL CELL (Electrical side)</u>

For the Fuel cell system, the design variable is the size of the SOFC in terms of kW that has to be installed (PFC,rated). The continuous operative variable is the electrical power output $PFC(t)$ that is linked to the input power of the fuel through the efficiency of the electrochemical device.

$$PFC(t) = \eta, el \ * \ PFC, in\ (t) \tag{14}$$

Moreover a binary variable is set in order to implement the generator limits and indicate the state of on or off (δ). According to the MILP theory, an auxiliary variable is required to transform the product of a continuous and logical variable [4]. Then, some inequalities equation have to be introduced.
The first constraints that we have to insert is the limit on the minimum operating power of the fuel cell:

$$PFC(t) \geq PFC, min \cdot \delta FC(t) \tag{15}$$

Where PFC,min is defined as:

$$PFC, min = yFC, min \cdot PFC, rated \tag{16}$$

and represent the minimum power that fuel cell system can produce. The variable yFC,min is the lower limit of its modulation range.

The following auxiliary variable is then introduced:

$$PFC{,}rated{,}aux(t) = PFC{,}rated \cdot \delta FC(t) \qquad (17)$$

The above logic *(15)* can be then expressed in our model as follows:

$$yFC{,}min \cdot PFC{,}rated{,}aux(t) - PFC(t) \leq 0 \qquad (18)$$

And the following inequalities have to be introduced:

$$PFC, rated, aux(t) - PFC, rated - PFC, rated, min \cdot \delta FC(t) \leq -PFC, rated, \min \qquad (19)$$
$$-PFC, rated, aux(t) + PFC, rated + PFC, rated, max \cdot \delta FC(t) \leq PFC, rated, \max \qquad (20)$$
$$PFC, rated, aux(t) - PFC, rated, max \cdot \delta FC(t) \leq 0 \qquad (21)$$
$$-PFC, rated, aux(t) + PFC, rated, min \cdot \delta FC(t) \leq 0 \qquad (22)$$

where $PFC, rated, max$ and $PFC, rated, min$ correspond to the maximum and minimum value of the design variable PFC_rated.

Same considerations are done on the maximum operating power of the fuel cell. All the not explained constraints are available in Appendix A3.

3.2 Thermal energy balance

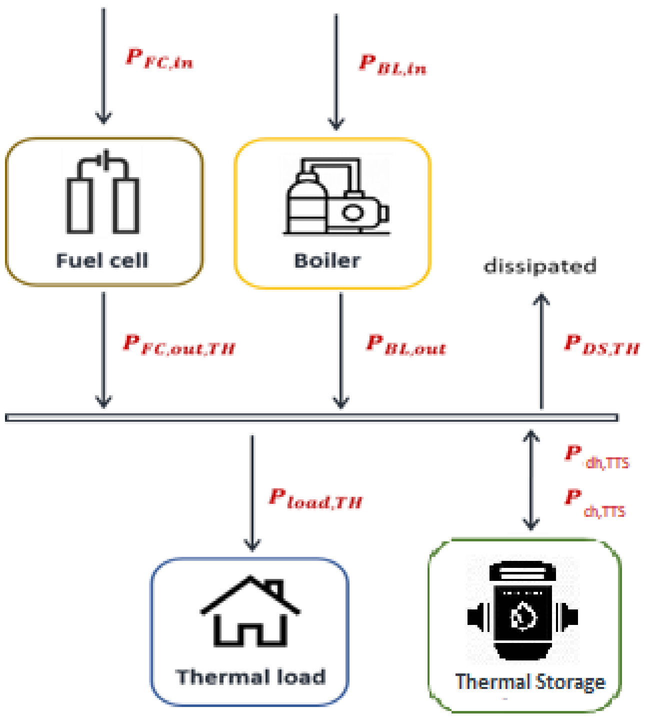


Figure 16 – schematic representation of the thermal side of general case

The thermal request is satisfied by the Gas boiler and the heat wasted from the FC. A hot water thermal storage is inserted to balance the inflow and outflow of thermal energy [[10]]

$$P_{FC,out,TH}(t) + P_{BL,out}(t) + P_{\mathrm{dh},TTS}(t) = P_{load,TH}(t) + P_{DS,TH}(t) + P_{\mathrm{ch},TTS}(t) \qquad (23)$$

GAS BOILER

The condensing gas boiler is designed by its size in kW (*GB_rated*). As for the fuel cell, the generator has some technical limit to take in account and a binary variable, checking the operative in each time steps, and an auxiliary variable must be introduced. The power input models the fuel input and thanks to the efficiency is converted to the power output of the boiler $P_{BL,out}(t)$.
All the constraints are available in APPEDIX A in the table which contains all the equality and inequality equation of the model.

FUEL CELL (Thermal side)

In the fuel cell system when the electrical energy is produced a certain quantity of heat is wasted. So, we can observe two different efficiencies, the electrical and the thermal one. By combining these two it is possible to obtain the thermal power released by the SOFC for each unit of electrical power produced.

$$\eta = \frac{\eta_{th}}{\eta_{el}} \qquad (24)$$

$$Q_{FC}(t) = \eta \, * \, P_{FC}, out\ (t) \qquad (25)$$

THERMAL TANK STORAGE

Thanks to the assumption of ideally stratified hot water storage tank, the energy storage level is determined by the only position of the stratification surface. This means that the state of charge of the tank reached the unit value when it is completely at high temperature.[10]

$$\mathrm{SoCH2O} = \frac{E_{TTS} \ - E_{min}}{E_{max} - E_{min}} \qquad (26)$$

The energy stored in the thermal storage is:

$$E_{TTS}(t)=E_{TTS}(t-1)+P_{ch,TTS}(t-1)\cdot\Delta t-P_{dh,TTS}(t-1)\cdot\Delta t \quad (27)$$

Where $P_{ch,TTS\,t}$ is the excess thermal power produced by the other two generator, and $P_{dh,TTS}$ is the discharged power of the storage.
As for battery, the first time step is fixed:

$$E_{TTS}(1)=Cap_{TTS}\cdot \mathrm{SoCH2O}_{in} \quad (28)$$

where $\mathrm{SoCH2O}_{in}$ corresponds to the state of charge at the beginning of the simulation and Cap_{TTS} (in kWh) is the tank rated capacity.AT the end of the year the self-sufficiency constraint is added:

$$E_{TTS}(t_{end})=E_{TTS}(t_{in}) \quad (29)$$

In the APPENDIX A3 all the design, binary, auxiliary variables and the constraints are fully reported.

Once we have considered all the variables and the rules to be repeated of our problem, the function that defines the value that each varaible will take must be created

<u>OBJECTIVE FUNCTION</u>

The objective function is the function that the MILP code have to minimize in order to obtain a certain optimal configuration of all the variable in the model. In this work a first objective function analysed is the total annual cost of the plant, successively other functions, contains information on the NOx emission and GHG emission, are reported.

It possible subdivide the annual capital cost in three main parts: the investment cost of the plant (Capex), the fixed operating and maintenance cost (O&M) and the variable operating and maintenance cost (O&M).

The first two of these are direct correlated to the size of each component in the system and assigned a cost to each design variable, the total investment cost and fixed O&M is easily calculated as:

$$C_{fixed}=\sum_{i=1}^{n}(capex,i+O\&M,i)*S,i \quad (30)$$

Where *S,i* is the optimized size of the energy component *i*.

A similar argument can be made for the variable operational costs. These costs are strongly associated with the running of the single component that makes up the plant. For example, for generator the variable operation costs are associated to the cost of the fuel in input, so in the case of a gas boiler and fuel cell, they are equal to the cost of methane. So, multiplying the value of the input operative variable of a generator at each time step with the respective fuel cost at the same time step we can find:

$$C_{var} = \sum_{t=0}^{t\_end}(Cvar, i, t) * P, i, t \tag{31}$$

Moreover, we have to remember that in our model a typical days' approach is performed. So, for the variable operational cost a further step is necessary. In fact, the costs input (and the operative variables) are referred to each typical days. These typical days are repeated with different number of times in order to reconstruct the data of the original year. It is necessary to multiply by the number of single typical days that occurs in that year to obtain the annual value.

At the end the annual capital cost is obtained as:

$$C_{tot} = C_{fixed} + C_{var} \tag{32}$$

Now we have to consider that usually an energy system has a medium-high lifetime, and we have to consider the time value of the money during all this lifetime.

Introducing the escalation rate (e_r), the annual rate of increase in the price of a good due to causes such as resource depletion or increased demand, the nominal interest rate (i_{nom}), that is the percentage increase in money value during the time, and considering a lifetime of the system of n years, we can evaluate the present value, n years in the future of a single amount today multiplying the cost by annual rate of interest (*i*).

$$i = \frac{(i_{nom} - e_r)}{(1 - e_r)} \tag{33}$$

$$Actualized\_C_{var} = Cvar, i, t * (1 + i)^n \tag{34}$$

$$Actualized\_C_{O\&M} = O\&M, i * (1 + i)^n \tag{35}$$

The values considered in our model are available in the Appendix A2.

The final objective function as consequence is:

$$C_{tot} = \sum_{i=1}^{n}((capex,i + Actulized\_O\&M,i) * S,i) + \sum_{t=0}^{t\_end}(Actualized\_Cvar,i,t) * P,i,t \quad (36)$$

In order to do a reliable comparison with other scenarios the LCOE is calculated. According to [22] is to calculate the levelized cost of electricity of a system as follow.

$$LCOE = \frac{\sum_{t=1}^{n}(I,t+O\&M_{fix},t+F,t)*(1+i)^{-t}}{\sum_{t=1}^{n} E,t*(1+i)^{-t}} \quad (37)$$

Where I,t is the Investment expenditures in year t, $O\&M_{fix}$ are the operations and maintenance expenditures in year t, F,t is the cost of fuel in year t , E,t is the electricity generation in year t, i is the discount rate and n is the total life of the system.

As we seen in the previous chapter, the numerator is exactly the value of our objective function minimized by the MILP model with the only difference that in the equation (33) only cost referred to the electric are considered. In other words, at our total cost, we need to subtract all the cost of the thermal energy production.

Another approach can be to consider the Levelized Cost of Energy. In this case is considered all the electrical and thermal energy produced and their respectively costs. However, the choice to sum kWh_{el} with kWh_{th} can be questionable and for this reason not considered.

When a CHP generator, like fuel cell, is implemented in the system a correction on the LCOE has to be done. The heat produced by the co-generator has to be considered as revenues so subtracted from the total costs. According to [23] we assumed a heat price based on the natural gas price, divided by the gas boiler efficiency. So, the final formula for the Levelized cost of electricity considered for a CHP system is:

$$LCOE = \frac{\sum_{t=1}^{n}(I,t+O\&M_{fix},t+F,t)*(1+i)^{-t}}{\sum_{t=1}^{n} E,t*(1+i)^{-t}} - \frac{Fheat,t*(1-i)^{-t}}{\eta GB} \quad (38)$$

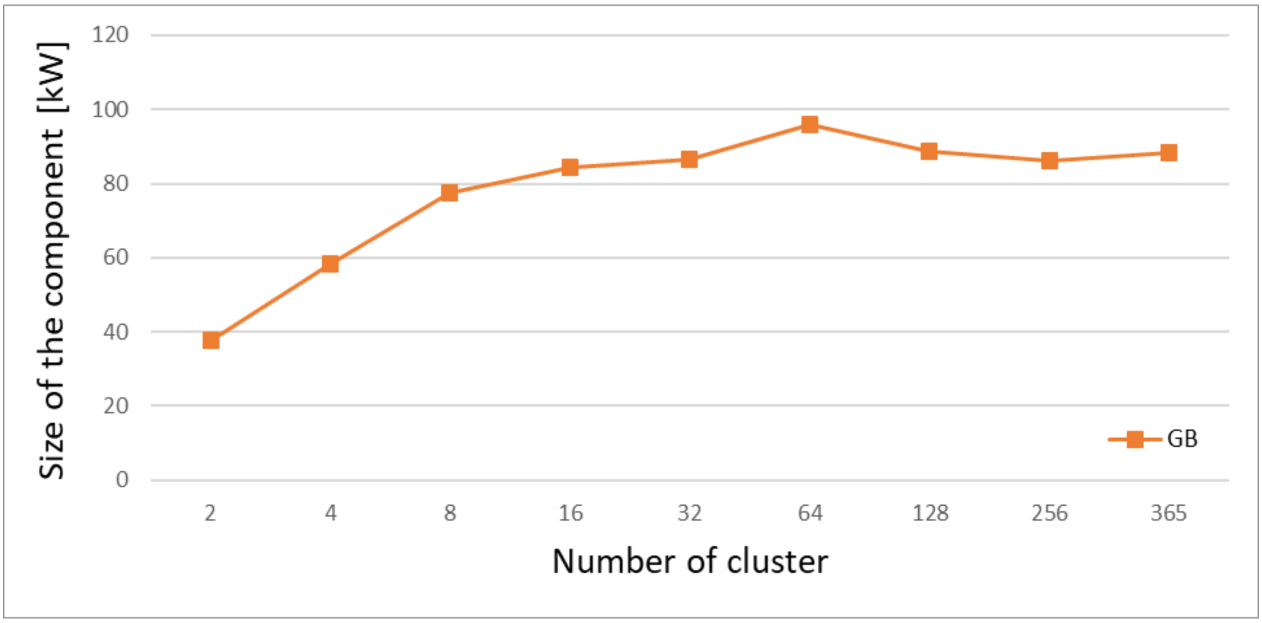
3.3 Optimal number of Typical Days

The typical days are calculated through the method explained in the previous chapters based on the hourly cost of electricity, methane, the hourly load of the building, temperature, and irradiation data of the location. Their plots are available in Appendix A1.

To reach those results another data input is necessary to be set in the k-means algorithm, the exact number of cluster that it needs to calculate. This type of information has to be a good compromise between time computational and the reliability of the result so in order to find an optimal number of clusters, a pre-simulation on the thermal sub-problem is performed.

The pre-simulations consist of making a comparison on the results obtained using different initial number of typical days. The reason why we are focusing only on a sub-problem is that the optimal value of the variable for the ideal case (k = 365) has to be researched and this let us to not have computational cost too high. Then, by decreasing the number of typical days, a plot with the respectively optimized variable obtained is done.

In Figure 17 the trend of the size of the gas boiler and the thermal tank storage at different initial number of typical days are illustrated.



(a)

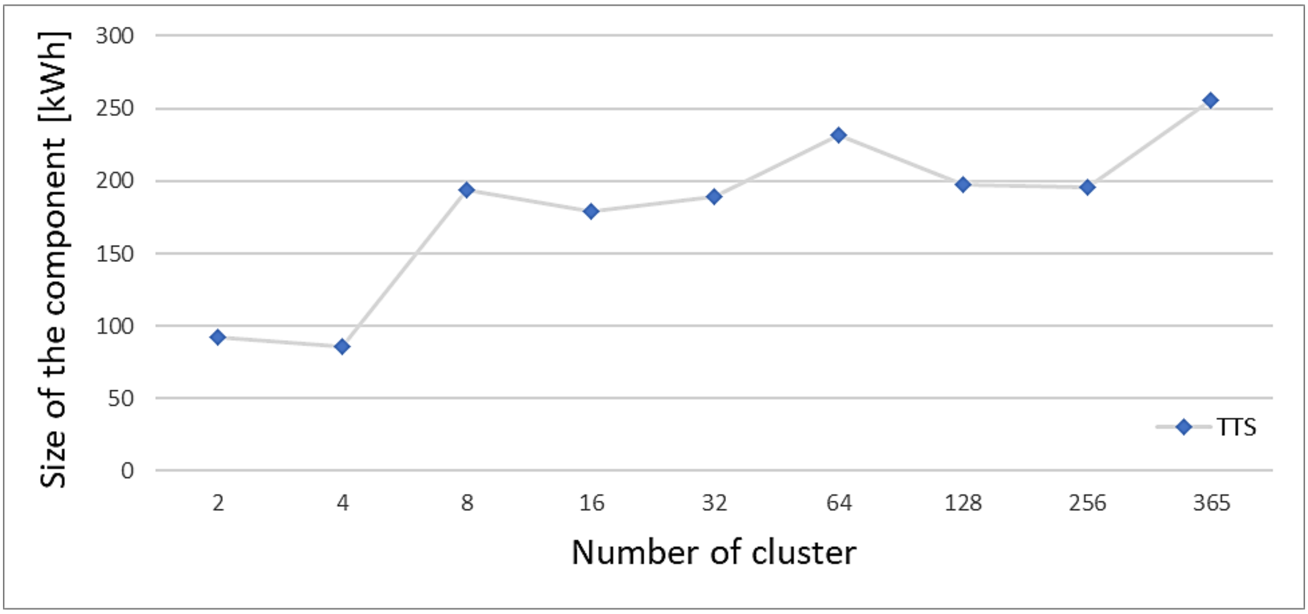


Figure 17 – Design variable of GB size (a) and TTS (b) vs different number of typical days

In theory, as the number of clusters increases, the sizes should tend more and more to the ideal case and reach a sort of plateau where, increasing more the number, the sizes don't vary anymore. This trend is visible in the graph of gas boiler, but it is possible that in some variable this doesn't happens like the trend of the Thermal tank's size. In these cases, the number of typical days chosen is that minimize the relative error respect to the sizes of ideal case. So, the optimal number chosen is equal to k=64 which approximate the perfect case with a relative error of 4.05%.

4. Baseline scenario results

In all the simulations no upper limits are set to the design variable in order to not influence the result and the choice of technologies. Lifetime of the system is considered equals to 20 years and the MILP model is solved by setting a relative MIP gap of 0.03%.

4.1 Reference scenario

The reference scenario GRID+GB+TTS is now simulated. All the electrical load is satisfied by the energy withdrawn by the grid and the gas boiler ensures the thermal request with the help of the hot water tank storage.
In this condition the optimal configuration that minimizes the total cost of the plant is illustrated in Table 8.

Table 8 - Reference scenario: optimal configuration

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	-
Battery (BT)	-
Gas Boiler (GB)	95.9 kW
Thermal tank storage (TTS)	231.4 kWh

In the figure 18 we can see the percentual of the load satisfied by each technologies.

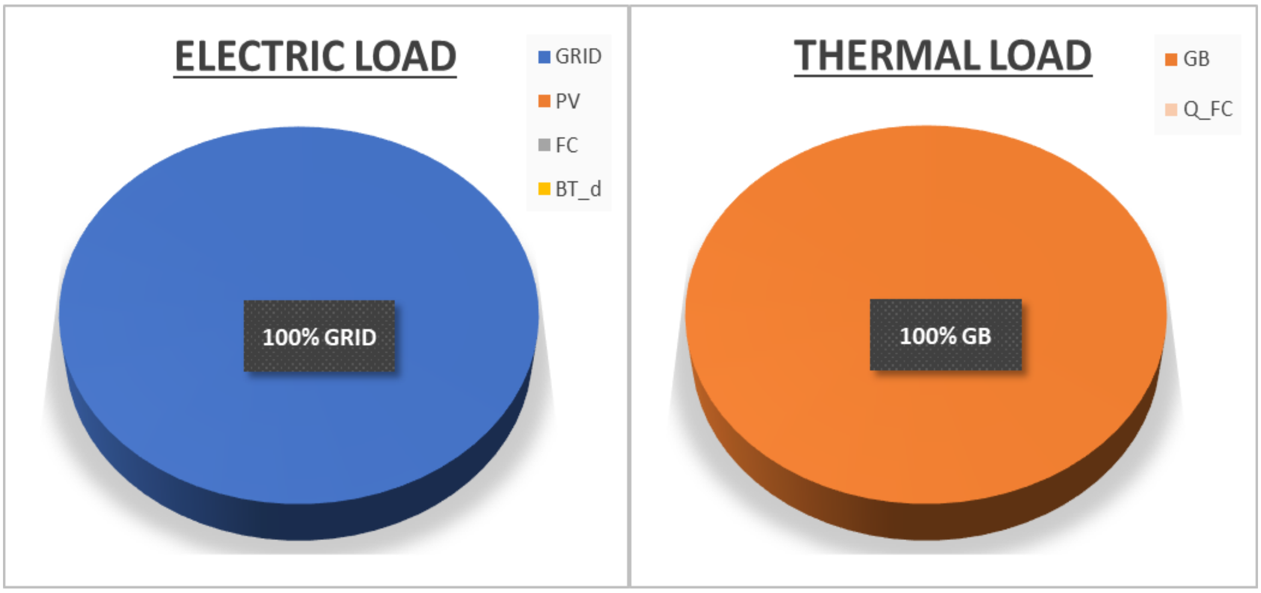


Figure 18 – Reference scenario: Percentual of the load satisfied by the energy component

Result of the simulation are reported in table 9.

Table 9 - Reference scenario: Results

Lifetime system Cost [€]	€ 2,297,670
LCOE [€/kWh$_{el}$]	0.148

Focusing on the value obtained we can observe that is very close to the mean value of the electricity cost used as data input. This condition is confirmed since all the electricity is withdrawn from the grid, the small difference may be caused by the approximation of the typical days and the MIP gap.

4.2 SOFC scenario

In this case the electric load is partially satisfied by the grid and the fuel cell system while the thermal request is guarantee by the heat recovered from fuel cell system with the help of a Thermal storge tank to satisfy the peak. The FC system is directly feed by the methane and also the battery model is implemented.

The optimized configuration of the systems GRID+FC+BT+TTS is reported in table 10

Table 10 - SOFC scenario:optimal configuration

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	126.1
Battery (BT)	-
Gas Boiler (GB)	-
Thermal tank storage (TTS)	6015.89 kWh

Regarding the total thermal request, it’s completely guarantee by the fuel cell as shown in Figure 19. The SOFC size installed is not sufficient to cover the peak of electrical demand and energy from the grid must be bought. However, the fuel remains switched on for whole year to guarantee always a minimum of base load. The electrical load is satisfied by the SOFC for the 57% and the remaining part from the electricity withdrawn from the grid as we can see in Figure 19. A little amount of energy is also sold to the grid, and this occurs mainly when the fuel cell is charging the thermal tank storage in the hour of less electricity request.

