Solid oxide fuel cell integration in combined heat and power systems: analysis of the business case in the commercial sector

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ABSTRACT

The purpose of this work is to build a tool which is able to integrate a Solid Oxide Fuel Cell (SOFC) in a Combined Heat and Power (CHP) system and to evaluate the economic performance of the project and the reduction of CO_2 emissions released in the air. The model was developed in Microsoft Excel and starting from few inputs it is able to predict the electric and heat consumption of a customer in the commercial sector. The forecasting process of the hourly consumption profiles of a customer is based on the consumption curves of different types of buildings realized by the U.S Department of Energy. The architecture of the model considers a SOFC fed with natural gas to provide the customer with electricity and heat, while extra energy will be absorbed from the grid when the demand is not yet satisfied by the SOFC. This study also comprises an overview regarding the Italian available subsidies to fund the integration of SOFC in CHP systems; and an analysis related to the economic value of uninterrupted supply of electricity, indicated as "Value of Lost Load" (VOLL). Several sensitivity analyses are also conducted to evaluate the weight of different parameters on the final result of the study. It resulted that the implementation of SOFC within a CHP system produces considerable savings in terms of carbon dioxide released in the air. Moreover, from the two examples of applications shown in this study, it is noticeable how the current price of the SOFCs is still a barrier to the spread of this technology, while the target price investigated leads to promising financial scenarios.

KEYWORDS: Solid oxide fuel cell, Combined heat and power system, Value of lost load, Italian subsidy system, ComSos

1. INTRODUCTION

Global warming is one of the central issues we are facing nowadays. The increase of the presence of greenhouse gases (GHG) in the atmosphere implicates the rise of the average temperatures on Earth. Among the various initiatives undertaken by the EU, this study will focus on the objective of the European project named ComSos, aimed to validate and demonstrate the advantages of fuel cell integrated into combined heat and power systems. The mid-sized power range (<60 kW) is the one addressed by the project (ComSos, 2019). Solid oxide fuel cell (SOFC) and more in general Fuel Cell (FC) are devices able to generate electricity and heat and they are particularly suitable for Combined Heat and Power (CHP) solutions. Moreover, their operations imply GHG emitted at a lower rate compared to traditional ways to obtain electricity and heat (E&H). Beyond the reduction of emissions respect to traditional ways to produce E&H, there are also consistent economic benefits in the introduction of SOFC in combined heat and power systems (European Commission H.2020, 2019). The objective of this study is to develop a tool able to evaluate the consequent benefits to the introduction of a solid oxide fuel cell in a combined heat and power system, focusing on the commercial sector. More specifically, the model implemented on Microsoft Office Excel receiving as input the electricity and heat consumption over a year (MWh), the type of business to be supplied and the country in Europe to be applied, is able to predict the possible economic convenience of its implementation and the overall reduction of CO_2 emissions released in the air. This study also comprises an overview regarding the Italian available subsidies to fund the integration of SOFC in CHP systems; and an analysis related to the economic value of uninterrupted supply of electricity, indicated as “Value of Lost Load” (VOLL).

2. THE COMSOS PROJECT

ComSos project is a 42-months project (2018-2020) with a budget of EUR 10.2 million, aimed to validate and demonstrate fuel cell-based combined heat and power solutions in the mid-sized power ranges (<60kW). The outcome gives proof of the superior advantages of such systems, underlying business models, and key benefits for the customer adopting these systems (ComSos, 2018). This project is conducted by different partners focused on specific areas:

- VTT Technical Research Centre of Finland Ltd
- Convion Oy
- BlueTerra
- Sunfire GmbH
- SOLIDPower Group
- Politecnico di Torino *(ComSos, 2018)*

This study is developed in collaboration and under the precious supervision of Politecnico di Torino and Researchers and Professors.