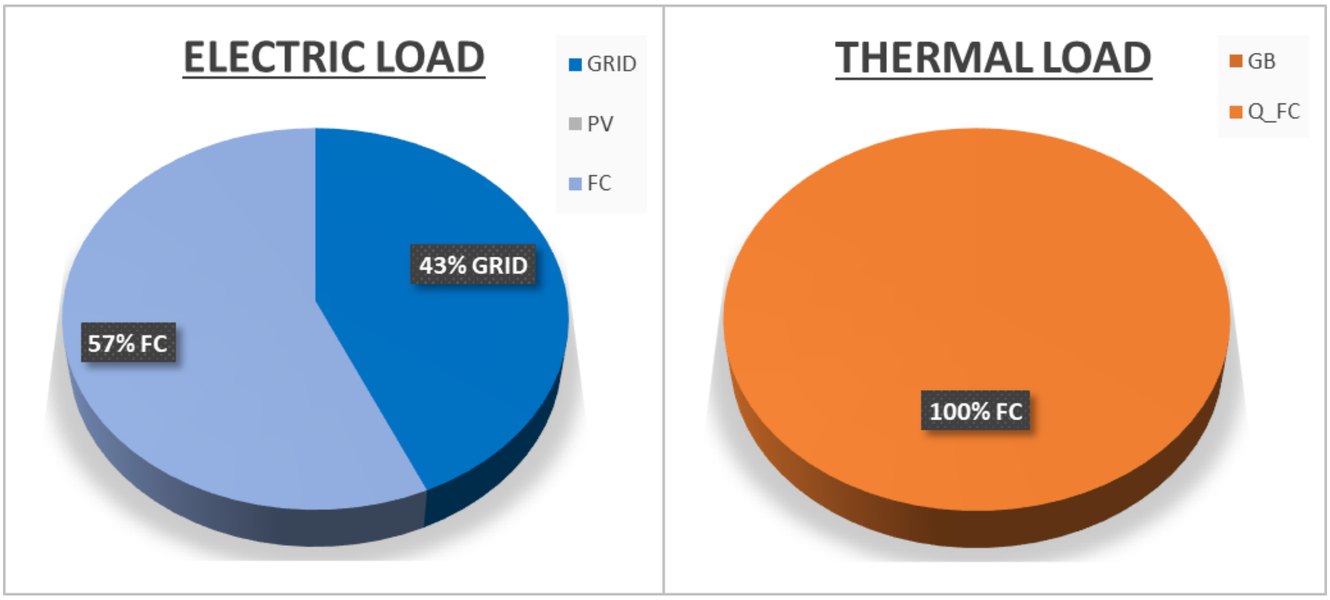


Figure 19 – SOFC scenario : Percentual of the load satisfied by the energy component

Table 11 summarize the result of the simulation:

Table 11 - SOFC scenario: Results

Lifetime system Cost [€]	€ 3,940,218
LCOE [€/kWh$_{el}$]	0.265

As we can see for direct comparison the implement of SOFC system, with the technical data input of Table 3, are not convenient on the point of view of the costs. The main cause of the total cost plant increase is due to the high investment cost of the fuel cell. It also has to be considered that the life stack of the SOFC is shorter than the lifetime of the plant, and its cost has to be considered for each replacement that we need to install to cover the whole life of the plant. Result demonstrates that the impact of Capex and O&M cost in the actual condition are almost the 60% of the total cost.

All these considerations are confirmed by the simulation of the system composed by the **GRID+GB+FC+BT+TTS.** Here, the electric load is partially satisfied by the FC and the remaining part not satisfied is covered buying the energy from the grid. The thermal Load is satisfied by the Gas boiler in a percentage lower than the reference system thanks to the heat recovered from the FC. A Thermal storge tank is always present.

The result of the optimal configuration is exactly equal to the Reference scenario of chapter 4.1.

5. GHG and NOx emissions analysis

When we are talking about a RES plant a particular attention is shifted to the environmental impact and the benefits that this entails. In the following section a more detailed description on the emission data in terms of NOx and CO_2 emission are performed and future scenario are analysed.

5.1 NOx Emissions

One of the main advantages of fuel cell systems are the low value of pollutants emissions (PM, NOx, SOx, VOC etc.) during their operation. The NOx pollutant is one of the main and important anthropogenic green gashouses. Normally molecular of nitrogen (N_2) is present in air with a percentage that is close to 80 as inert gas, however, the single atom nitrogen (N), can be reactive and produce toxic molecule. The NOx is the main cause of acid rain in the world, and they are produced mainly by human activities as: vehicle emission (50%), Electric Power Plants (20%) and other sources (30%) as [24] reported. It easy to observe that SOFC can be an important technology which can reduce emissions in both leading categories.

For the analysis of NOx emissions, the emission values caused by the operation of the technology alone were obtained (LCA approach was not considered). For each energy component in the model, we obtain the NO_X emissions [mg / kWh].

Table 12 - NOx emission of each technology

Technology	NOx emissions [mg/kWh]
GRID	211
PV	0
FC	35
GB	45

Is important to notice that the effective value of the SOFC's NO_X emission is very low and very difficult to contend. According to the manufacturer of the cosmos project [1], the value chosen is the limit of the measuring instrument taken as the maximum limit of the technology, but it is possible that the actual emissions of the stacks are lower.

The new gas boiler installed have to respect strict laws on limitation on pollutant emission, the data select from the datasheet of the manufacturer [16], are therefore verified by a study conducted in Great Britain on the exhaust fumes of boiler which ascertain the goodness of the value. [[17]

In order to find the optimal configuration that minimize the NOx emission the objective function of our MILP model has to be changed. All the emission data are referred to the kWh produced and so to the operational variable of our model. The calculation of NOx emission it is quickly done multiplying each emission factor, (E_{NOX}, i, t) with the hourly power produced by each technology.

$$NOx = \sum_{t=0}^{t\_end}(E_{NOX}, i) * P, i, t \tag{39}$$

As for the operative variable cost, in order to obtain the annual value, we have to remember to multiply the result carried out by the number of single typical days that occurs in the year. The simulations were made by analysing the system formed by FC + GB + BT + TTS + GRID. The results are illustrated below.

Table 13 - Simulation's result of the optimal NOX minimum plant with no cost constraints

RESULT	
Lifetime System Cost [€]	€ 29,586,947
LCOE [€/kWh$_{el}$]	0.372
Tot NOx [kg/y]	40.01

As we can notice the cost and therefore some sizes have gone out of range. This is due to the fact that the above simulation only serves to know what the minimum NOx value is. The LCOE value is to be recalculated by setting that NOx constraint and minimizing the cost.

In fact, in this simulation, the technologies that do not interact with NOx have no cost constraints and can assume random values compatibly with the constraints it has set.

In other words, since it is not possible a priori to know the number of how many configurations of my system can give me this result, we imposed on the system the maximum quantity that it can emit exactly equal to the minimum one just found and with this limitation we are gone to minimize the total cost of the system during its life.

Table 14 - NOx minimum scenario: optimal configuration

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	208.8 kW
Battery (BT)	-
Gas Boiler (GB)	28.4 kW
Thermal tank storage (TTS)	55,241.95 kWh

Table 15 - NOx minimum scenario with cost costraits: results

RESULT	
Lifetime system Cost [€]	€ 6,725,662
LCOE [€/kWh$_{el}$]	0.356
Tot NOx [kg/y]	40.01

By setting several NOx limits and always going to minimizing the total cost of the plant, it's possible to plot a kind of Pareto curve where we find the cost of our system on the y axis and the corresponding emissions produced on the x axis. As can already be understood, the point calculated above corresponds to the minimum emission point (and higher cost).

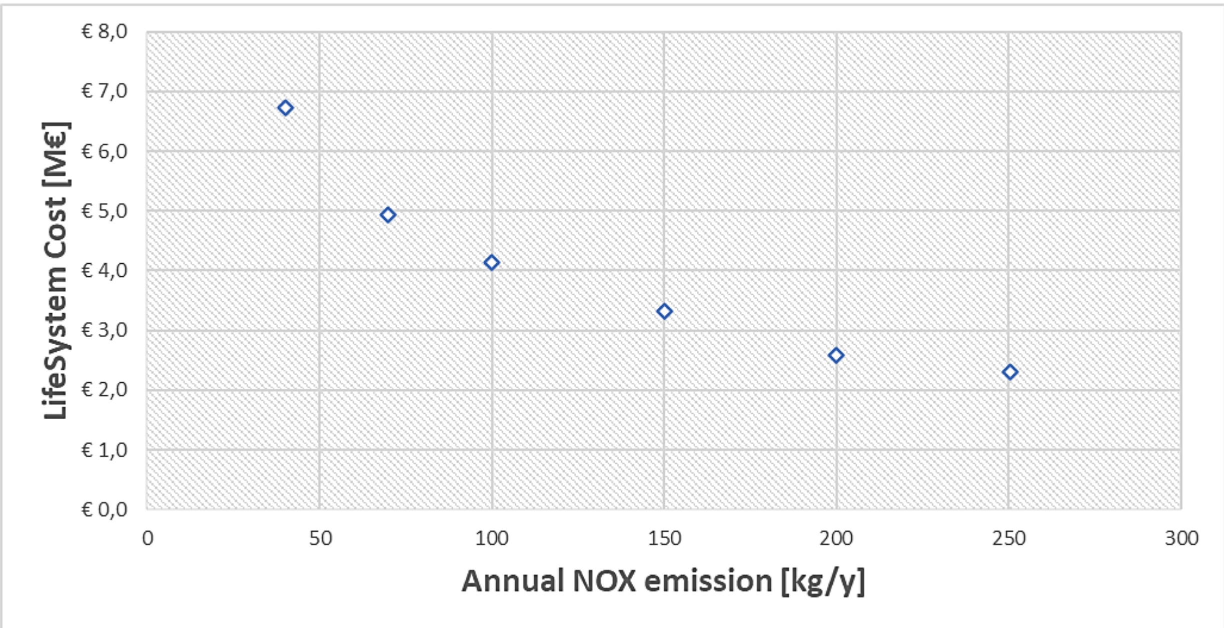


Figure 20 – Pareto Curve: NOx emission vs total plant cost.

For each point of the curve is interesting to see how the size of selected technologies vary. The graph below shows the results.

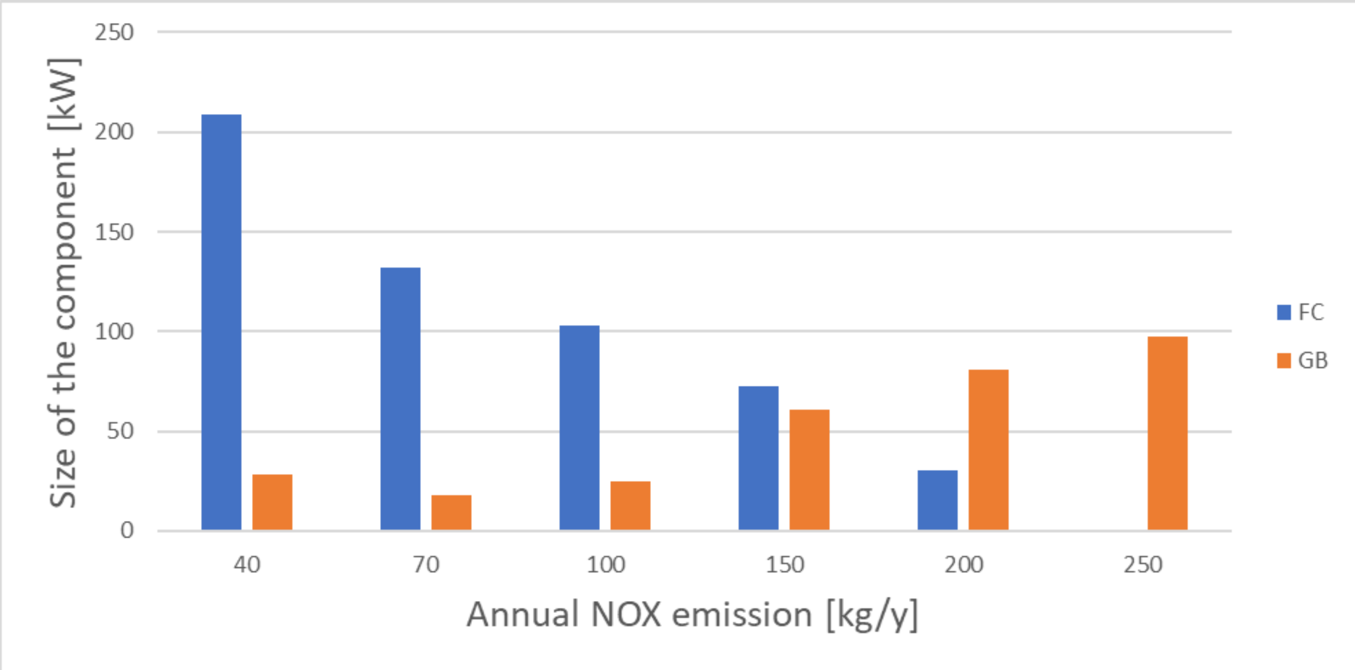


Figure 21 – Size of technology respect each point of Pareto curve.

As we can see in figure 21, more the size of SOFC system increase more the NOx emissions are reduced. On the other hand, the cost of plant enhances up to three times in the configuration of the best environmental condition, so a careful analysis has to be performed in order to find a good compromise between emission reduction and total cost of the plant.

5.2 GHG Emission

A further study of environmental impact is done analysing the CO_2 emitted by the systems. in this chapter, not only the CO_2 emitted during operation is considered but also the emission due to make, transport and install a selected technology is taken in account. The end-use and disposal are not considered in the work due the little impact that they have in most cases according to Inergio. [25].

MANUFACTURING GHG EMISSION

The following table summarizes the $gCO2_{eq}$ due only to the production, transport, and installation of each technology.

Table 16 -GHG emission manufacturing and install process

GHG emissions [$kgCO_{2eq}$/kW)]	
GRID	-
FC	500
GB	1060
BT	85 KgCO2eq/kWh
PV	1400

For the battery an average between two different references [26], [27] has been done while for the other technologies the Inergio data are considered.

A particular observation has done on the manufacturing emission on the gas boiler. Since no data in terms of CO_2eq/kW are found in any scientist paper, a statical approach is performed. From literature[28], it appears that ca. 12% of the entire impact of a gas boiler system is due to manufacturing and different source indicate a range of 200 – 250 gCO_2eq/kWh_{th} as a good estimation of the total impact of gas boilers reported on their thermal energy produced. A reliable data can be taken from [29] equal to 235 gCO_2eq/kWh_{th}.

Therefore, on average, assuming a boiler operation equal to 60% of the hours in a year for 20 years (life system), we are able to obtain the total hours of operation ca. 105,120 h (according to the lifetime result of literature [28]. Considering during the year an average power operation equal to 36% of nominal power (45 kW) we can easily obtain the total energy produced and dividing by our its nominal size (125 kW), we are able to obtain a value in terms of kWh / kW that represent the total energy release in the whole life for each kW installed.

$$E_{GB}tot = 36\% * NominalSize * \ htot \ = \ 4.730.400 \ kWh \tag{40}$$

$$SpecifPowerGB = \frac{E_{GB}tot}{NominalSize} = \ 37843{,}2 \ kWh/kW \tag{41}$$

Considering now the percentual due to manufacturing the boiler and the carbon footprint selected before we will obtain as result:

$$CO2eq = 12[\%] * 235 \left[\frac{\mathrm{gCO2eq}}{\mathrm{kWh}}\right] * \frac{1}{1000} \left[\frac{\mathrm{kg}}{\mathrm{g}}\right] * SpecifPowerGB \left[\frac{\mathrm{kWh}}{\mathrm{kW}}\right] = 1060 \left[\frac{\mathrm{kgCO2eq}}{\mathrm{kW}}\right] \quad (42)$$

OPERATIONAL GHG EMISSION

As specified by [30] , the amount of CO_2 equivalent indicate the environmental impact of all the GHG gas, referred to CO_2 as unit.

In our case, for the operational GHG emission, we assume the hypothesis that only CO_2 gas occurs in the formation of CO2eq and fuel all considered 100 % composed by methane (CH_4).

Table 17 - Methane LHV and CO_2 mass molar

LHV CH_4	0,247	kWh/mol
mCO_2	44	g/mol

Therefore, a simple chemical analysis on generator can be performed in order to obtain their respective emission factor. The method is similar to the one used in [25]. A generator can be expressed as a box with an input and output energy flow and these energies are linked one each other by the generator's efficiency.

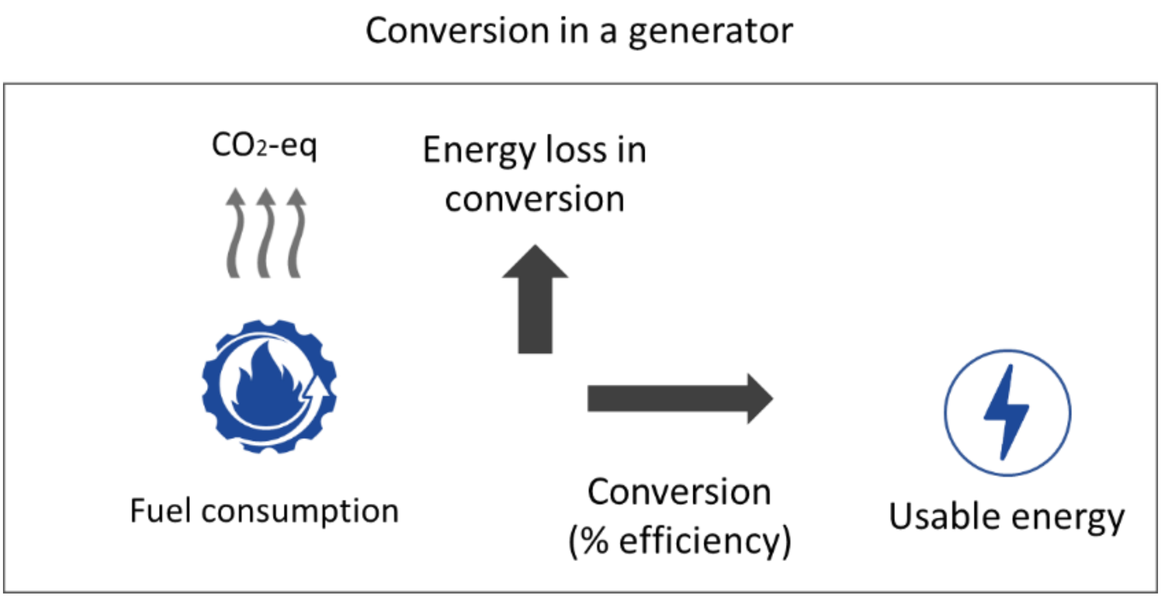


Figure 22 – Schematic representation of generator. Source: Inergio [25]

With the assumption considered before, we have that, for each CH_4 mole entering in the generator, 1 mole of CO_2 is emitted. Knowing therefore the efficiency of the gas boiler, LHV of CH_4 referred to moles and known the molecular weight of CO_2, is possible to find the generator emission as:

$$GHG_{gen} = \frac{mCO2}{(LHV_{ch4} * Eff_{gen})} \tag{43}$$

For the gas boiler unit, the energy associated to a single mole of methane is converted with an efficiency of 98% corresponding to 0.243 $kWh_{th}/molCH_4$. By dividing the mass molar of CO_2 with this net usable energy we have obtained 181.6 gCO_2 emitted for each kWh_{th} produced by the gas boiler. Regarding Fuel cell system the same methane energy of input is converted to electrical and thermal energy with respectively the 55% and 27% of efficiency, that means that for each mole of CH_4 entering in the system are produced contemporanely 0.124 kWh_{el} and 0.067 kWh_{th}..

For the calculation of the GHG emission the SOFC's electrical efficiency has been considered, and the result reports 323.6 gCO_2 emitted for each kWh_{el} produced, fully compatible with the results provided by other scientific paper that indicates a range from 250 – 450 gCO_2/kWh. [30]

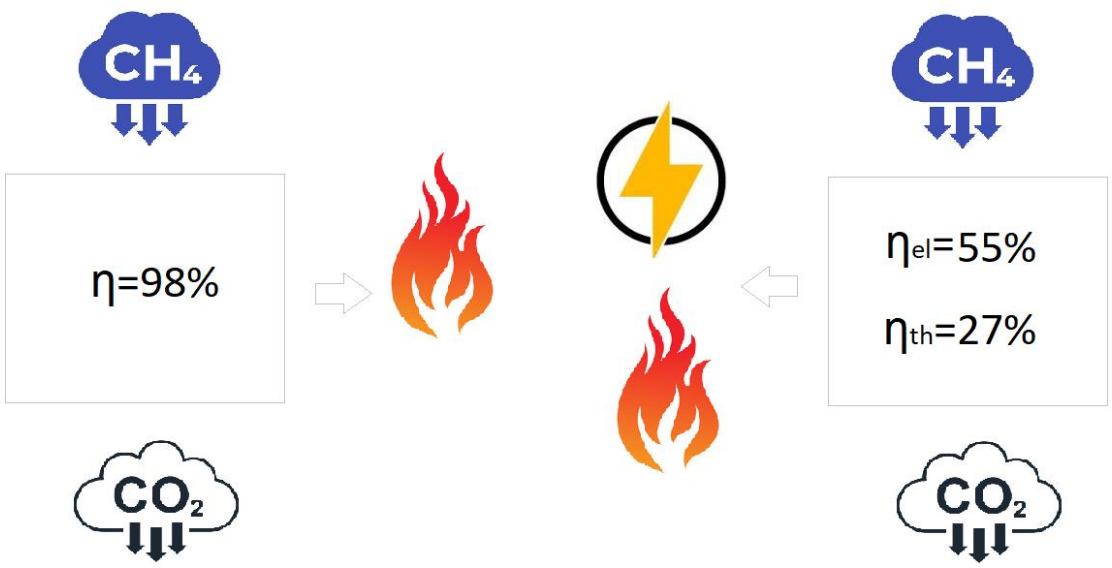


Figure 22b– Schematic operation of gas boiler and FC generator.

The emission due to the operation of the energy component used in the model are indicated in Figure 23

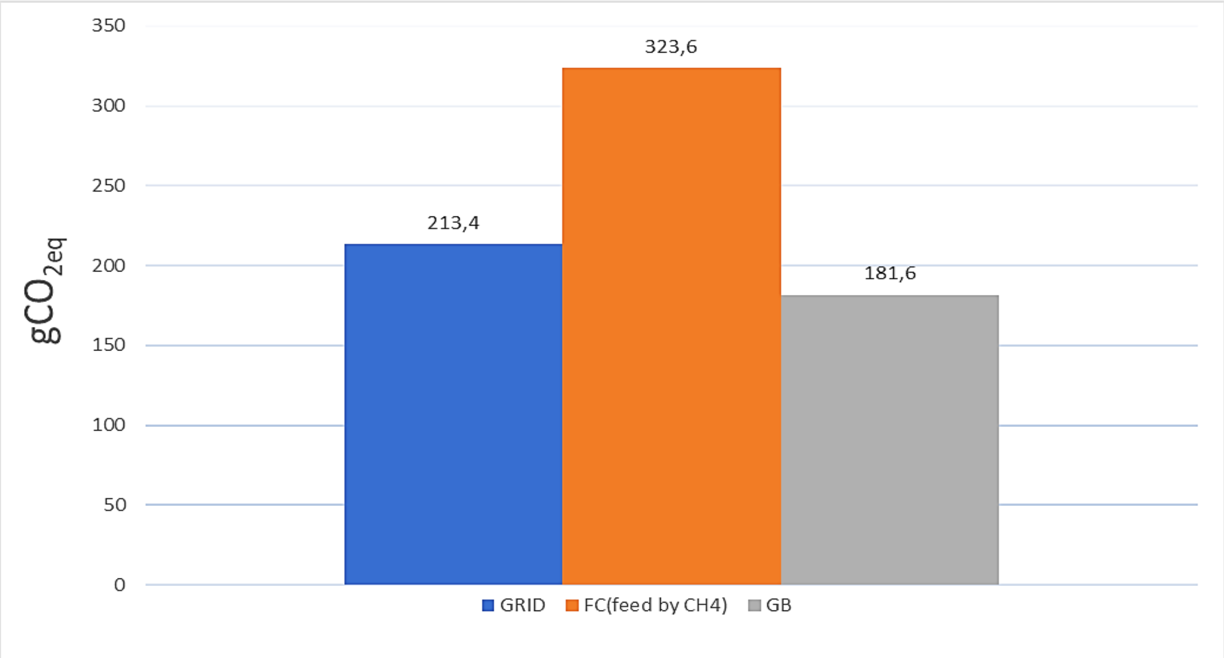


Figure 23– GHG operational emission of the technologies in the model

To the energy withdrawn by grid is assigned the value of the carbon intensity of the Italian Grid according to the IEA [31] while for both the Battery and PV system their operational emissions are considered null.

The objective function to minimize is close to the one explained in the chapter 2 with the difference that the not actualized capex+O&M_{fix} and the not actualized variable cost are respectively substituted by the emission factor of production process and the emission facto for operating. The annual value is then multiplied by the value of lifetime to obtain the total amount of CO_2 emitted during the whole life of the plant.

In the following page, the result for the case FC + GB + BT + TTS + GRID is shown.

Table 18 - GHG minimum scenario: optimal configuration

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	-
Battery (BT)	-
Gas Boiler (GB)	66.2 kW
Thermal tank storage (TTS)	3223.5 kWh

The best cost GHG emission optimized plant is composed only by GRID+GB+TTS.

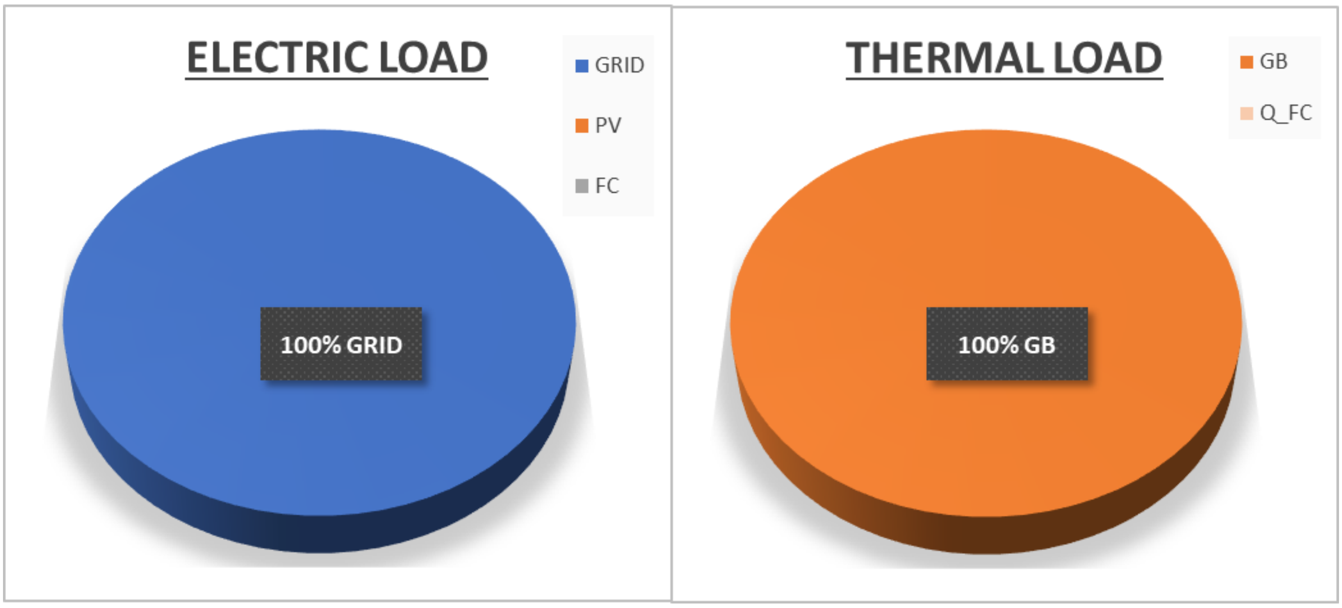


Figure 24– Percentual of load satisfied by the technologies

Table 19 - GHG minimum scenario: results

RESULT	
Lifetime system Cost [€]	€ 2,382,239
LCOE [€/kWh el]	0.148
Tot NOx [kg/y]	250.6
Tot CO_2 [ton]	5900.6

In figure 25, it possible to notice that the manufacturing of the GB does not affect almost total emission (1.78%) according to [28]. This confirm that our initial hypothesis can be considered reliable.

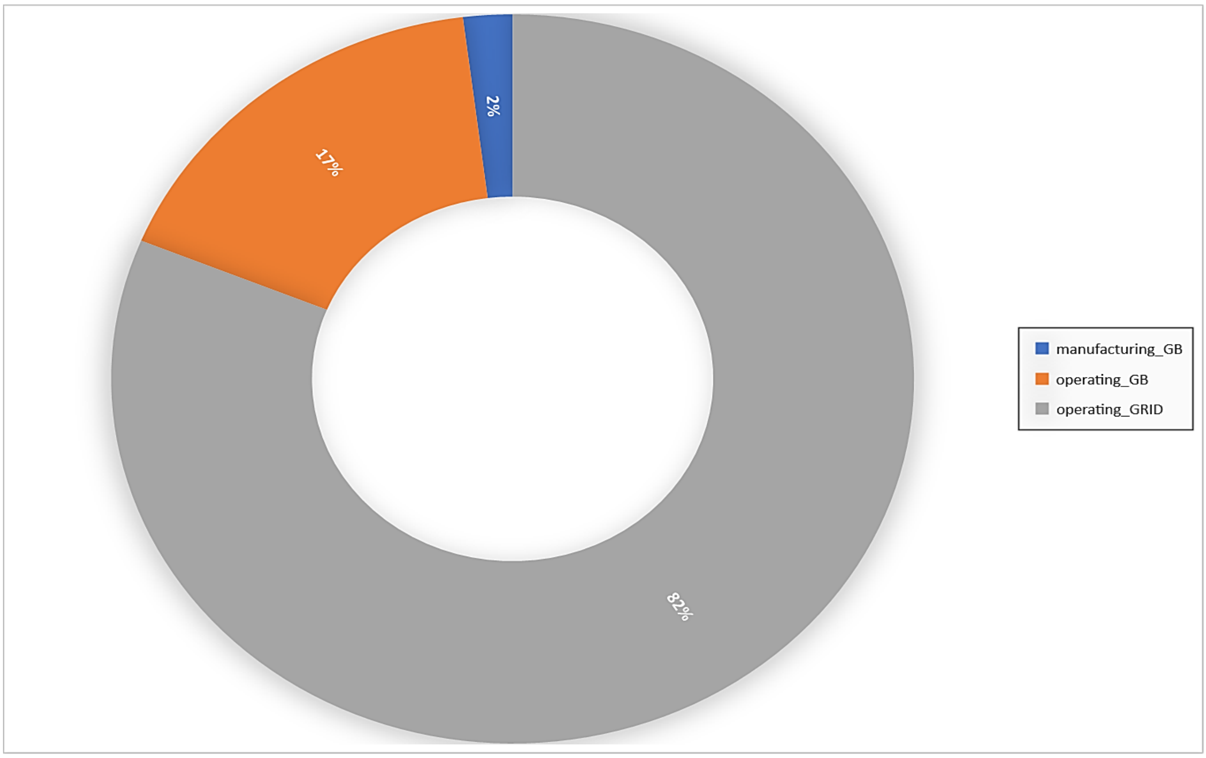


Figure 25– Emission fraction in GHG minimum scenario

Moreover, to understand which factor of the GHG emissions weighs the most, a simulation was performed first by minimizing only the CO_{2eq} emitted by the operation of the technologies and then considering only the CO_{2eq} emitted for their production.

Both simulations confirm that the optimal configuration respect to the GHG emission is the system GRID+GB. The fuel cell has a quite high emission factor for the manufacturing and the short life amplify this value, moreover the efficiency influences its operational emission.

It must be considered that the carbon intensity of the Italian grid is quite low compared to the European and world media as we can see in Figure 26.

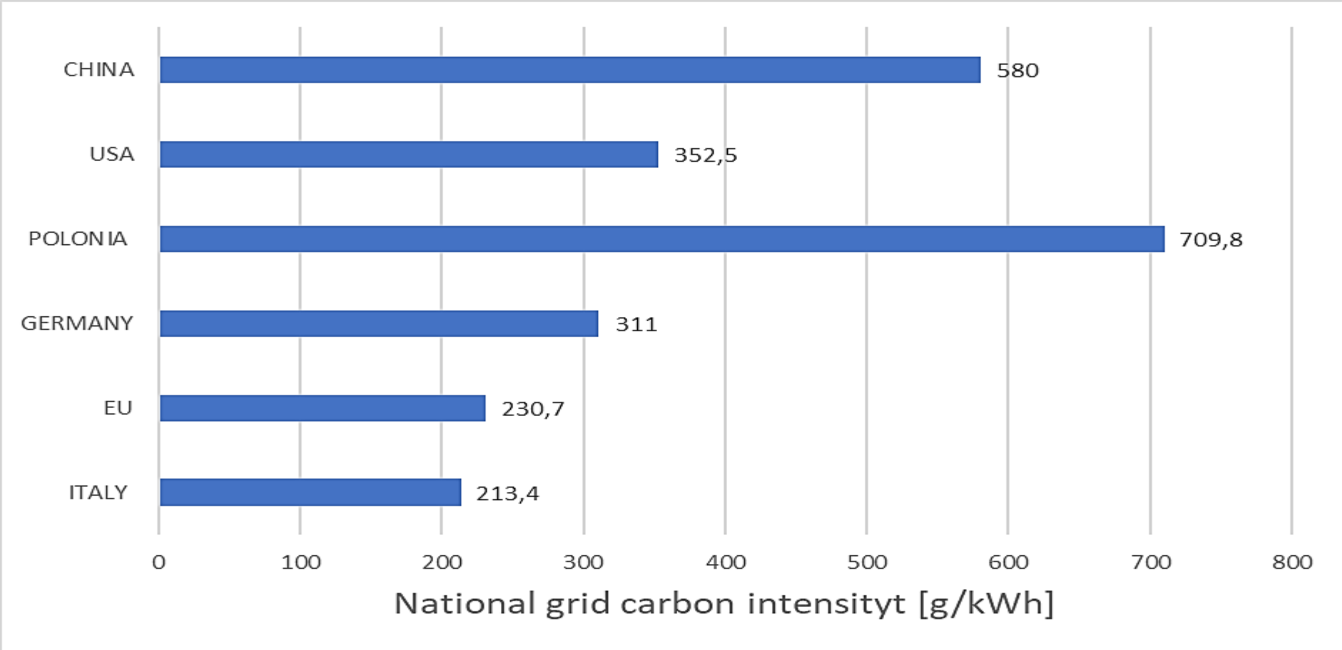


Figure 26– Carbon intensity of different national contest- Source: IEA

Therefore, considering foreign contexts, Figure 27 shows how the implementation of the fuel cell becomes a useful choice to guarantee a low GHG emission of the plant in countries with still a high rate of carbonation.

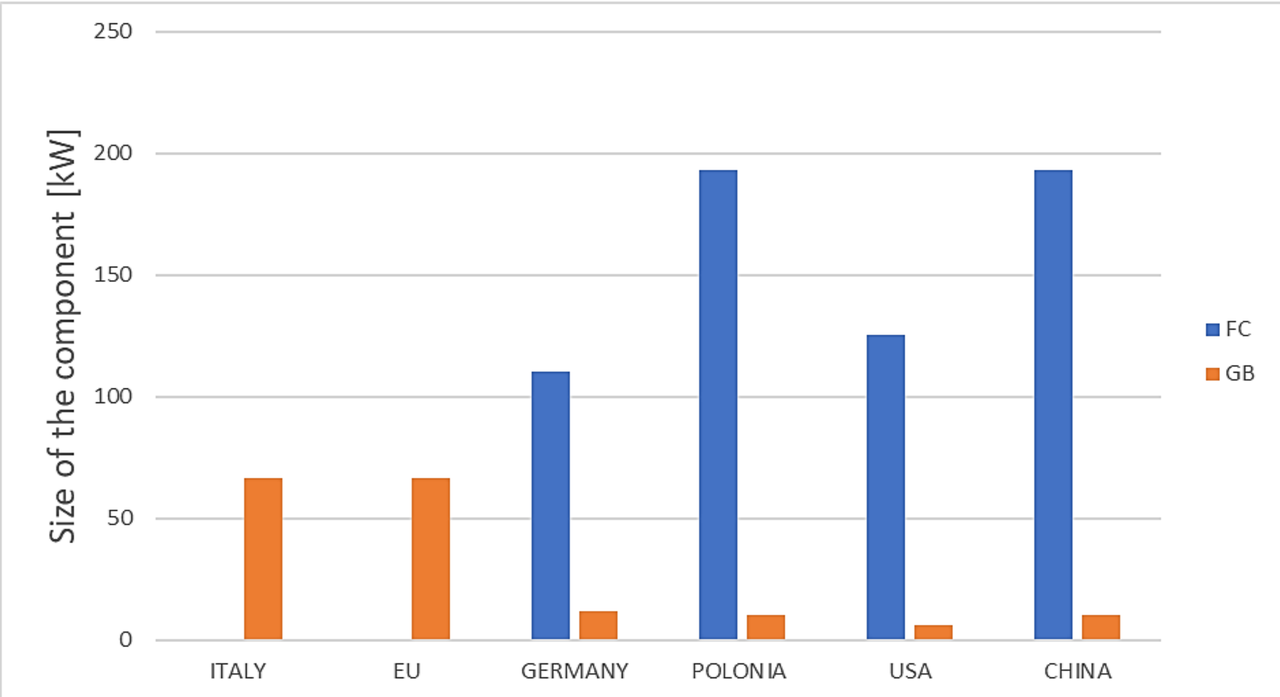


Figure 27– FC and GB size in different national context

Also increasing SOFC's efficiency can bring a benefit by reducing its operational emissions. Considering 1 kWh_{el} electrical energy produced by fuel cell we obtain at the same time ca. 0.491 kWh_{th} of thermal energy with a total emission of 323,6 gCO_2eq.

Satisfying the same quantities of energy by withdrawn electricity from the grid and using heat produced by gas boiler we obtain respectively an emission of 213.4 gCO_2eq for the electrical side and 89,15 gCO_2eq for the thermal one with a total emission of 302.55 gCO_2eq.

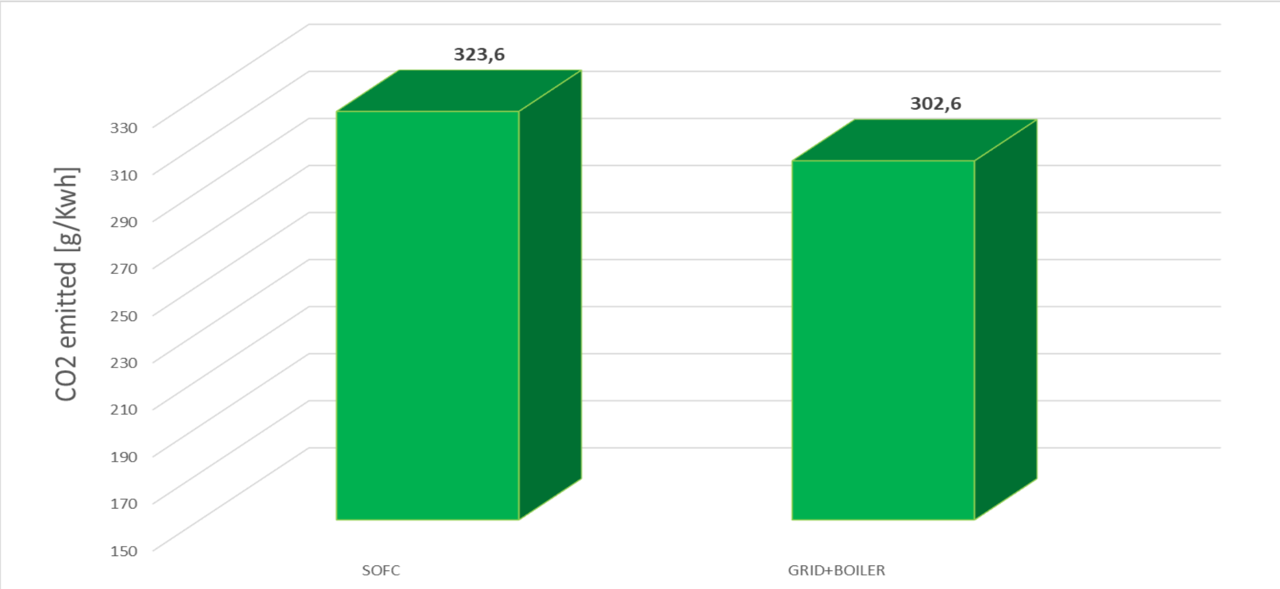


Figure 28– Total operational emission of FC stack and GRID+GB system for the same amount of total energy

The increase in the electrical efficiency of the fuel cell leads to different scenario.

Table 20 -FC electrical efficiency and respective GHG emission

η_{el}	**GHG emission**
55%	323.6 gCO_{2eq} /kWh_{el}
60%	293.6 gCO_{2eq} /kWh_{el}
65%	273.7 gCO_{2eq} /kWh_{el}

In our initial case, maintaining constant the thermal efficiency, we obtain that SOFC system becomes to be an optimal choice with aelectrical efficiency equal or greater than 65% with a reduction of total emission emitted equal to almost 100 ton at year.

The same increase in thermal efficiency also leads to an improvement in the condition of the fuel cell. This is due to the fact that will have a greater amount of thermal energy for each kWh of electricity produced but the same CO_{2eq} emitted. This additional thermal energy, in the event that the system does not include the fuel cell, must be supplied by the gas boiler and will therefore worsen the condition of the GB + GRID system. For example, remembering equation (43) descripted in chapter 5.2, and increasing thermal efficiency up to 35%, with actual value of electrical efficiency, is possible to recover 0.636 Kwh_{th} for each 1 kWh_{el} produced from the SOFC stack.

Table 21 - GHG operational emission of FC and GRID+BOILER with FC's thermal efficiency 35%

SOFC	323.6	g CO_2 emitted
GRID+BOILER	328.9	g CO_2 emitted

The results of the simulations obtained on our system says that the fuel cell becomes convenient in terms of tot GHG emissions by increasing the η_{th} up to 40% maintaining the η_{el} equal to 55%.

5.3 Sensitivity analysis

The choice of the fuel cell system remains notoriously disadvantaged by its high cost and the short lifetime. Analysing the case GRID + FC + GB + TTS a sensitivity analysis on those parameters is done in order to find possible target value.

CAPEX REDUCTION

In Figure 29 the result of reducing in percentual at each step of the CAPEX on the size of the fuel cell is shown. The simulations are done minimizing the total plant cost.