3. SOLID OXIDE FUEL CELL

Solid oxide fuel cells are the most efficient devices yet invented for the conversion of chemical fuels directly into electric power and heat (Kendall & Kendall, 2015). A fuel cell consists of two electrodes: a negative electrode (or anode) and a positive electrode (or cathode), sandwiched around an electrolyte. A fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. A catalyst at the anode separates hydrogen molecules into protons and electrons, while at the cathode it separates the molecule of oxygen into ions negatively charged. The electrons go through an external circuit, creating a flow of electricity. The oxide ions migrate through the electrolyte to the anode, where they unite with hydrogen and to produce water and heat. Fuel cells produce electricity and heat as long as fuel is supplied.

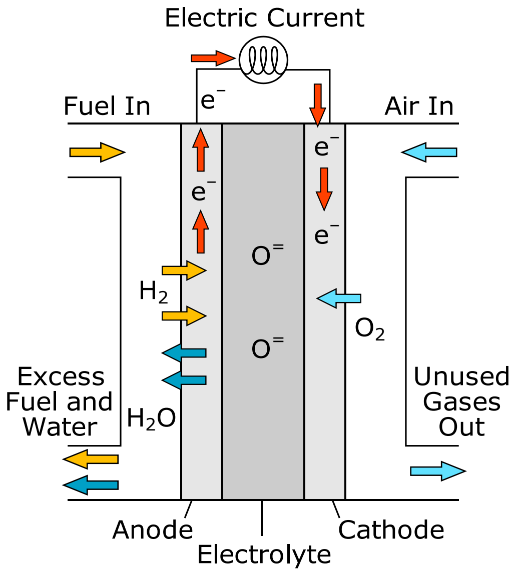

Figure 1: General scheme of a fuel cell (Office of energy efficiency & renewable energy, 2019)

There are different types of fuel cells, each of those composed by the different materials and involving different chemical reactions. This study will be only focused on SOFCs and their applications. SOFCs are around 60% efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (cogeneration), overall fuel use efficiencies could top 85% (Kendall & Kendall, 2015).

SOFC fuels

A SOFC can receive as input different substances, the main ones are: hydrogen; hydrocarbon gases such as methane (CH_4) and propane (C_3H_8); biofuels such as methanol (CH_3OH) and formic acid (HCOOH) (Kendall & Kendall, 2015). The SOFC in this study will be simplified to a device which receives natural gas at the inlet and that at the outlet will make available electricity and heat according to the relative efficiency, as shown in Figure 2:

Figure 2: Simplified model a SOFC used in this study

The presence of methane in natural gas is decisively superior with regard to other constituents of the mixture. For this reason, in this study methane is assumed to be the only active component of natural gas eventually, in fact, feeding the SOFC.

4. LOAD PROFILES DATABASE

The Excel tool is based on the concept of re-creating the E&H profiles potentially for any customer and to do so, it’s necessary to build the profiles from existing models. The U.S. Department of Energy (DOE) developed commercial reference buildings. These models, divided in 16 different building types are: large office, medium office, small office, warehouse, stand-alone retail, strip mall, primary school, secondary school, supermarket, quick-service restaurant, full-service restaurant, hospital *(U.S DOE, 2017)*. From the website the hourly values of E&H consumptions (kW) for these types of building for most of the cities in the Unites States are available. For the purpose of this study, 5 different areas/countries in the U.S. have been chosen to be analysed in order to comprise different climatic zone:

- East, California;
- South, Texas;
- West, West Virginia;
- North, Minnesota;
- Center, Colorado.