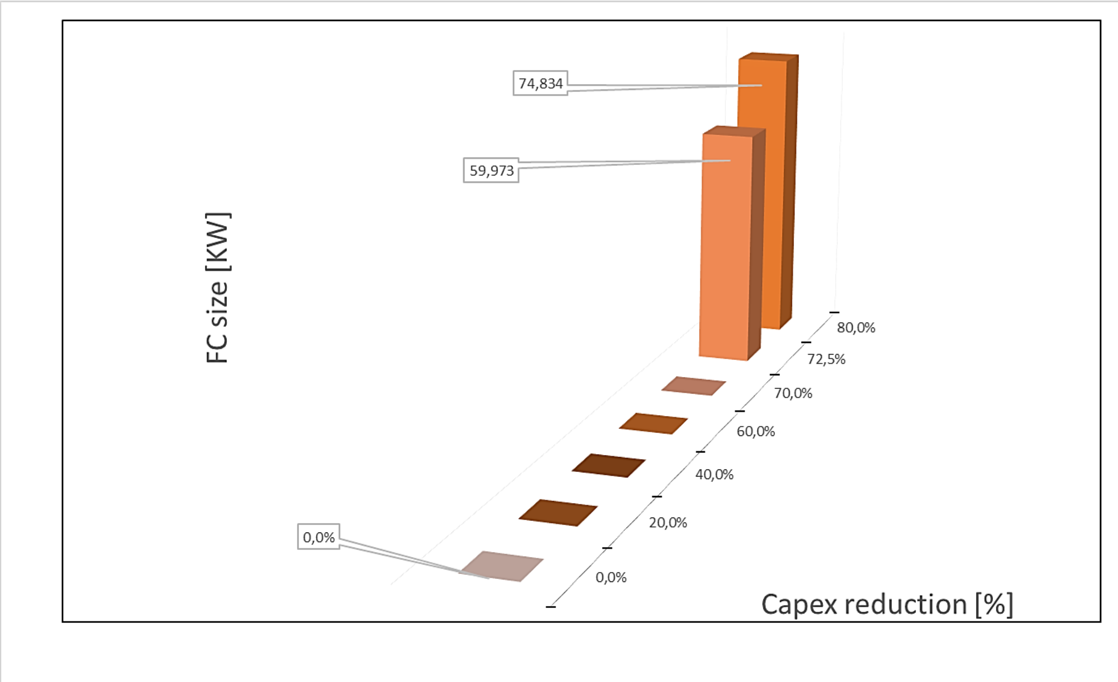


Figure 29– Fuel cell size reducing its investment cost

As we can see, the target cost for which to use the fuel cell became advantageous is equal to € 3266, with a reduction of 72.5% of its current value according with manufacturer [1]

Table 22 - Value of capex reduction considered

Reduction	Capex[€]
0	11800
20%	9440
40%	7080
60%	4720
70%	3540
72.5%	3266
80%	2360

LIFETIME IMPROVEMENT

Another important aspect against the fuel cell is its short life span. The increased lifetime means that fewer replacements are needed and so a lower cost of the system. Analysis are be done analysing the size of SOFC respect to the varying of the year of life at step of 5 years.

With the current cost no benefits derive from increasing the value of life stack. As we can see in the figure 30 the use of fuel cell, with the current costs, is still disadvantageous from the point of view of the total cost of the pant and electrical energy continues to be withdrawn by the grid.

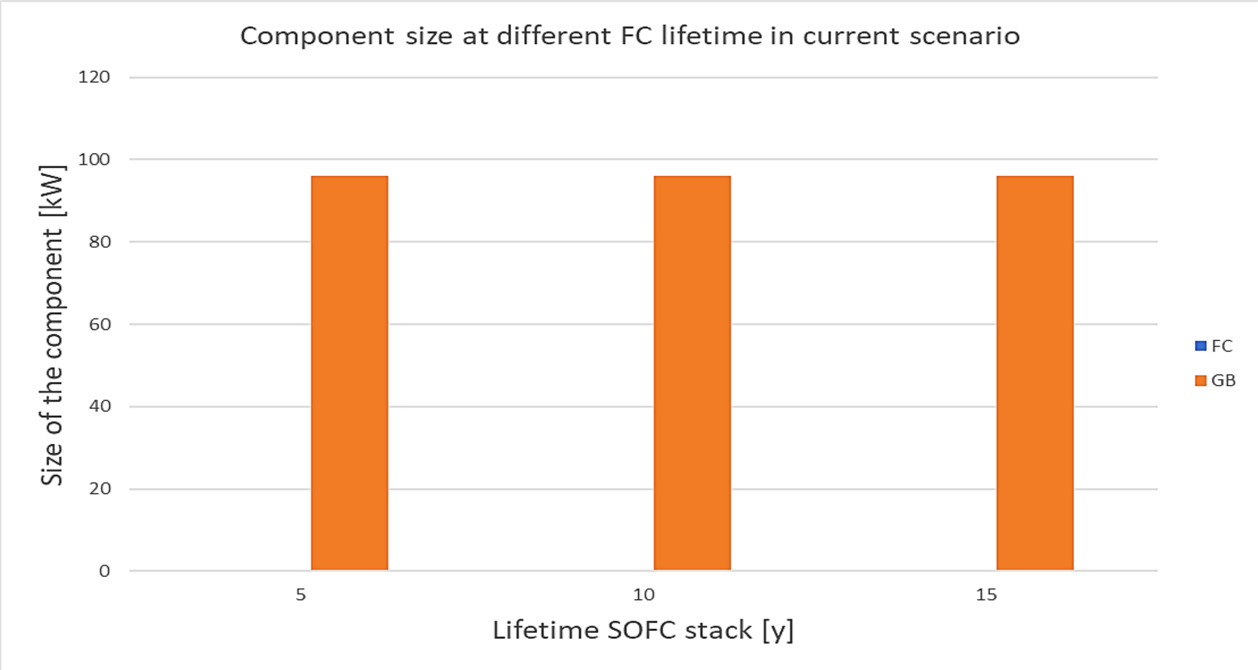


Figure 30- Optimal size of the component respect to the increase of FC life

Therefore, it may be useful to carry out an analysis by observing how the size of the fuel cell varies with the reduction of its capex (equal to 30% and 50%) and its duration.

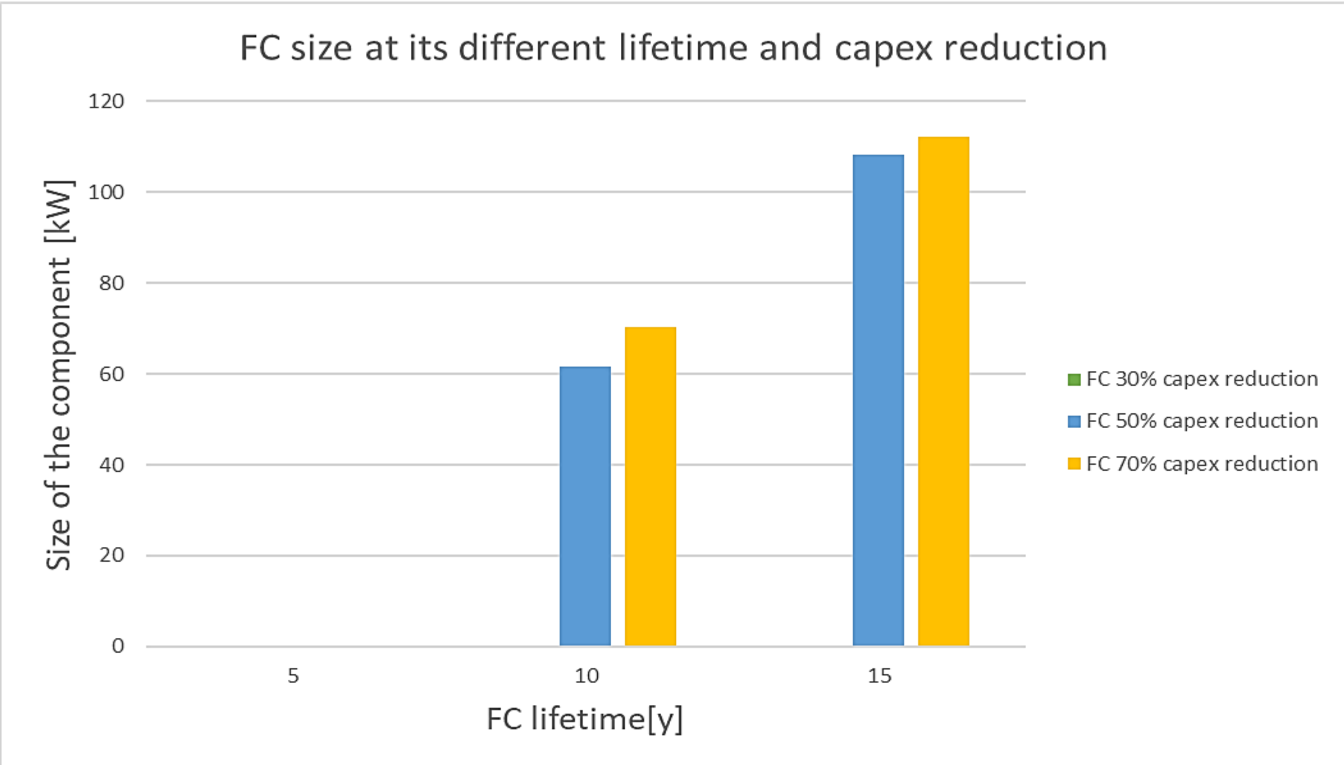


Figure 31- Optimal size of FC respect to the increase of FC life and capex reduction

Considering future realistic scenarios, the case of the reduction of capex equal to 50% and the respective increasing to 10 years of the life stack can be really interesting.
Moreover, reducing the number of replacements, the GHG emission for the total production of the fuel cell system is reduced. From our simulations, in any case, the SOFC becomes cost effective by reducing the environmental impact only when the useful life of the stack covers the entire life of the plant (20 years) and for the moment this is a very utopistic view.

6. Discussion

A comparison between all the simulation and some considerations are now performed.

For a more general and realistic analysis, to the previous results, it's added a case with an implement of a RES plant like photovoltaic system. The table below summarizes the result of our simulations considering the total cost of the plant as objective function that has to be minimized.

Table 23 - Results of the simulations

System option	Lifetime system cost [€]	LCOE [€/kWh$_{el}$]	NOx [Kg]	CO_2 [ton$CO_{2,eq}$]
GRID+FC+TTS+BT	€ 3,940,218	0.265	127.4	6982.0
GRID+GB+TTS	€ 2,297,670	0.148	250.5	5954.8
GRID+FC+GB+TTS+BT	€ 2,297,670	0.148	250.5	5956.2
GRID+PV+GB+TTS+BT	€ 2,078,079	0.133	188.4	5002.4
GRID+PV+FC+TTS+BT	€ 3,802,806	0.261	88.6	5956.2

The complete data of the simulations are available for consultation in the Appendix A4.

By analysing the total lifetime system cost of each optimal configuration, we can note immediately that, in actual cost, plants which implements fuel cell system have a high value of LCOE for the reason that we have made in the previous chapter. In figure 32 a graphical comparison of the total cost of the plant are available. The blue column indicates the effective cost of each optimized systems while the orange one shows how much the selected system is more or less expensive respect to the reference case GRID+GB+TTS.

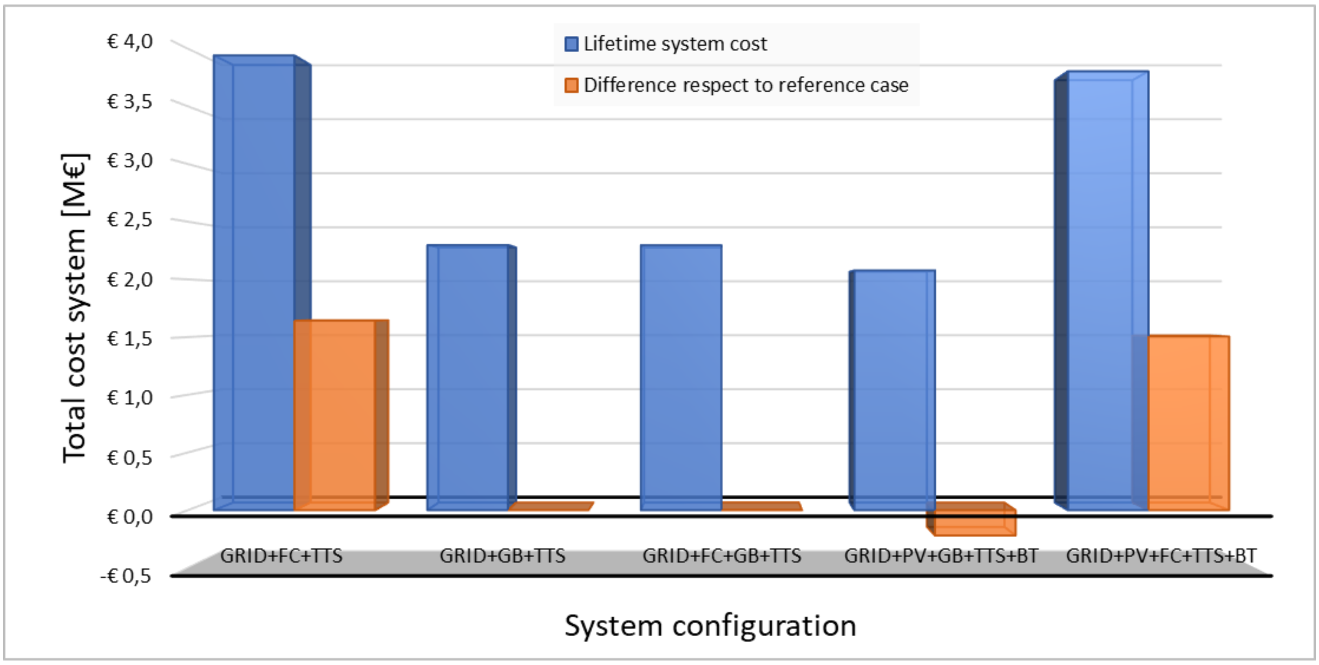


Figure 32- Comparison of the total lifetime system's cost

As we have already said, the optimal configuration of GRID+FC+GB+TTS coincide with the reference case and the result reports equal value. The only system that signs a reduction in cost respect to base scenario is the system constituted by PV+GB+BT+TTS+GRID. By analysing the optimized size of this case, and compared to all other ones, a particular consideration has to done on the battery unit. In fact, it is never used in all cases where it's selectable. This can be due to the fact that battery have a high specific cost respect to the energy density and also it should be noted that we are referring about an industrial user and so the cost of electricity is less expensive than a residential house in which consumptions are lower and the concept of self-consumption becomes important.

Interesting is compare the actual data with a possible future scenario where the lifetime of fuel cell is increased, and its capex is reduced. Taking as example cases explained in the chapter 5.3, the research of the optimal size with the same configuration option is done, considering the lifetime of SOFC equal to 10 years and its capex equal to the half of the actual value.

Table 24 – Result of future SOFC scenario

System option	Lifetime system cost [€]	LCOE [€/kWhel]	Nox [Kg]	CO_2 [$tonCO_{2,eq}$]
GRID+FC+TTS+BT	€ 2,663,784	0.175	127.7	6982.0
GRID+GB+TTS	€ 2,297,670	0.148	250.5	5954.8
GRID+FC+GB+TTS+BT	€ 2,193,031	0.147	193.3	6066.7
GRID+PV+GB+TTS+BT	€ 2,078,080	0.133	188.4	5002.4
GRID+PV+FC+TTS+BT	€ 2,505,048	0.170	88.5	5669.0

Figure 33 shows the difference cost of the plants in which fuel cell system is implemented. The blue columns represent the cost in the new scenario while the orange ones are the current cost.

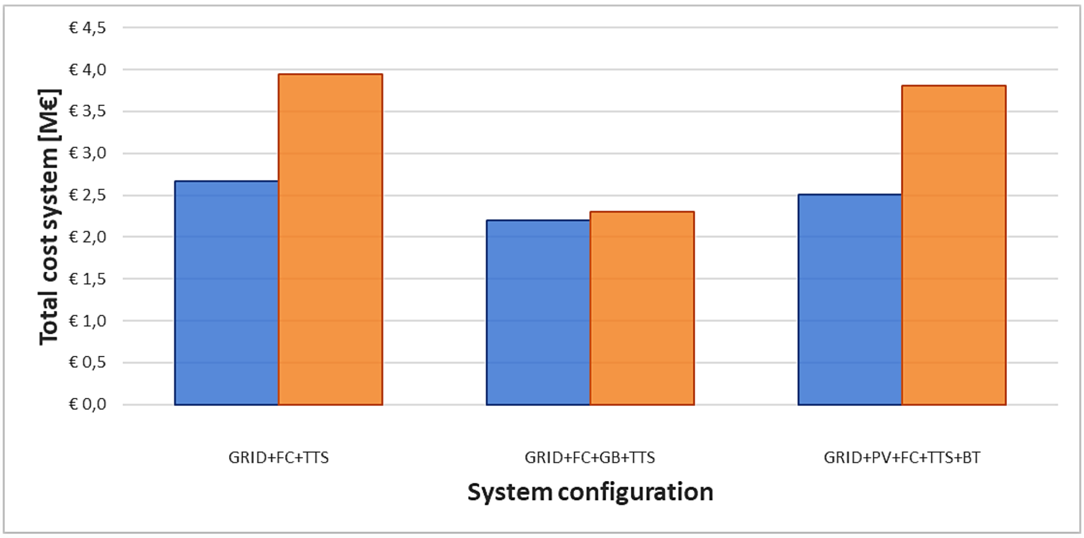


Figure 33- Comparison of the total lifetime system's cost in the future SOFC scenario

As we can see, the plant composed by GRID+FC+GB+TTS becomes one of the most cost-effective system with also a significant reduction of the environmental impact in terms of NOx respect to the reference case. The sizes of this optimal configuration are shown in table 25.

Table 25 - Optimal configuration of future SOFC scenario GRID+FC+GB+TTS

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	35.4 kW
Battery (BT)	-
Gas Boiler (GB)	28.4 kW
Thermal tank storage (TTS)	130.1 kWh

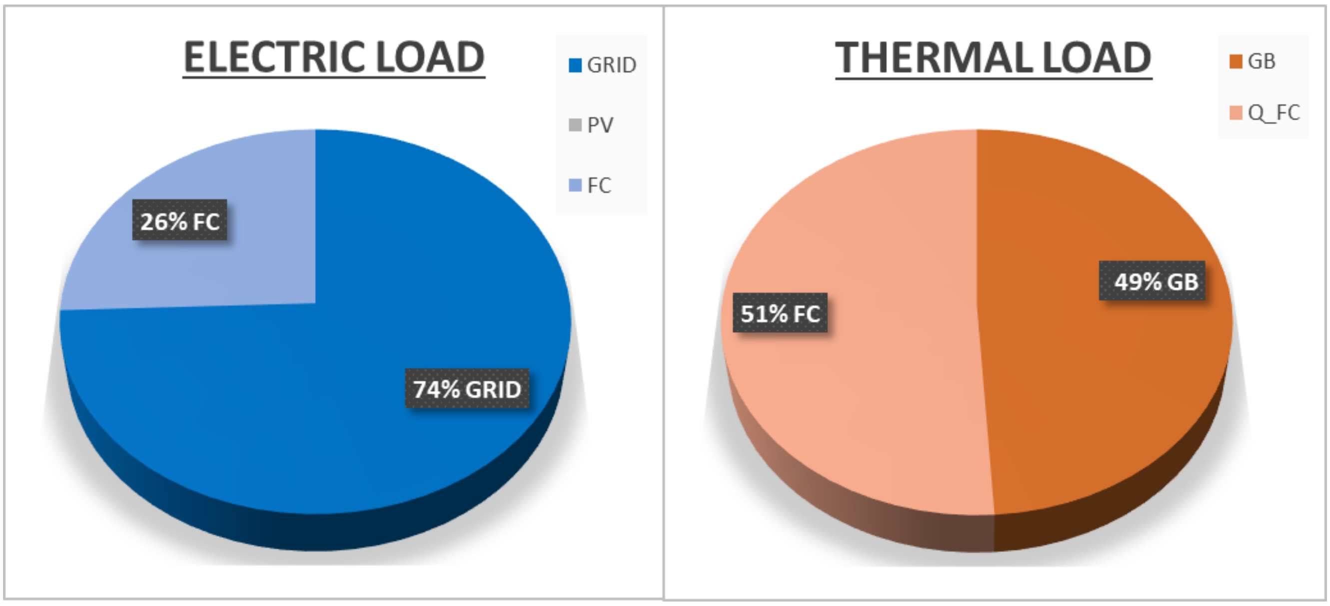


Figure 34- Percentual of the load satisfied by each technology

One of the disadvantages of the SOFC stacks is its low flexibility, it means that a maximum number of shutdowns for year allowed. The figure 35 shows the operating power of the FC during the whole year. We can observe that the trend is close to the realistic behaviour of the SOFC.

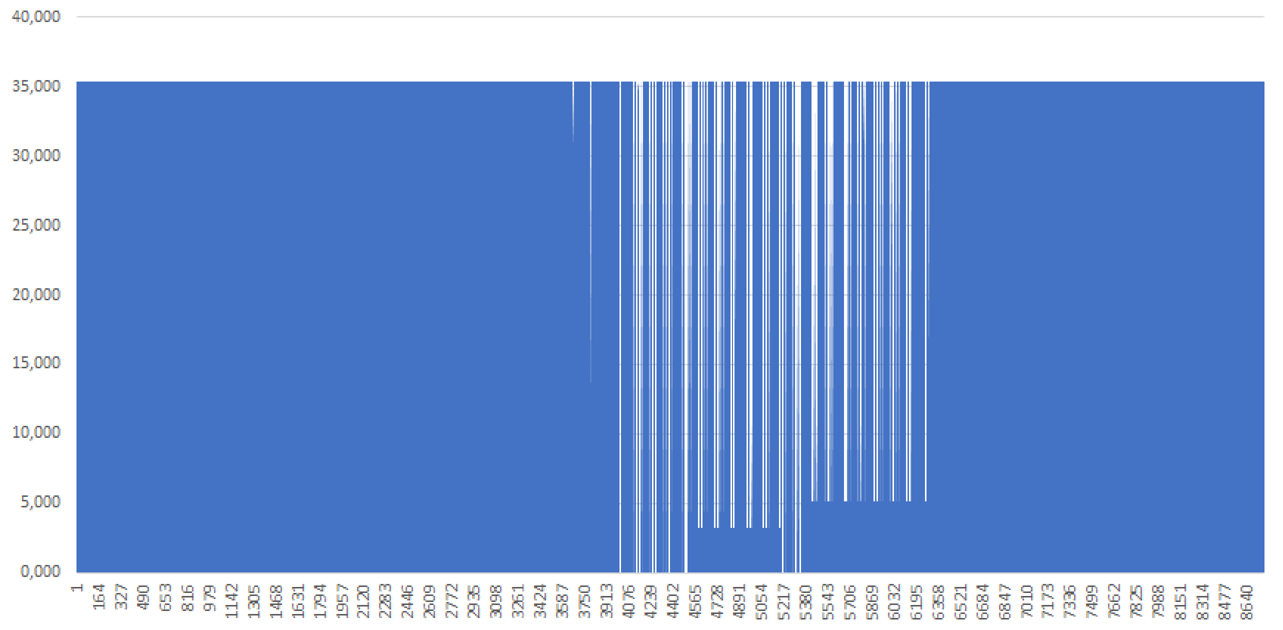


Figure 35- Power output of SOFC stack during the year

We can notice that the fuel cell works at its nominal value almost all year, only in the central part, during summer, the FC start to modulate more, concurrently with a lower thermal request and with a reduction of the electricity from the grid as reported in figure 11. At any rate, the shutdowns of the stacks are in the norm.

Back to the current result and talking about NOx emission, in figure 36 we can see the comparison of the systems with the same concept descripted before.

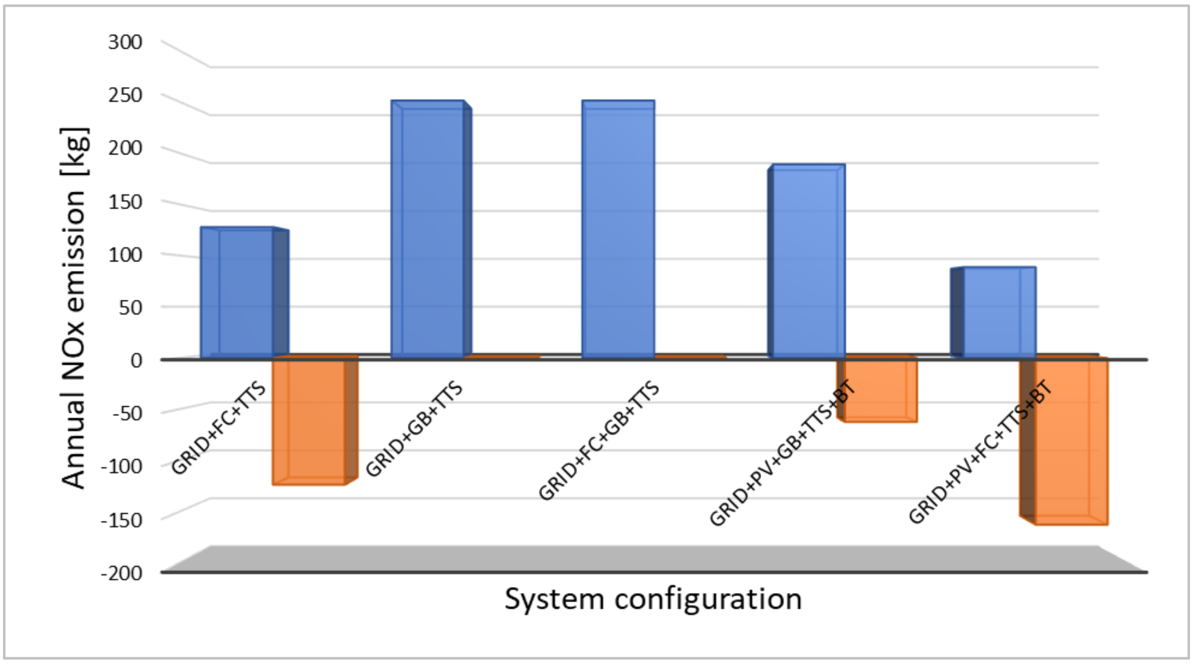


Figure 36- Comparison of the NOx emission by the optimized system

The plants designed with a SOFC system have a bigger reduction of emission respect to other ones. Interesting is the case when the fuel cell system and PV are implemented together with a reduction of 65% on the annual emission. Focusing on this last case an analysis is performed on the size of the technologies selected when the objective function is the NOx emission (data available in Appendix A4).

In figure 37 the size of the storage units in the optimal configuration is shown for both the simulations.

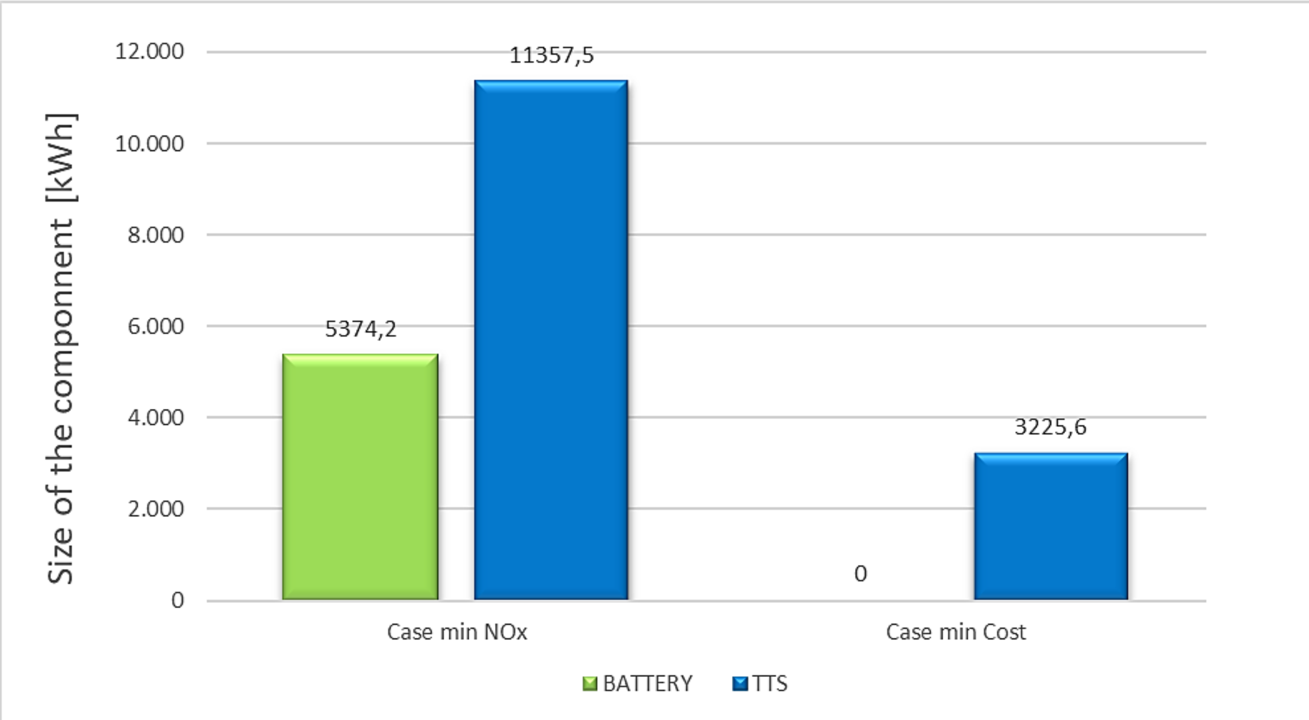


Figure 37- Storage unit size respect to the objective function minimized

As we can see the choice of this technologies becomes favourable and important when the objective function is the operative emission to minimize. Normally, renewable systems produce almost clean energy and storing more energy as possible from them makes that a relevant way to reduce the total emission of the plant as also confirmed by Figure 38.

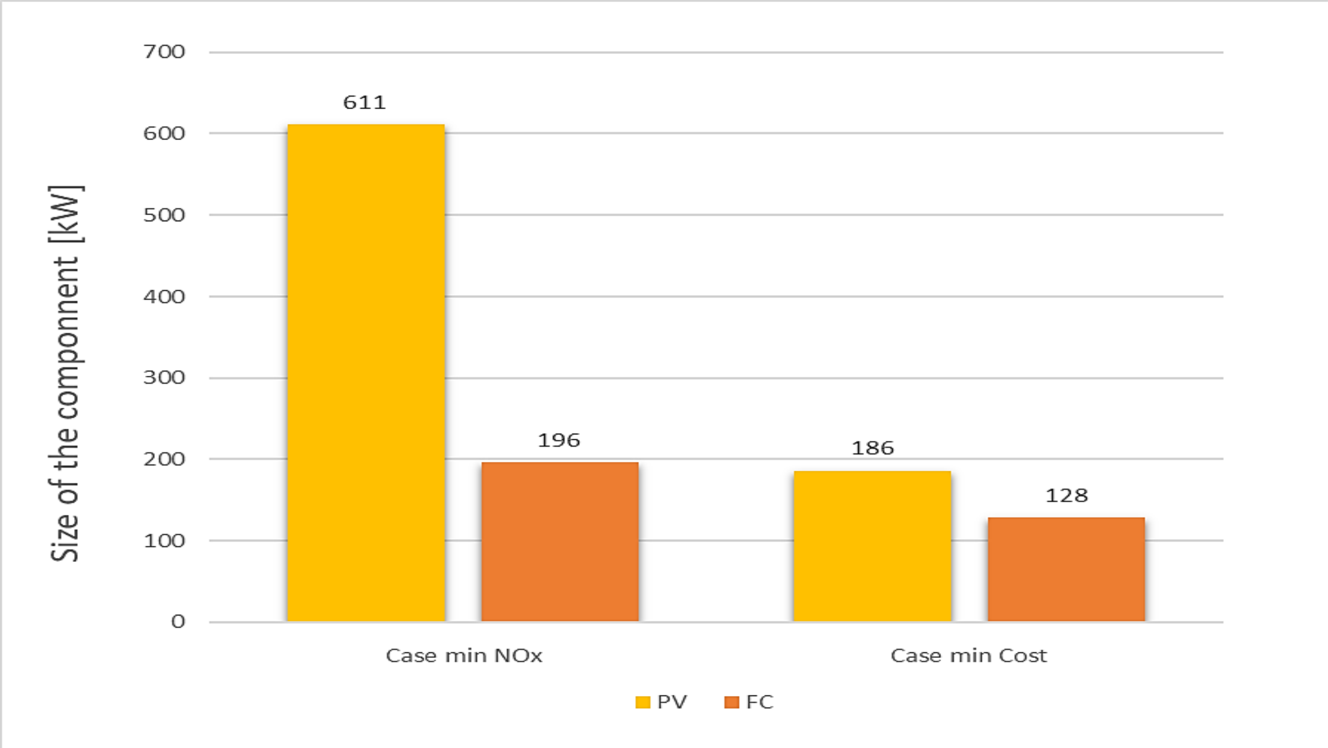


Figure 38- PV and FC size respect to the objective function minimized

The PV size has the bigger increment due to the associated emission factor equal to 0 but also size of fuel cell stack increment. It also has to be noticed that implement FC together Battery and PV systems in our model, can bring to a behaviour that cannot be considered real. In figure 39 the power output of the SOFC during the year for this case is shown.

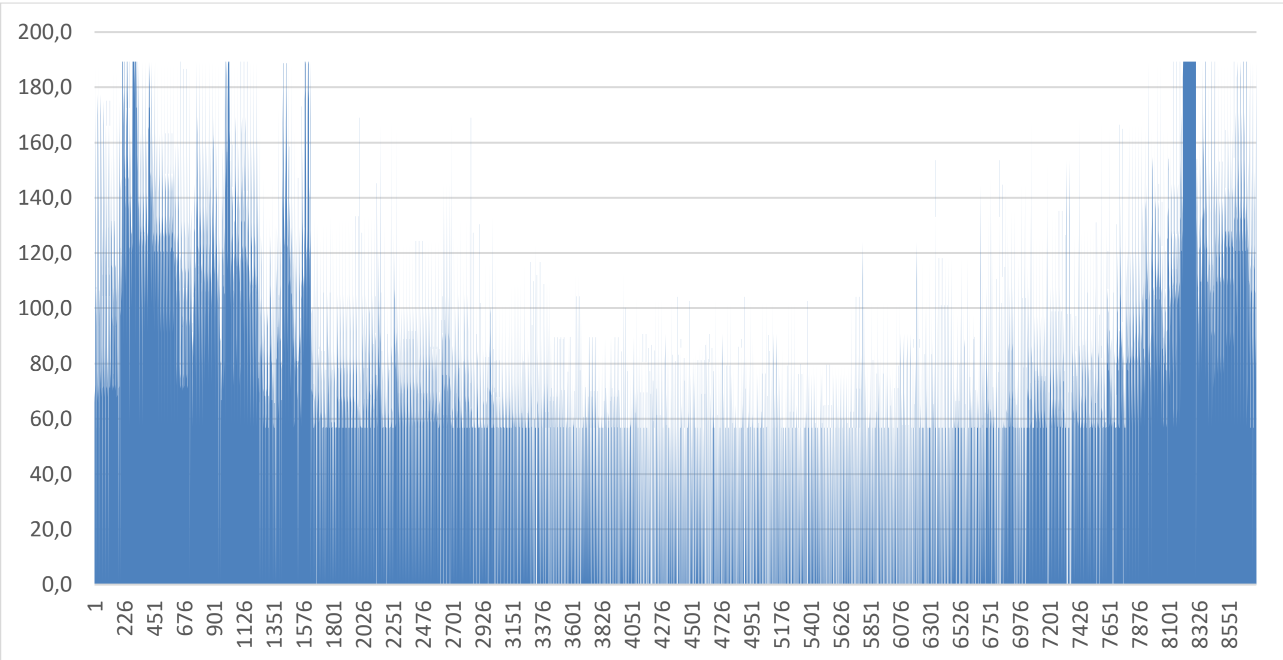


Figure 39- SOFC output power with PV and BT units

As we can see the trend is very different from figure 33, with a very huge number of switches on and off that can damage the fuel cell.

Regarding GHG emission, the SOFC system has the disadvantages of a quite high manufacturing impact and quite high CO_2 operational emission considering the low value of efficiency respect to other generator like gas boiler. The simulation's results confirm this thesis. As figure 40 shown, plants designed with fuel cell have a greater impact in terms of $CO_{2,eq}$ emitted respect to no fuel cell-based systems.

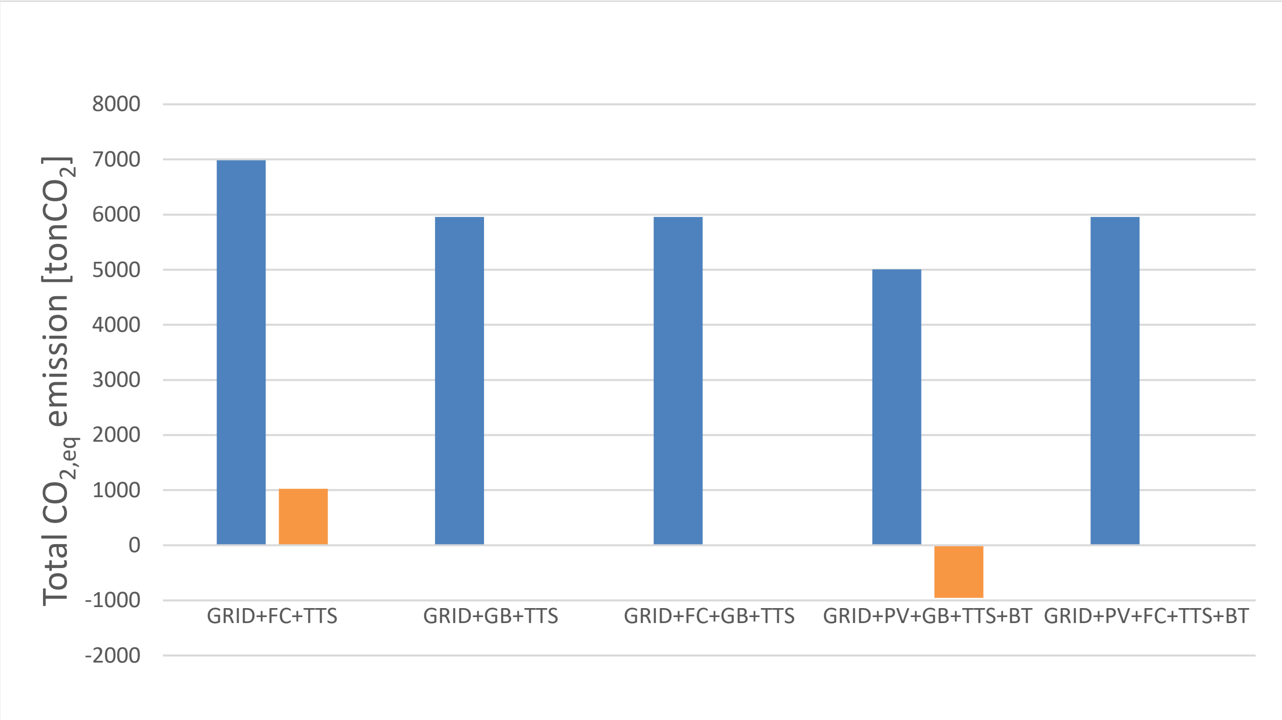


Figure 40- Comparison of the total GHG system's emission

Minimizing the total cost, the optimal configuration of the system composed by GRID+PV+GB+TTS+BT result as the best plant. The same system with the gas boiler unit substituted by the fuel cell, let us to reach the same level of emission of the reference scenario but with a cost that is 65% higher. As we can see the system composed only by FC+GRID+TTS is the worst. Respect on $CO2_{eq}$ emission, Figure 41 show the emission weights of the optimal sized technology in this last case.

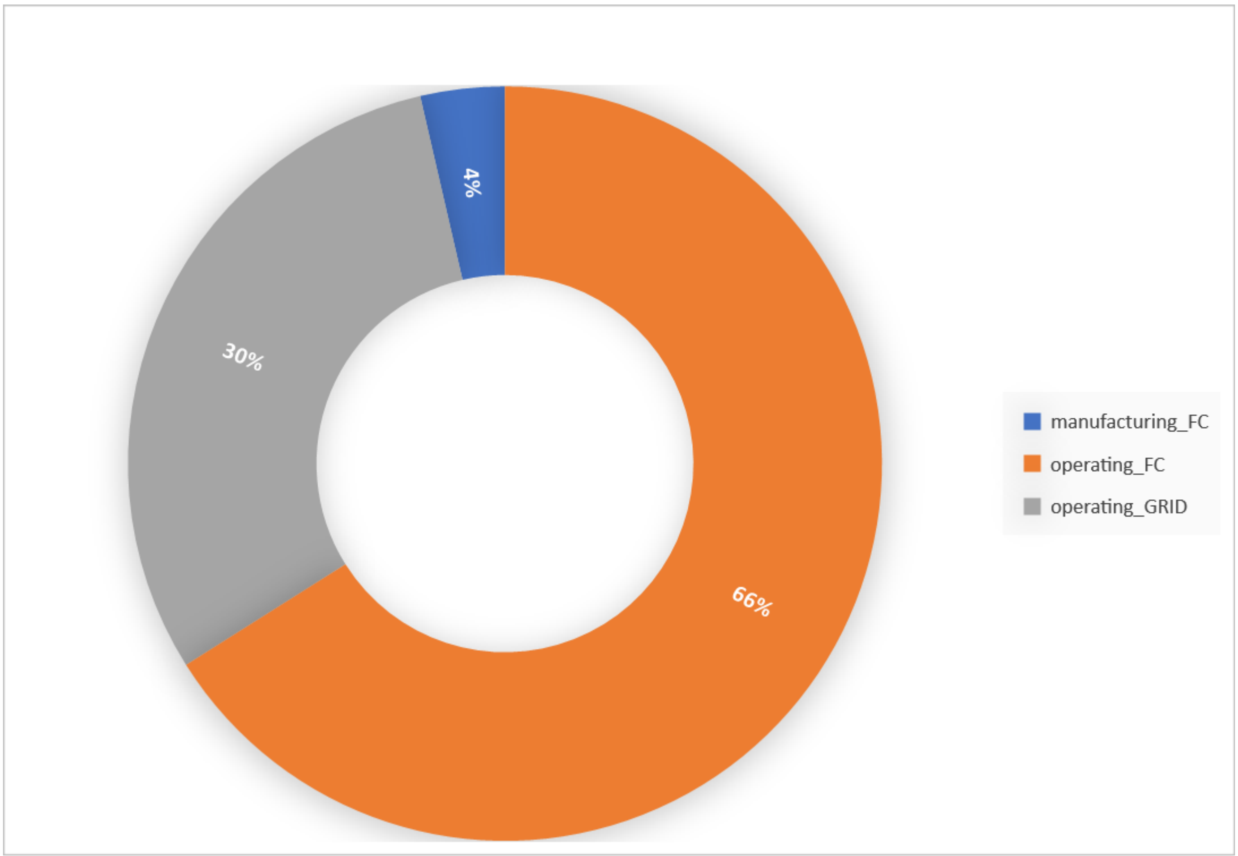


Figure 41- Emission weight of the system FC+GRID+TTS

An important aspect that has to be taking in account is the fuel used to fed SOFC stacks.

The production and combustion of 1 kg of methane has a big environmental impact around 300 g CO_{2eq} per kWh of potential energy. The same amount of hydrogen produced from renewable sources (green hydrogen) has an impact on 55 g CO_{2eq} per kWh. Then, combining this impact with the efficiency of fuel cell stack, we can find its operational impact respect to the usable energy. According to Inergio [25], a SOFC feed to hydrogen has an operational impact around 157 g $CO_{2eq}/kWh_{el.}$. Considering the system composed only by FC+TTS+GRID the simulations result corresponds to a total emission equal to 4282.8 $tonCO_{2eq}$, with a reduction of almost 40%. In the figure 42 and figure 43 we can see the reduction due to the change of fuel on the operating emission of the fuel cell and the respective weight on the total emission.