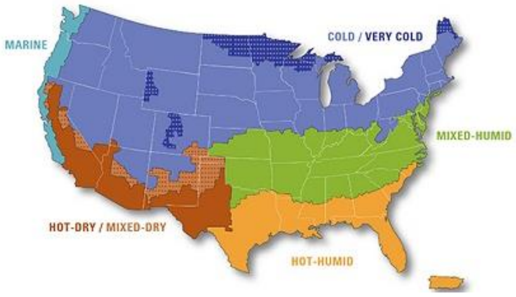

Figure 3: United states different climatic areas

For each of these 5 countries, data regarding all the 16 types of building were analysed. For each of these 80 combinations, 6 graphs were plotted representing:

- The electric consumption over a year;
- The electric consumption during a typical winter day (average of the days in January);
- The electric consumption during a typical summer day (average of the days in July);
- The heat consumption over a year;
- The heat consumption during a typical winter day (average of the days in January;
- The heat consumption during a typical summer day (average of the days in July);

An example of graphs is here reported:

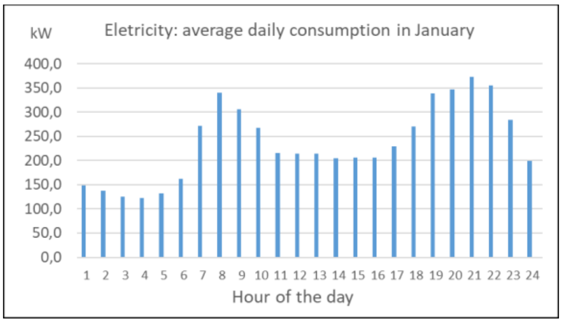

Figure 4 Hourly electric consumption profile of a large hotel in Colorado in a typical winter day

For all the profile analysed the minimum value of the electric consumption, referred as base load, has been individuated, it is a key figure to size the SOFC system.

From plotting the graphs of the aforementioned combinations of types of building and in the 5 countries in the U.S., and analysing their base loads, it was possible to rule out several structures because the base load was too small since the SOFC in order to be profitable needs a consistent minimum base load. Analysing all the graphs deducted from the data, it was possible to notice that the curve of the same building types, even if it shows different values for the consumptions (kW), always maintains approximately the same shape also in different regions of the U.S. This means that different climatic conditions scale up or down the values, while the general trend during the days and the whole year is approximately the same. The idea of re-creating the E&H consumptions profile is based on this consideration.

5. METHODOLOGY

The ideal customer for a convenient introduction of such devices has a consistent need of electricity and heat over the year. In the following illustration the architecture of the system is shown in the next figure where the yellow, blue and red lines represent respectively electricity, natural gas and heat.

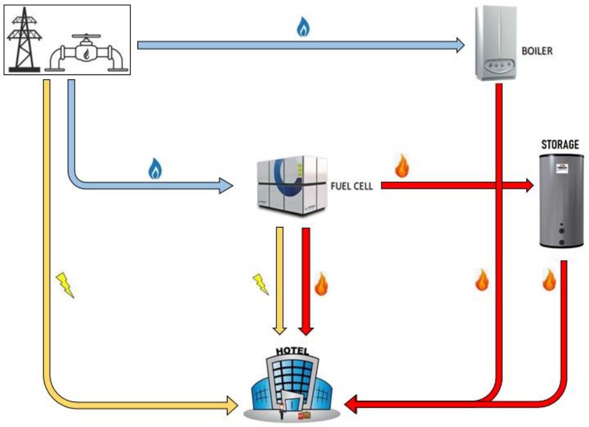

Figure 5 General scheme of the system after the introduction of the SOFC

The SOFC receives in input natural gas from the grid. According to the electrical and thermal efficiency, the chemical power contained in the natural gas gets converted in electricity and heat used to supply the customer's activities. However, the electricity and heat provided by the SOFC are likely to not be sufficient to cover the whole necessity of the customer, for this reason extra heat and electricity are required from the grid. A storage unit is considered in this study with the hypothesis that is able to save 10% of the extra heat produced. In order to utilize the tool is necessary to insert 4 inputs regarding the customer:

- Country;
- Type of customer;
- Annual electricity consumption (MWh/y);
- Annual heat consumption (MWh/y);

Type of customer corresponds to the type of activity the customer runs which needs to match with the type of building from the database. Annual electricity and heat consumption are the total amounts of energy expressed in MWh consumed over a year respectively for electricity and heat. Heat comprises the energy used for heating and to have hot water. To scale the curves from the database the values of consumptions inserted in input are used and this allows to re-create the E&H consumption profile for any customer.