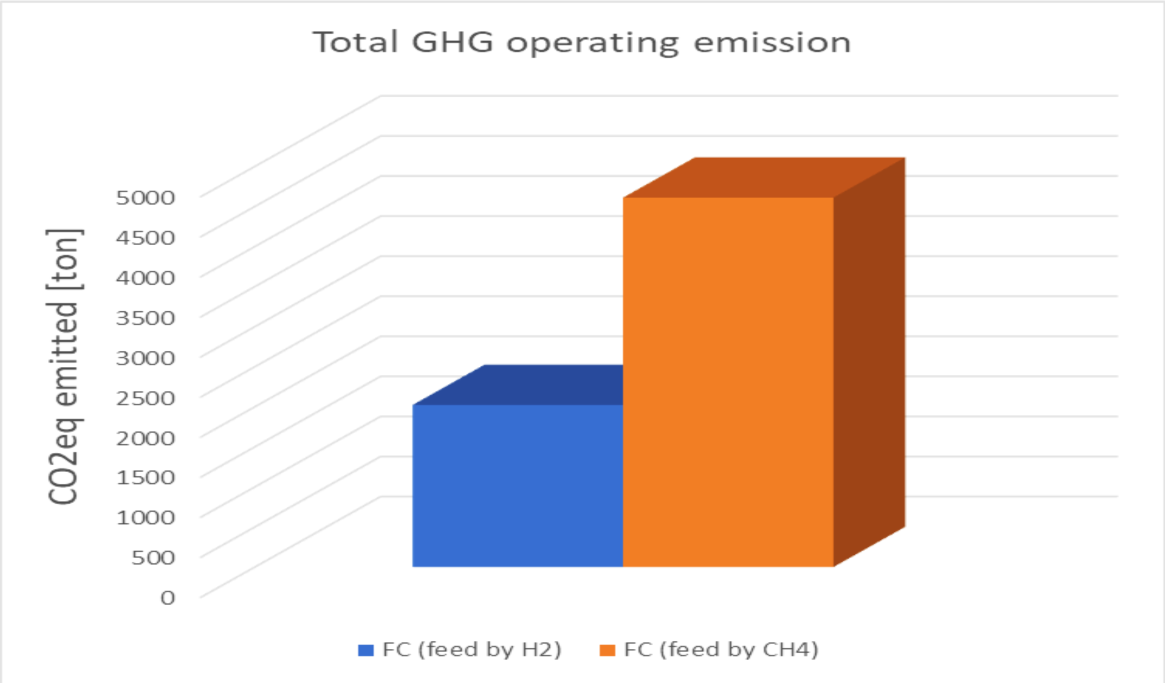


Figure 42- Comparison on the GHG operating emission of fuel cell feed with hydrogen and methane

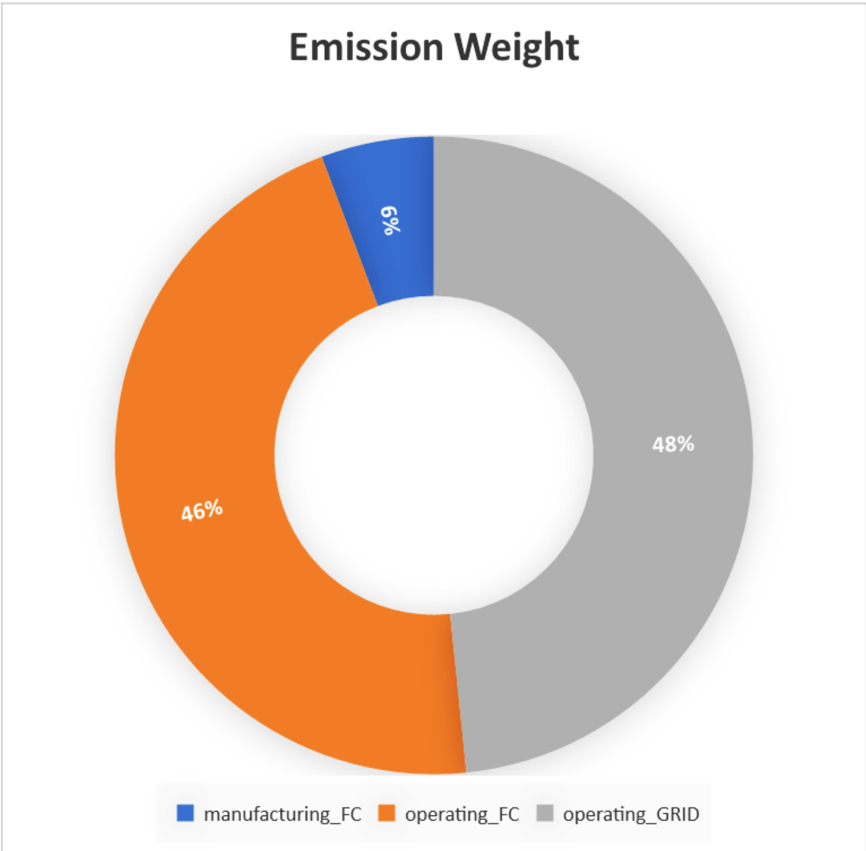


Figure 43- Emission weight of the system FC+GRID+TTS with hydrogen as fuel

As we can see, the introduction of hydrogen brings to a significant reduction on emission. According to [32] hydrogen will be a key instrument for meeting the climate neutral objective of UE. A really relevant future scenario is to consider the transport of hydrogen within the same natural gas distribution network, many studies and experiment have already been done and significant result in terms of the containment of emissions can be obtained. An analysis on our system is performed considering the blending fuel in a mixture of 30/70%.

Regarding generators, the same study performed in the chapter 5.2 can be done, considering the new heating value of the blended fuel as:

$$LHV_{CH4+H2} = 0.3LHV_{H2} + 0.7LHV_{CH4} \tag{43}$$

According to [33], lower value of the heating value is obtained. This means that to produce the same energy, the more fuel it will be needed, but assuming the fuel composed only by CH_4 and H_2 , to 1 mole of blended fuel entering in the generators corresponds only 0.7 mole of CO_2 exiting from them. This gives us a reduction of ca. 10% on their emission. Table 27 reports the results obtained.

Table 26 - GHG operating emission with blended fuel

	CH_4	$CH_4 + H_2$
BOILER [g CO_2/kWh_{th}]	181.6	162.7
FUEL CELL [g CO_2/kWh_{el}]	323.6	289.8

With this value, plants with cogeneration system becomes the powerful way to reduce GHG emission. Considering the current efficiency of the SOFC, Table 27 shows the CO2 emitted for the production of 1 kWh_{el} and 0.49 kWh_{th} (corresponding to the heat recovered from fuel cell for each unit of electrical energy produced) for the fuel cell system and the system composed by GRID+GB

Table 27 – GHG emission for the same amount of energy with blended fuel

	CH_4	$CH_4 + H_2$
BOILER [g CO_2/kWh_{th}]	323.6	289.8
FUEL CELL [g CO_2/kWh_{el}]	302.6	293.3

Table 28 and Figure 44 confirm this result and summarize the size of each technology for the GHG-optimized system in case of blending in the FC+GB+GRID+TTS case.

Table 28 - GHG optimixed system with blending fuel

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	118.1 kW
Battery (BT)	-
Gas Boiler (GB)	9.1 kW
Thermal tank storage (TTS)	2868.8 kWh

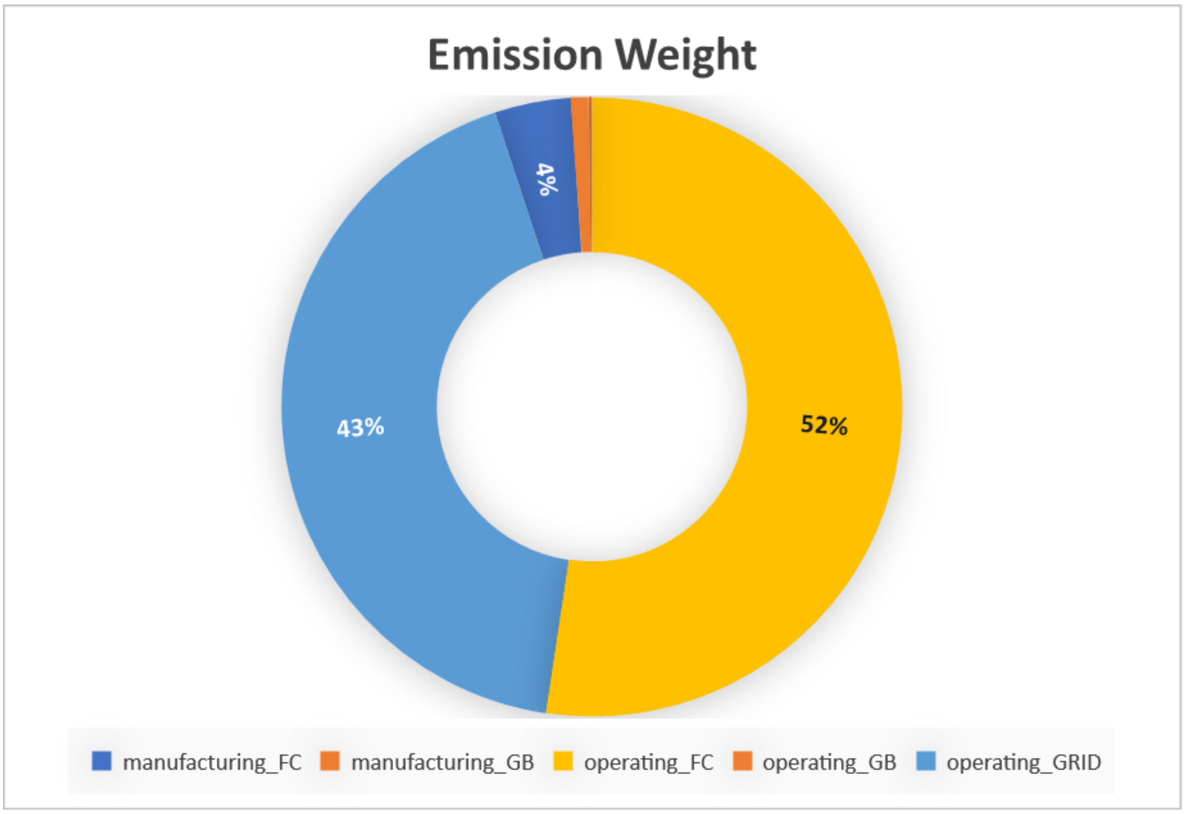


Figure 44- Emission weight of the system FC+GRID+TTS with blending fuel

In figure 45 and figure 46 is shown the difference respect to the GHG-optimized system feed only by methane analysed in chapter 5.2. respectively in terms of size of component and CO_{2eq} emitted

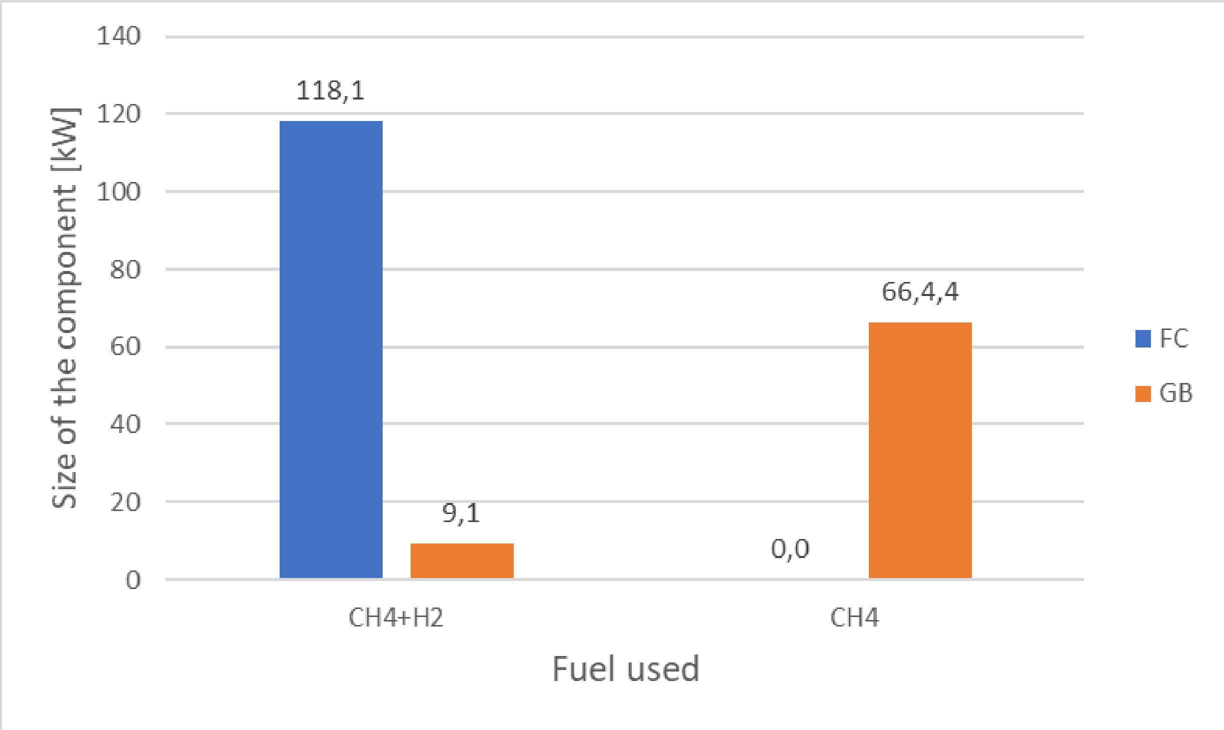


Figure 45- Size of the component in the GHG optimized systems in function of the fuel used

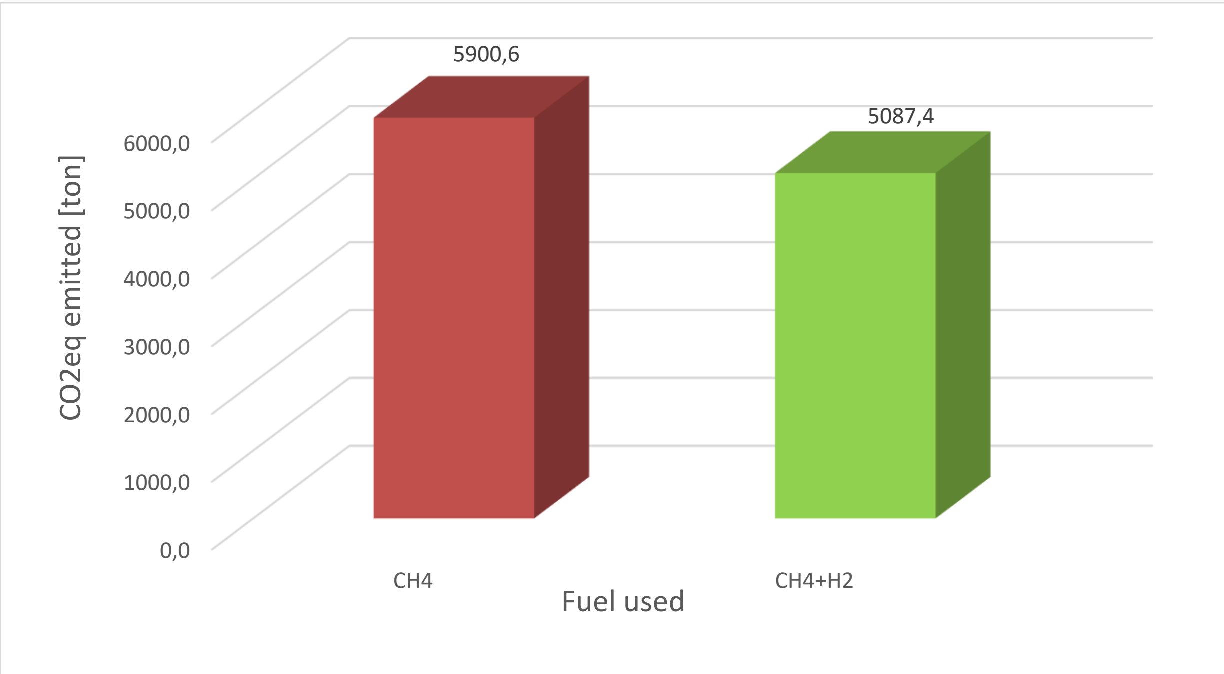


Figure 46- Total GHG emission of the GHG-optimized system in function of the fuel used

We have to remember that in all simulation analysed, no upper limits to the size of the various technologies are settled in order to not influence the choice of the optimized configuration. As we can easily assert, a lot of the size we have found are difficult to realize and in same case also unrealistic.

Taking in account all the results that we have reached in the previous section can be useful thinking to a real future possible scenario. So, the following assumption are done.

Table 29 - Realistic upper limits of the technologies

	LIMIT UPPER SIZE
Photovoltaic (PV)	200 kW
Fuel cell (FC)	250 kW
Battery (BT)	200 kwh
Gas Boiler (GB)	125 kW

The photovoltaic size's limit is imposed, taking in account of the possible available space of a small hotel.[34]
As confirmed by [1],[35] a realistic prospective of future lifetime SOFC stack are respectively between 7- 10 years while regarding the efficiencies several manufactures assure that reach a total efficiency of 90-92% is a reasonable target. The FC's lifetime and efficiency settled are reported in table 33.

Table 30 - Improved SOFC data

Fuel cell life time	7 years
Electrical efficiency	60%
Thermal efficiency	30%

Considering a reduction of capex equal to 50% of its current value and methane as fuel, the result that minimize the total cost of the plant is shown.

IMPROVED SOFC SCENARIO WITHOUT PHOTOVOLTAIC SYSTEM

Table 31 - Improved SOFC scenario without PV: optimal configuration

	SIZE
Photovoltaic (PV)	-
Fuel cell (FC)	32.3 kW
Battery (BT)	-
Gas Boiler (GB)	74.3 kW
Thermal tank storage (TTS)	313.4 kWh

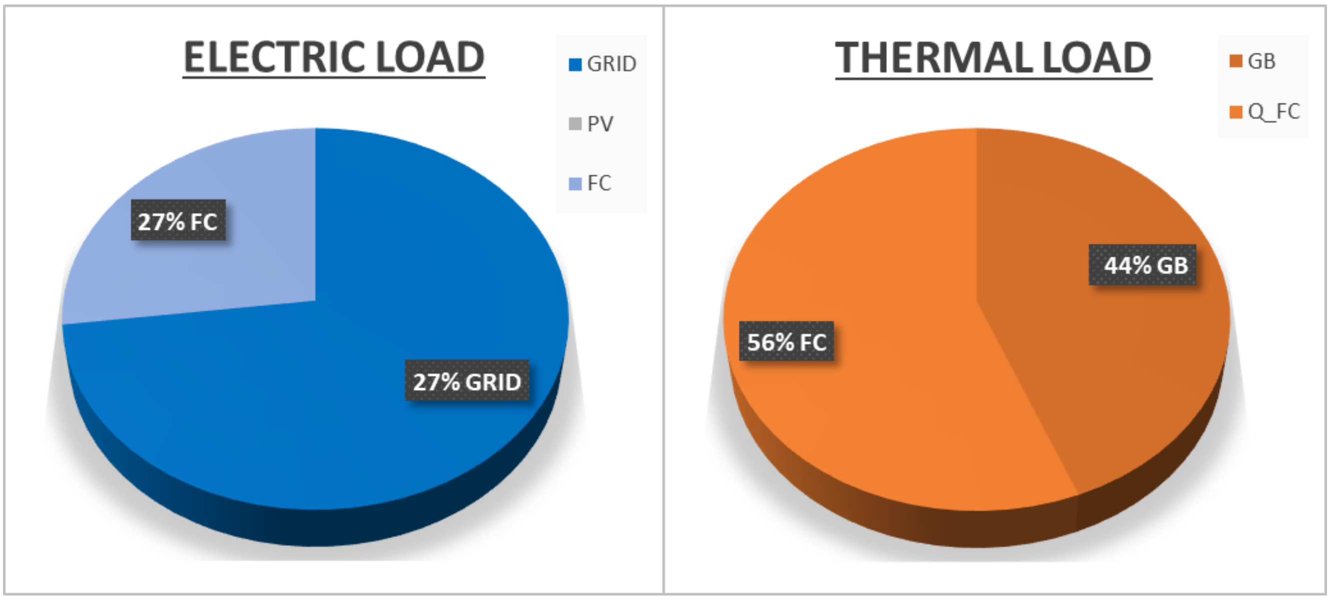


Figure 47– Percentual of load satisfied by the technologies in the improved SOFC scenario without PV

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Table 32 - Improved SOFC scenario without PV

RESULT	
Lifetime system Cost [€]	€ 2,230,016
LCOE [€/kWh$_{el}$]	0.150
Tot NOx [kg/y]	189.1
Tot CO_2 [ton]	5898.1

IMPROVED SOFC SCENARIO WITH PHOTOVALTAIC SYSTEM

Table 33 - Improved SOFC scenario with PV: optimal configuration

	SIZE
Photovoltaic (PV)	186 kW
Fuel cell (FC)	28 kW
Battery (BT)	-
Gas Boiler (GB)	82.7 kW
Thermal tank storage (TTS)	162.7 kWh

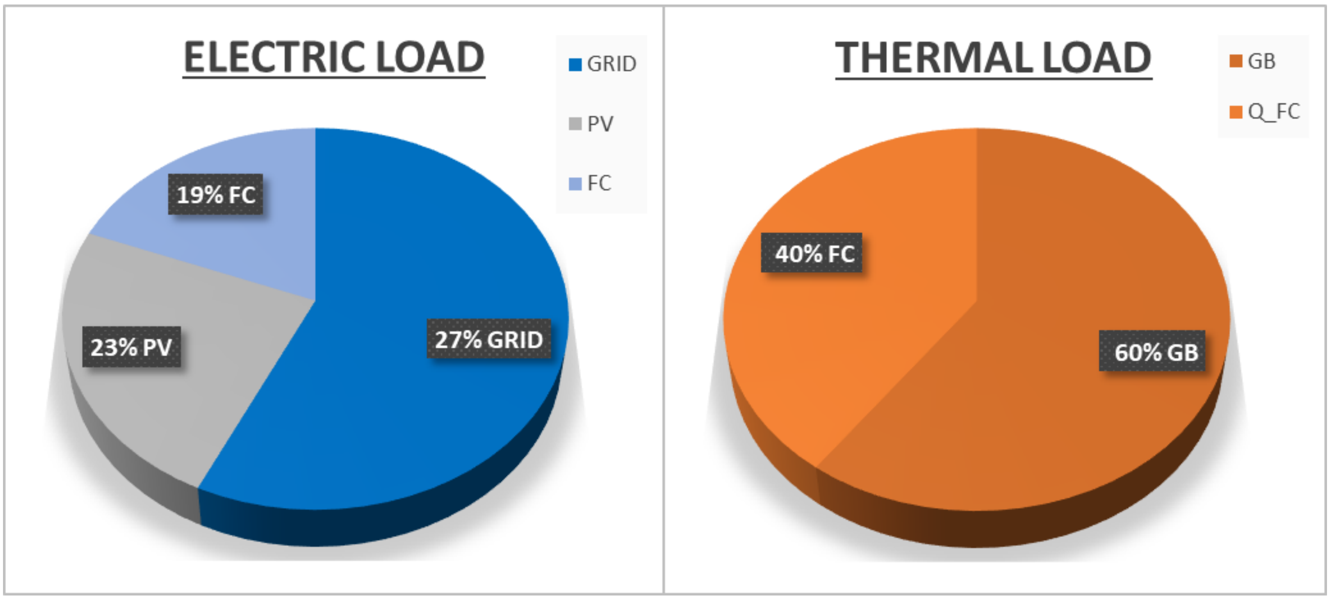

Figure 48– Percentual of load satisfied by the technologies in the improved SOFC scenario with PV

To the grid is also injected 10907.2 kWh of electricity mainly from the PV excess.

Table 34 - Improved SOFC scenario with PV: results

RESULT	
Lifetime system Cost [€]	€ 2,039,343
LCOE [€/kWh$_{el}$]	0.135
Tot NOx [kg/y]	150.8
Tot CO_2 [ton]	5032.5

In that we can call ‘near future scenario’ the implementation of SOFC system let us to drastically reduce the emission of NOx and containing the total lifetime of the system.

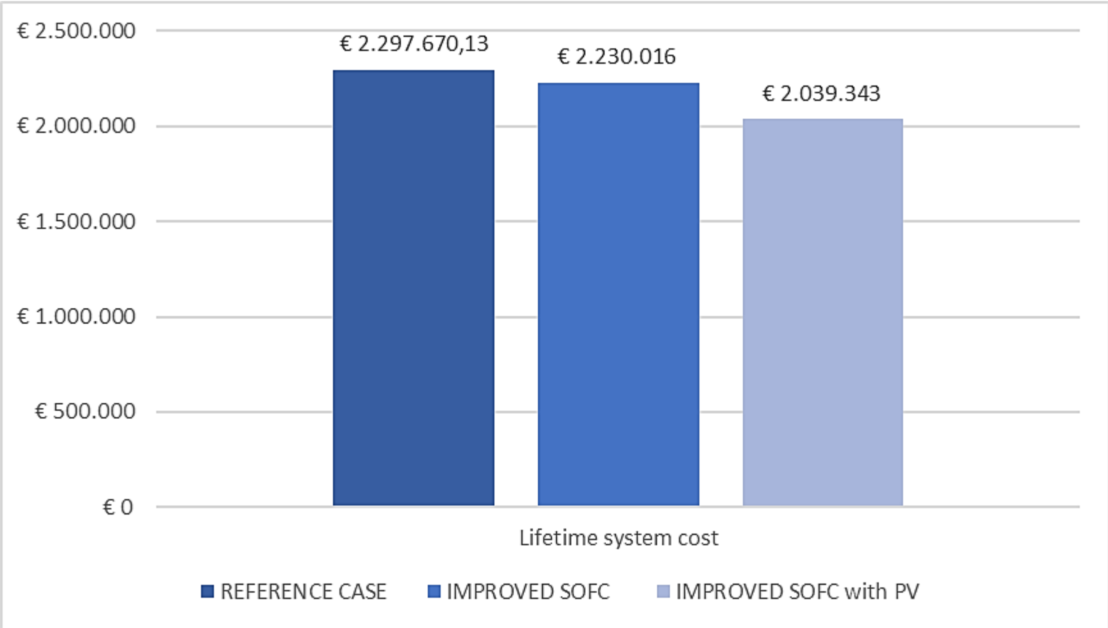

Figure 49– Lifetime cost comparison between reference and SOFC improved scenarios

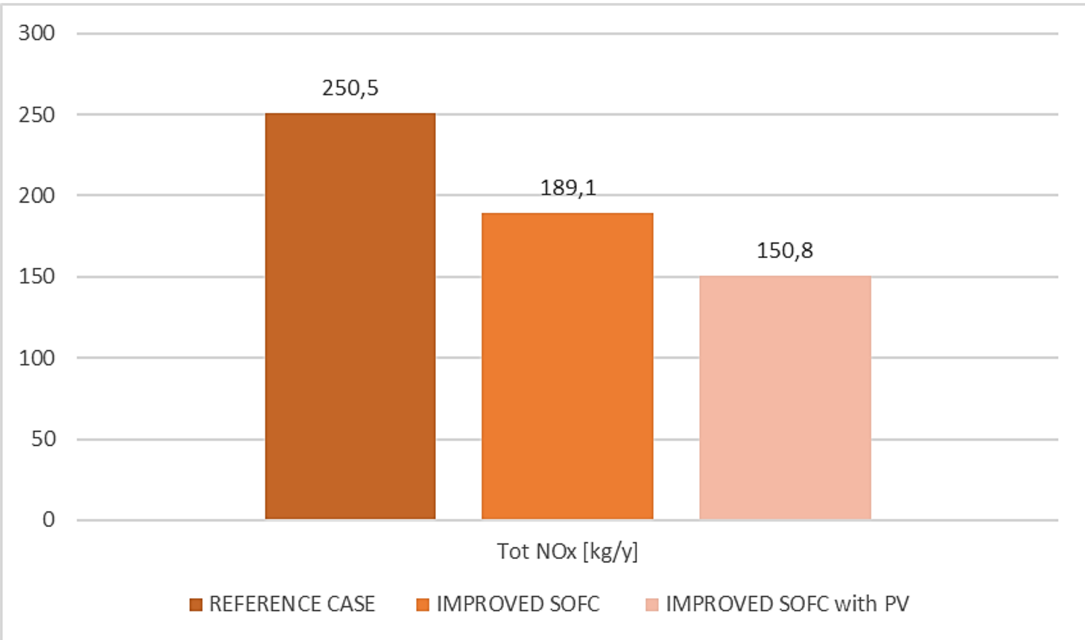

Figure 50– NOx annual emission comparison between reference and SOFC improved scenarios

The NOx reduction is up to the 25 % of the reference case without RES plant implemented and can reach a reduction of ca. 40 % when photovoltaic system is also present.

Regarding the total GHG emission, the amount of CO_{2eq} produced has a greatly drop only when the photovoltaic system is installed. At any rate, the scenario with only the improved SOFC stacks is in line with the reference result, signing a little improvement.

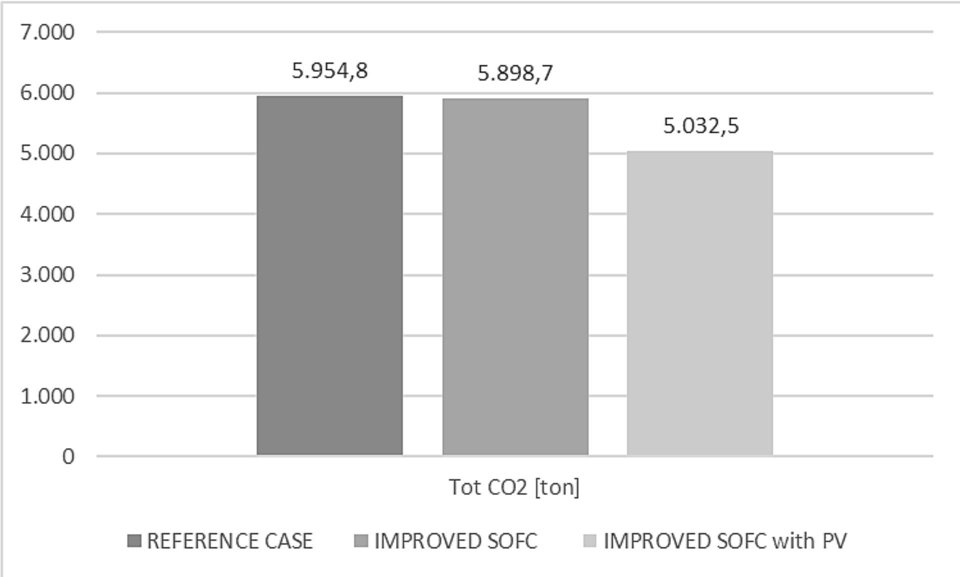

Figure 51 – GHG total emission comparison between reference and SOFC improved scenarios

7. Conclusions

This work has been focused on the research of the feasibility and the optimal configuration of SOFC-based system in the building sector. The building examined was a small hotel situated in Cuneo (Italy) due to the typical base load demand that it has necessary to be satisfied. The electrical and thermal consumption has been analysed, and a Mixed Integer Linear Programming was built in order to make technical, environmental, economic evaluation and to understand better the convenience of the use of SOFC stacks in the plant. Several scenarios are analysed and the result of all the simulations reports that, at current cost, the SOFC-based systems are not convenient due to their high investment cost. A further analysis on this aspect let to assert that the SOFC system become the optimal choice, that minimize the total cost of the plant, when its price undergoes a reduction of ca. 70%.

The evaluation on the environmental emission of the several scenarios, confirms the studies conducted by various scientific paper respect to the reduction of NOx that a SOFC-based system can bring. On the other hand, the analysis conducted on the GHG emission, considering manufacturing and operational emission and methane as fuel, reports that they are not the best performance choice. The main reason is due to low efficiency respect to other generator like condensing gas boiler and the high number of the replacements needed to cover the whole lifetime of the plant. At any rate, analysing possible new scenario, SOFC can be considerable a very reliable technology to bet on. Assuming, in the near future, increment on the electrical, thermal efficiencies and considering more and more optimized and performing production process that let to increase the lifetime combined with a price reduction, SOFC-based systems became the best choice not only in terms of reduction of emissions but also terms of cost-effective systems. The results indicate that a SOFC with a total efficiency (electrical + thermal) equal to 90%, 7 years lifetime and a Capex of ca. 6000€ can be an optimal support to traditional systems helping to reduce the total cost of the plant and reduce the emission.

Reference

[1] "Comsos." https://www.comsos.eu/ (accessed Nov. 18, 2021).

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APPENDIX A1

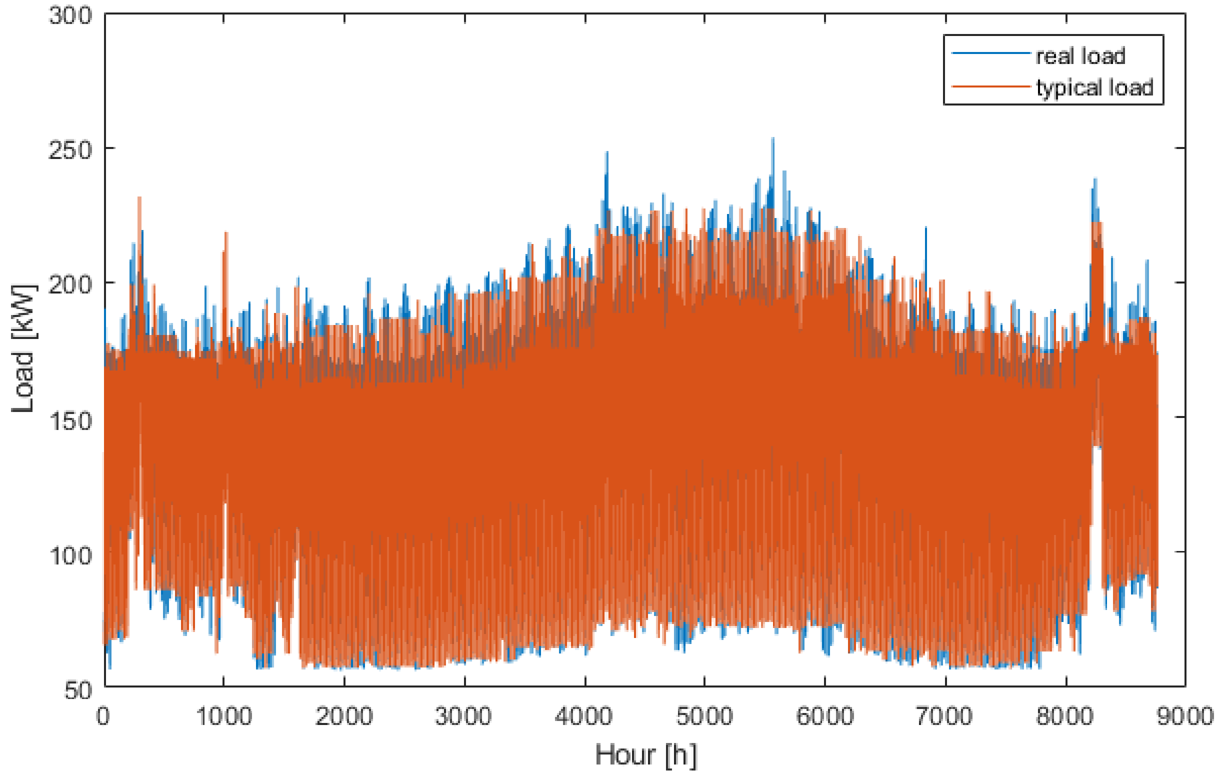

Figure A1.1 – Electrical load of small hotel

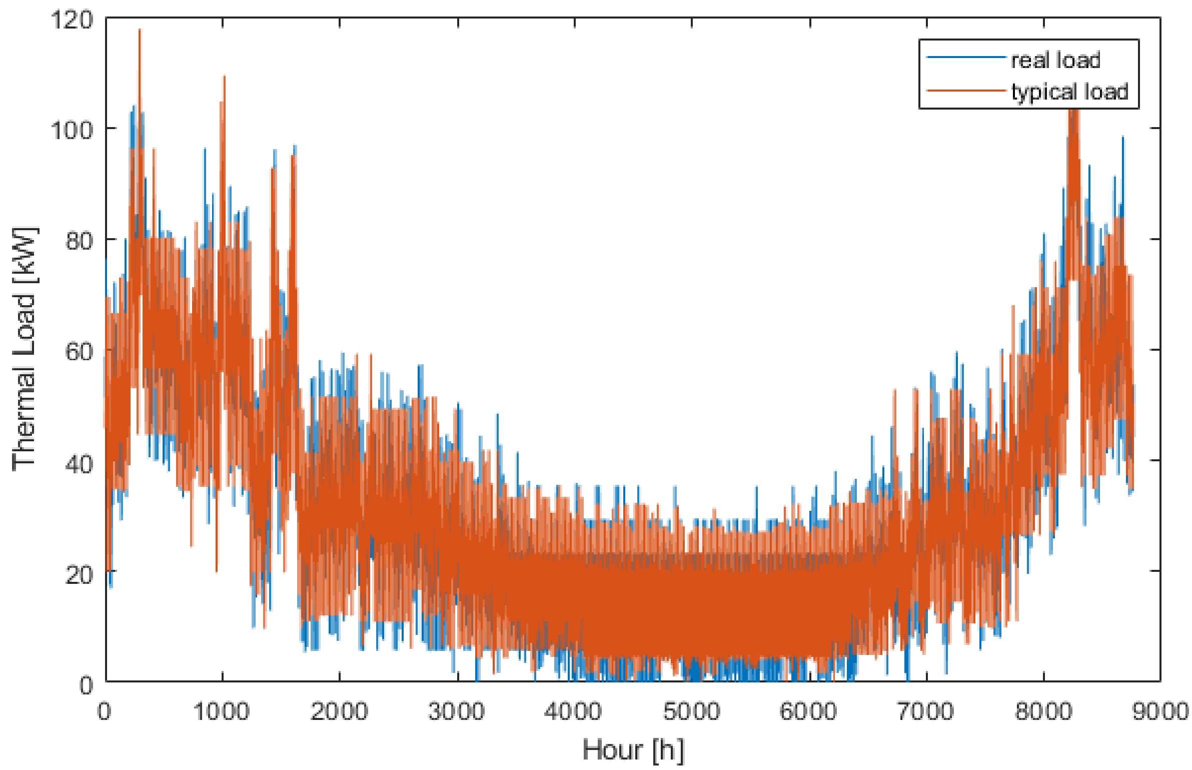

Figure A1.2 – Thermal load of small hotel

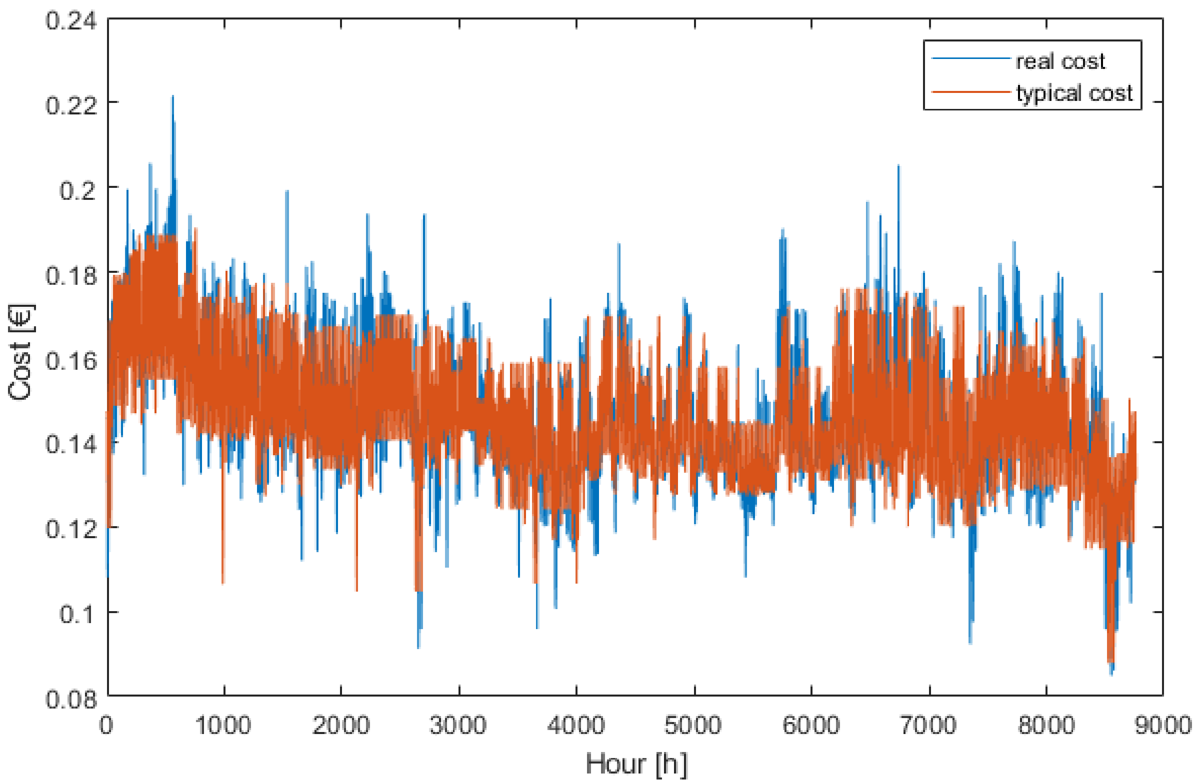

Figure A1.3 – Electricity cost

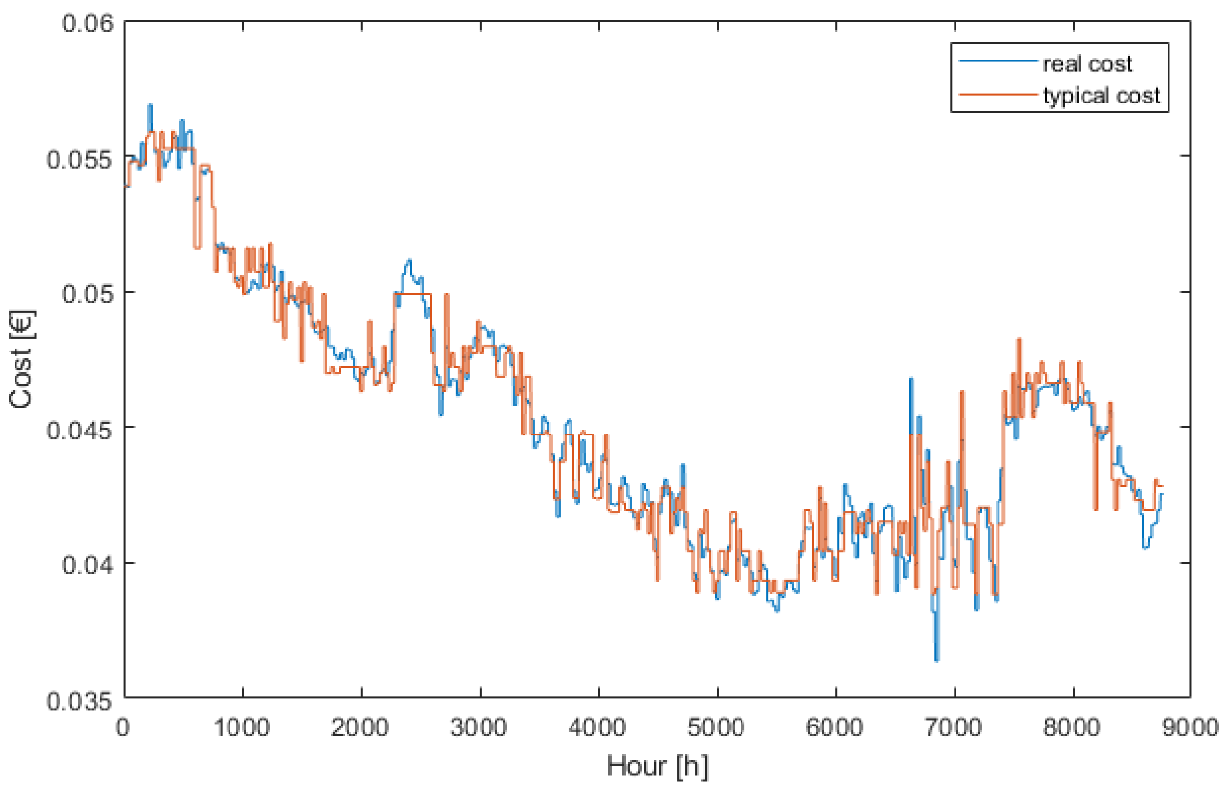

Figure A1.4 – Methane cost

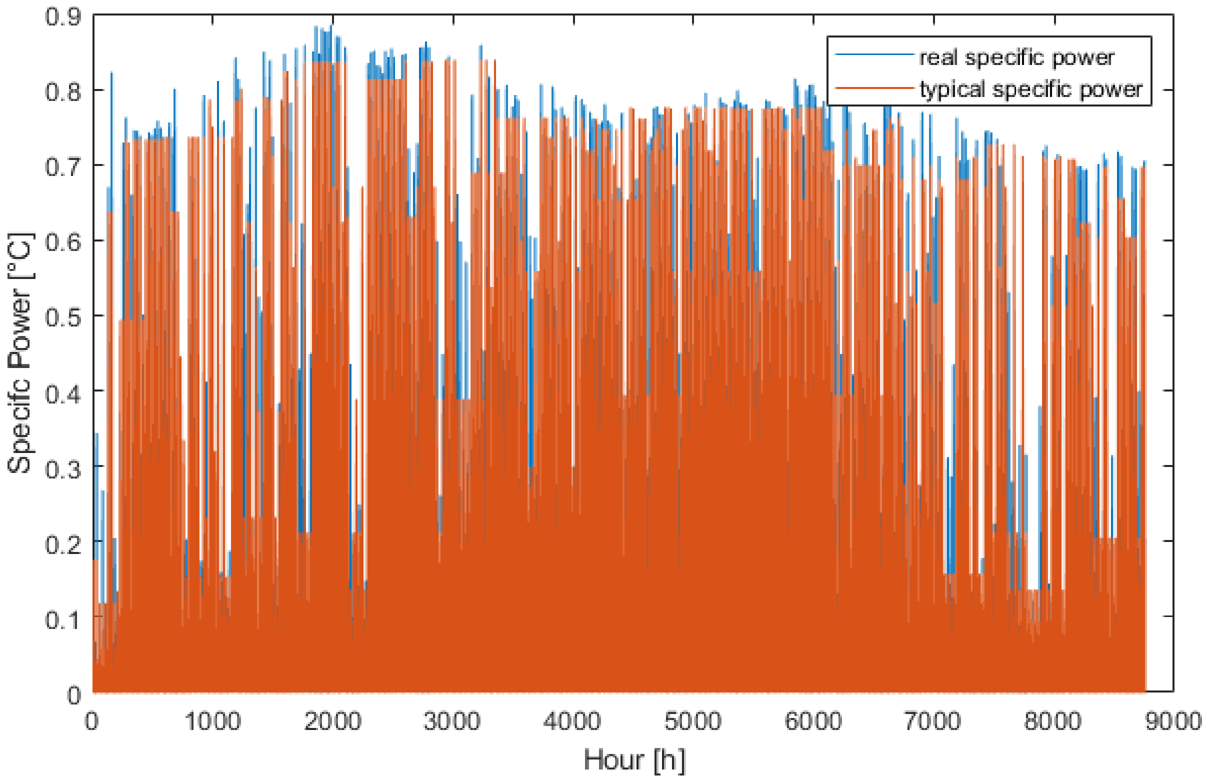

Figure A1.5 – PV specific power

APPENDIX A2

IMPOSTE	USI CIVILI			USI INDUSTRIALI		
	< 120 m3	120-480 m3	480-1.560 m3	> 1.560 m3	< 1,2 M(m3)	> 1,2 M(m3)
ACCISA						
Normale	4,40	17,50	17,00	18,60	1,2498	0,7499
Territori ex Cassa del Mezzogiorno(A)	3,80	13,50	12,00	15,00	1,2498	0,7499
ADDIZIONALE REGIONALE(B)						
Piemonte	2,20000	2,58000	2,58000	2,58000	0,62490	0,52000
ALIQUOTA IVA (%)	10	10	22	22	10(C)	10(C)