Conventional SOFC characteristics

To perform this study and the calculation it implies, 3 different conventional SOFC have been used. They represent average values deducted from those of the manufacturers of the project. The assumed values are summarized in the following table:

Characteristics	Type 1	Type 2	Type 3	Unit
Nominal size	6	60	300	KW
Electrical efficiency	55%	55%	55%	
Thermal efficiency	30%	30%	30%	
Maintenance	72	72	72	h/y

Minimum electrical efficiency	40%	40%	40%	
Degradation rate	0.4%	0.4%	0.4%	%/1kh
SOFC module manufacturing cost (current scenario)	8000	8000	8000	€/kW
SOFC module manufacturing cost (target scenario)	4000	4000	4000	€/kW
O&M cost	500	1500	5000	€/y
Commissioning and installation cost	2000	4000	6000	€
Manufacturer margin	20%	18%	15%	
CO_2 emissions	1.78	1.78	1.78	kg/m^3

Table 1 Characteristic of the assumed conventional SOFCs

Sizing of the SOFC system

In the model the cell is sized according to the base load In the model the largest possible SOFC is preferred: If Base load < 60 kW, a certain number of Type 1 SOFC will be used in accordance with the following formula:

$$N° \, SOFC = ROUNDDOWN\left(\frac{Base\ load\ kW}{6\ kW}\right) \tag{1}$$

The same criteria is used for type 2 and 3. Then it is possible to calculate the electric and heat power to be installed:

$$E_p = N°SOFC * Nominal\ size \tag{2}$$

$$H_p = \frac{E_p}{\varepsilon_e} * \varepsilon_{th} \tag{3}$$

Where: E_p is electric power and consists of the total amount of electric power the SOFCs can provide, H_p *is* the heat power is the amount of heat expressed in kW which are released by the SOFCs during its operation ε_e is the electric efficiency of the cell, ε_{th} is the thermal efficiency of the cell, which can be used to supply useful heat to the customer using a system of heat exchangers. Due to the degradation rate it might be necessary to replace the stack of the SOFC

Energy flows

The electrical efficiency of the SOFC varies over time. It is assumed the reduction of electrical efficiency leads to an increase of wasted heat which translates into an increased thermal efficiency that maintains the overall efficiency of the SOFC constant over the years:

$$\Delta\varepsilon_e = -\,\Delta\varepsilon_{th} \tag{4}$$

$$\varepsilon_e + \varepsilon_{th} = \varepsilon_{tot} = constant \tag{5}$$

Where: ε_{tot} is the total efficiency of the cell. For each year of usage was possible to calculate the values in the following table:

	Unit
Electricity needed by the customer	kWh
Heat needed by the customer	kWh
Input energy in the SOFC	kWh
SOFC gas input	m^3
Hour of replacement induced by degradation	h
Operating hours stack	h
Electrical efficiency at the end of the year	-
Average electrical efficiency during the year	-
Electric need covered by the SOFC	kWh
Electric coverage of the need	%
Electric need left uncovered by the SOF	kWh
Average thermal efficiency during the year	-
Total thermal energy produced by the SOFC	kWh
Thermal need covered by the SOFC	kWh
Thermal need covered by the SOFC + storage	kWh
Thermal need covered by the SOFC + storage	%
Thermal need uncovered by the SOFC + storage	kWh
Thermal need uncovered by the SOFC + storage	%
Input energy for the boiler	kWh
Boiler efficiency	%
Energy saved by the storage unit	%
Cost of the storage unit	€
Heat directed to the storage unit	kWh
Heat to storage / heat produced by SOFC	%
Energy saved by the storage unit	kWh
Savings achieved by the storage unit	€

Table 2: List of the items calculated in the model

The model for its functioning also considers the price of electricity and natural gas deducted from Eurostat website (Eurostat, 2019).