Figure A2.1 – Extra cost of gas for different consumption [c€/smc]

According to Arera, march 2020 [21] and considering a heating value (LHV) of 10.5 kWh/smc, the total consumption in smc of the model is calculated as:

$$V_{ch4} = \frac{P_{ch4}}{LHV} \qquad (44)$$

Where the P_{ch4} is the total amount of methane consumed in terms of energy [kWh].

PHOTOVOLTAIC [36]

Table A2.1 –PV economic data

Description	Value	Unit
CAPEX	1100	€/kW
OPEX (fixed)	33	€/(kW*year)

LI- ION BATTERY [37]

Table A2.2 –Battery economic data

Description	Value	Unit
CAPEX	500	€/kWh
OPEX (fixed)	10	€/(kWh*year)
Lifetime	10	Years
Replacement Cost	60	% of capex

FUEL CELL [1]

Data are an average on the three SOFC manufacturer.

Table A2.3 – Fuel Cell economic data

Description	Value	Unit
CAPEX	11880	€/kW
OPEX (fixed)	1.33	% capex/year
Lifetime	5	Years
Replacement Cost	21.04	% of capex
Installation cost	2500	€/stack
OPEX (var)	Hourly cost of natural gas	

GAS BOILER[16]

Data are select direct from the site of the manufacturer and are confirmed by literature [38].

Table A2.4 –Gas boiler economic data

Description	Value	Unit
CAPEX	64.46	€/kW
OPEX (fixed)	20	% of capex/year
OPEX (var)	Hourly cost of natural gas	

GRID[19], [39]

Table A2.4 –GRID economic data

Description	Value	Unit
CAPEX	/	/
OPEX (var)	Cost of hourly electricity	
Cost of electricity injected in the grid	-0.06	€

The energy sold to the grid is negative because it is considered as a revenue and consists in the minimum guaranteed by [39]

THERMAL TANK STORAGE [40], [41]

Table A2.5 –TTS economic data

Description	Value	Unit
CAPEX	5	€/kwh
OPEX (fixed)	2	% of capex

ECONOMIC PARAMETERS

Table A2.6 –Economic data

Description	Value	Unit
Escalation rate (*e*)	2	%
Nominal Interest Rate(i_{nom})	7	%
Annual rate of interest (*i*)	4.90	%

APPENDIX A3

In the following table all variable defined in our MILP model are indicated

Table A3.1 – variables used in the MILP model

#	Tag	Description
1	P_BT_c	Battery charging power
2	P_BT_d	Battery discharging power
3	P_sold	Power sold to the grid
4	P_FC	Fuel cell operating power (net outlet)
5	Q_FC	Fuel cell thermal power out
6	P_GB_in	Gas boiler power in (methane consumed)
7	P_GB	P_GB variable: gas boiler power (net outlet)
8	P_GRID	Power absorbed by the grid
9	Q_EXC	Variable to guarantee the converge on thermal side
10	P_FC_in	Fuel cell power (methane/hydrogen consumed)
11	P_TTS_c	Battery charging power
12	P_TTS_d	Battery discharging power
13	delta_FC	Delta_FC variable (1 if FC is on; 0 if FC is off)
14	delta_GB	Delta_GB variable (1 if GB is on; 0 if GB is off)
15	P_FC_rated_aux	P_FC_rated_auxiliary variable
16	P_GB_rated_aux	P_GB_rated_auxiliary variable
17	E_BT	Energy stored within batteries
18	E_TTS	Energy stored within tts
19	P_PV_rated	Design variable of PV system
20	P_FC_rated	Design variable of FC system
21	Cap_BT	Design variable of BT system
22	P_GB_rated	Design variable GB system
23	Cap_TTS	Design variable TTS system

All equality, inequality equations and constraints considered in the model are reported in the following table.

Table A3.2 – MILP model's equations

#_eq	Description	Equation
AAeq1	Equality constraints of electric load	$P\_PV + P\_GRID + P\_BT\_d + P\_FC = P\_BT\_c + P\_EL + P\_LOAD + P\_SOLD$

AAeq2	Equality constraints of thermal load	$Q\_FC + Q\_GB + Q\_TTS\_d = Q\_LOAD + Q\_TTS\_c + Q\_EXC$
AAeq3	Fuel cell efficiency	$P\_FC - eff\_FC * P\_FC\_in = 0$
AAeq4	Fuel cell thermal efficiency	$Q\_FC - (ratio\_eff\_FC) * P\_FC = 1$
AAeq5	Gas boiler efficiency	$P\_GB - eff\_GB * P\_GB\_in = 0$
AAeq6	Energy stored in the TTS storage	$E\_TTS(i) = E\_TTS(i - 1)$
AAeq7	TTS self-sufficiency	$E\_TTS(t\_end) = E\_TTS(t\_in)$
AAeq8	Energy stored in the Battery storage	$E\_BT(i) = E\_BT(i - 1)$
AAeq9	Battery storage self-sufficiency	$E\_BT(t\_end) = E\_BT(t\_in)$
AAd1	Inequality constraints for Photovoltaic design variable	$P\_PV >= P\_PV\_rated\_min$
AAd2	Inequality constraints for Photovoltaic design variable	$P\_PV <= P\_PV\_rated\_max$

AAd3	Inequality constraints for Battery design variable	$Cap\_BT >= Cap\_BT\_min$
AAd4	Inequality constraints for Battery design variable	$Cap\_BT<=Cap\_BT\_max$
AAd5	Inequality constraints for Fuel Cell design variable	$P\_FC>=P\_FC\_rated\_min$
AAd6	Inequality constraints for Fuel Cell design variable	$P\_FC<=P\_FC\_rated\_max$
AAd7	Inequality constraints for Thermal Tank Storage design variable	$Cap\_TTS>=Cap\_TTS\_min$
AAd8	Inequality constraints for Thermal Tank Storage design variable	$Cap\_TTS<=Cap\_TTS\_max$
AAd9	Inequality constraints for Gas Boiler design variable	$P\_GB>=P\_GB\_rated\_min$
AAd10	Inequality constraints for Gas Boiler design variable	$P\_GB<=P\_GB\_rated\_max$
AA1	Lower boundary of the fuel cell	$LB\_FC*P\_FC\_rated\_aux-P\_FC<=0$
AA2	Upper boundary of the fuel cell	$P\_FC-UB\_FC*P\_FC\_rated\_aux<=0$

AA3	Inequality constraints in order to express the auxiliary variable of Fuel Cell	*P_FC_rated_aux-P_FC_rated-P_FC_rated_min*delta_FC<=-P_FC_rated_min*
AA4	Inequality constraints in order to express the auxiliary variable of Fuel Cell	*(-P_FC_rated_aux)+P_FC_rated+P_FC_rated_max*delta_FC<=P_FC_rated_max*
AA5	Inequality constraints in order to express the auxiliary variable of Fuel Cell	*P_FC_rated_aux-P_FC_rated_max*delta_FC<=0*
AA6	Inequality constraints in order to express the auxiliary variable of Fuel Cell	*(-P_FC_rated_aux)+P_FC_rated_min*delta_FC<=0*
AA7	upper boundary of the battery charging power	*P_BT_c-UB_BT_c*Cap_BT_c<=0*
AA8	upper boundary of the battery discharging power	*P_BT_d-UB_BT_d*Cap_BT_d<=0*
AA9	limit on the maximum energy content in the battery	*E_BT(t) - Cap_BT*SOC_max <= 0*
AA10	limit on the minimum energy content in the battery	*(-E_BT(t)) + Cap_BT*SOC_min <= 0*
AA11	limit on the maximum energy content in the hydrogen storage	*E_h2(t) - Cap_h2*LOH_max <= 0*
AA12	limit on the minimum energy content in the hydrogen storage	*(-E_h2(t)) + Cap_h2*LOH_min <= 0*

AA13	lower boundary of the gas boiler	LB_GB*P_GB_rated_aux-P_GB<=0
AA14	upper boundary of the fuel cell	P_GB-UB_GB*P_GB_rated_aux<=0
AA15	Inequality constraints in order to express the auxiliary variable of Gas Boiler	P_GB_rated_aux-P_GB_rated-P_GB_rated_min*delta_GB<=-P_GB_rated_min
AA16	Inequality constraints in order to express the auxiliary variable of Gas Boiler	-P_GB_rated_aux+P_GB_rated+P_GB_rated_max*delta_GB<=P_GB_rated_max
AA17	Inequality constraints in order to express the auxiliary variable of Gas Boiler	P_GB_rated_aux-P_GB_rated_max*delta_GB<=0
AA18	Inequality constraints in order to express the auxiliary variable of Gas Boiler	(-P_GB_rated_aux)+P_GB_rated_min*delta_GB<=0
AA19	upper boundary of the TTS charging power	P_TTS_c-UB_TTS_c*Cap_TTS_c<=0
AA20	upper boundary of the battery discharging power	P_TTS_d-UB_TTS_d*Cap_TTS_d<=0
AA21	limit on the maximum temperature in the TTS	E_TTS(t) -TTS_max <= 0
AA22	limit on the min energy in the TTS	(-E_TTS(t))+ TTS_min <= 0

APPENDIX A4

The optimal configuration and percentual of load satisfied by each technology in the cost-minimized simulation that aren't explained in the main text are here shown.

GRID+GB+TTS+PV+BT

Table A4.1 – GRID+GB+TTS+PV: optimal configuration

	SIZE
Photovoltaic (PV)	216.4 kW
Fuel cell (FC)	-
Battery (BT)	-
Gas Boiler (GB)	97.6 kW
Thermal tank storage (TTS)	173 kWh

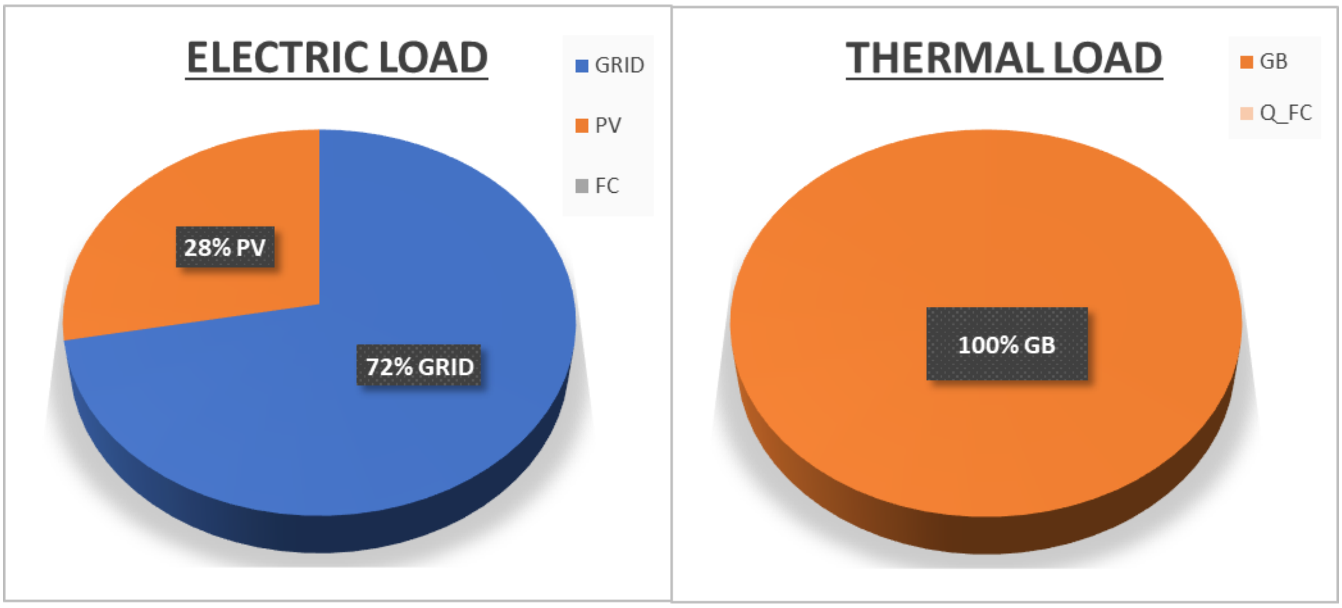

Figure A4.1 – Percentual of load satisfied by each technologies.

To the grid is also injected 27,505.3 kWh of electricity from the PV excess in the typical year.

Table A4.2 – GRID+GB+TTS+PV: result

RESULT	
Lifetime system Cost [€]	€ 2,078,080
LCOE [€/kWh el]	0.133
Tot NOx [kg/y]	188.4
Tot CO2 [ton]	5002.4

<u>GRID+FC+TTS+PV+BT</u>

Table A4.3 - GRID+FC+TTS+PV: optimal configuration

	SIZE
Photovoltaic (PV)	186.2 kW
Fuel cell (FC)	128.2 kW
Battery (BT)	-
Gas Boiler (GB)	-
Thermal tank storage (TTS)	3225.6 kWh

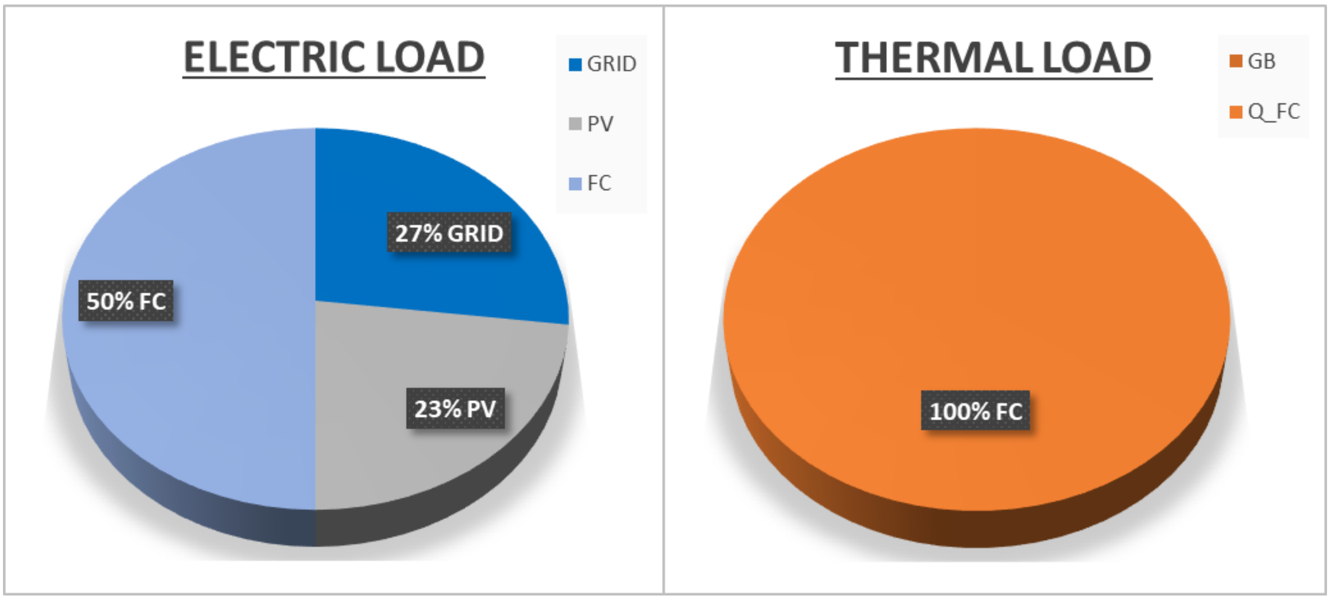

Figure A4.2 – Percentual of load satisfied by each technologies.

To the grid is also injected 73,318.1 kWh of electricity mainly from the PV and FC excess in the typical year.

Table A4.4– GRID+FC+TTS+PV: result

RESULT	
Lifetime system Cost [€]	€ 3,802,806
LCOE [€/kWh el]	0.261
Tot NOx [kg/y]	88.6
Tot CO2 [ton]	6.186.7

GRID+FC+TTS+PV+BT: NOx minimized

The objective function minimized is the NOx emission in the year.

Table A4.4 - GRID+FC+TTS+PV+BT: NOx minimized optimal configuration

	SIZE
Photovoltaic (PV)	611 kW
Fuel cell (FC)	196 kW
Battery (BT)	5374.2kWh
Gas Boiler (GB)	-
Thermal tank storage (TTS)	11357.5 kWh

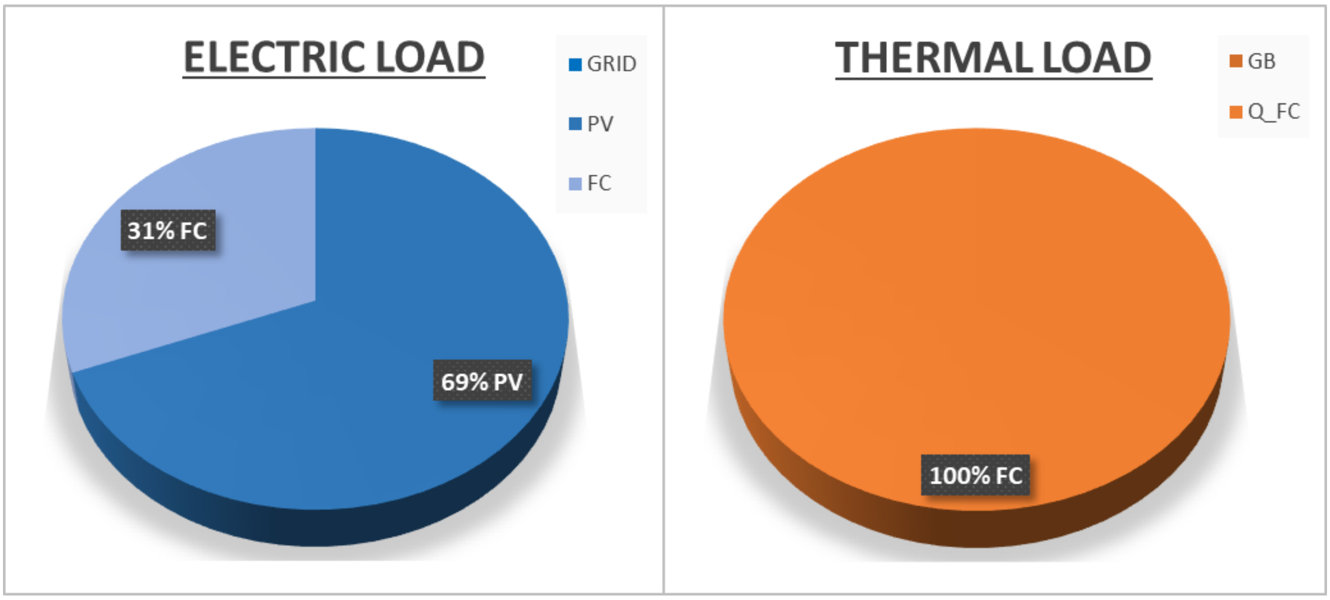

Figure A4.3 – Percentual of load satisfied by each technologies.

To the grid is also injected 124,895.1 kWh of electricity mainly from the PV and FC excess in the typical year.

Table A4.5– GRID+FC+TTS+PV+BT: result for NOX emission minimized configuration

RESULT	
Lifetime system Cost [€]	€ 8,383,640
LCOE [€/kWh el]	0.582
Tot NOx [kg/y]	19.8
Tot CO2 [ton]	4473.7