Emissions

Assuming methane as the only active component in the natural gas conveyed in the SOFC as explained in chapter 3, the reaction which will take place at the anode and cathode will be respectively:

$$CH_4 + 4O^{2-} \rightarrow CO_2 + 2H_2O + 8e^- \qquad (6)$$

$$O_2 + 4e^- \rightarrow 2O^{2-} \qquad (7)$$

Applying a multiplying factor of 2 to the reaction at the cathode, the overall reaction is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (8)$$

In this case beyond water production, carbon dioxide is produced as well. From the formula it is noticeable that for every cubic meter of CH_4 introduced in the cell, one cubic meter of CO_2 is produced. Using CO_2 density it is possible to find the kg of CO_2 produced according to the methane fed to the cell:

$$SOFC\ CO_2 = \frac{SOFC\ gas\ input\ * CO_2\ density}{1000} \qquad (9)$$

Where: $SOFC\ CO_2$ are the tons of carbon dioxide produced in a year and $SOFC\ gas\ input$ are the cubic meter of methane the SOFC receives in one year.

The case in which the same amount of energy had to be withdrawn from the grid (reference case) has been explored. The carbon dioxide emissions related to this case are calculated with the following formula:

$$Ref\,CO_2 = \frac{\left(E_{covered}^{SOFC} * Em_f\right)}{1000} + \frac{H_{covered}^{SOFC+storage}}{LHVm *\ CO_2\ d. * 1000} \qquad (10)$$

Where: $Ref CO_2$ is the number of tons of CO_2 produced over in a year in the reference case, $E_{covered}^{SOFC}$ is the energy produced by the SOFC which covers the load of the costumer, $H_{covered}^{SOFC+storage}$ is the amount of thermal energy which actually covers the thermal need of the customer, also including the recovered heat from the storage unit, Em_f is the Italian emission factor equal to 0.446 $\frac{kg\ CO_2}{kWh\_e}$. The reduction of CO_2 is calculated respect to the reference case:

$$CO_2\ red. = \frac{(RefCO_2 - SOFC\ CO_2)}{Ref\ CO_2} * 100 \qquad (11)$$

Where $CO_2\ red$ stands for CO_2 reduction expressed as a percentage.

Cash flow

The cash flow section is dedicated to the calculation of the benefits, costs and consequently the possible profit, taking into account discount rate and inflation assumed to be respectively 5% and 2% (“Inflation forecasts,” 2019). The quantities calculated are summarised in the following table:

Costs	**Unit**
SOFC module manufacturing	€
Commissioning and installation	€
Stack replacement	€
Manufacturer profit	€
Storage unit	€
Operation and maintenance cost	€
Cost of the fuel to the SOFC	€
Benefits:	
VOLL	€
Electricity not bought from the grid (+ i)	€
Heat not bought from the grid (+ i)	€
Subsidy	€

Table 3 Costs and benefits calculated in the model

Once all the costs and benefits have been introduced, it is possible to calculate the economic balance. The cash flow is estimated for every year, then the discounted cash flow considers the discount rate and finally the net present value (NPV) of the investment is obtained. The NPV determines whether the installation of the SOFC is profitable or not.

6. SUBSIDY SYSTEM

Subsides and economic supports from governments or other institutions are key factors to be considered for an accurate economic evaluation. SOFCs constitute a high efficiency system which has the qualification to access these funding.

Italian funding

Italian Government supports the transformation towards more efficient energy systems through the mechanism of the Energy Efficiency Certificates (TEE), also known as "White Certificates" (GSE, 2019). To know the economic support the SOFC can receive, firstly is necessary to calculate the Primary Energy Saving (PES) index according to the following formula:

$$PES = 1 - \frac{Ef}{\left(\frac{Echp}{\varepsilon_{e,rif}} + \frac{Hchp}{\varepsilon_{th,rif}}\right)} \qquad (12)$$

Where:

- PES is the yearly amount of energy saving as input of the CHP system;
- Ef is the yearly amount of energy in form of fuel introduced in the CHP system;
- $Echp$ is the yearly amount of electricity produced by the CHP system;
- $Hchp$ is the yearly amount of heat produced by the CHP system;
- $\varepsilon_{e,rif}$ is the average Italian efficiency to produce electricity separately equals to 0.46;
- $\varepsilon_{th,rif}$ is the average Italian efficiency to produce heat separately equals to 0.9;

The amount of savings in terms of energy [MWh] achieved by the introduction of the CHP system can be calculated with the following formula:

$$RISP = \frac{Echp}{\varepsilon_{e,rif}} + \frac{Hchp}{\varepsilon_{th,rif}} - \ Ef \qquad (13)$$

Where:

- $RISP$ is the amount of energy expressed in MWh saved by the CHP system;

The amount of TEE that the system can obtain can be calculated with the successive equation:

$$TEE = RISP * K * 0.086 \qquad (14)$$

Where:

- K is a parameter that for application below 1 MW it's equal to 1.4;
- TEE is the yearly number of white certificates the system can obtain for a maximum duration of 10 years.

The white certificates can then be sold according to the current economic value of the certificates. The actual price of the TEE assumed for this study is equal to €300 (GSE, 2019).

7. VALUE OF LOST LOAD

One of the features of fuel cells is the ability to supply electricity without interruptions. To economically evaluate this feature three methods have been explored in literature (Wolf & Wenzel, 2016):

- survey-based approaches
- market-based approaches
- production-function approaches.

In this study the third method is preferred, and an average value of 8.50 €/kWh is assumed, calculating the consequent benefit with the next formula:

$$Benefit \ = VOLL \, x \, Energy_{lost}^{yearly} \qquad (15)$$

Considering:

$$Energy_{lost}^{yearly} = Avg.h\ of\ outage\ x\ Annual\ cons. \quad (16)$$

Where $Energy_{lost}^{yearly}$ is the amount of energy lost because of the outages and benefit is the amount of saving per year.

8. MODEL APPLICATIONS

Two different cases placed in Italy were implemented in the model and analysed:

1. Supermarket with E&H: 1400 and 600 MWh;
2. Hospital with E&H: 6500 and 3000 MWH;

In the first case the study conducted showed savings of CO_2 respect to the reference case utylizing electricity and natural gas from the grid, equal to 25%. Conducting the study utilyzing the SOFC module manufacturing cost equal to 8000 €/kW the net present value (NPV) reports a negative value equal to -243 k€.

In the second case of the hospital the savings of electricity correspond to 32% over the reference case. This time the current scenario has been used (4000 €/kW) to perform the calculation and the NPV at the end of the 14 years is a positive balance of 1.02 M€.

9. SENSITIVITY ANALYSIS

This section is intended to evaluate how the different parameters involved in the study affects the result produced by the model. The analysis shown in this chapter is based on the first application example shown in the previous chapter.

NPV versus SOFC manufacturing cost

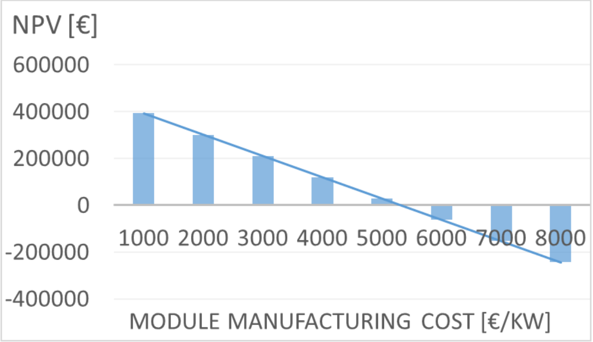

Figure 6 NPV vs SOFC module manufacturing cost

As expectable, a variation on the price of the manufacturing of the SOFC has a huge impact on the NPV. With the price of 6000 €/kW the implementation of the SOFC is still not profitable. The application becomes positive with a SOFC module manufacturing cost equals to 5317 €/kW.

NPV versus electricity price

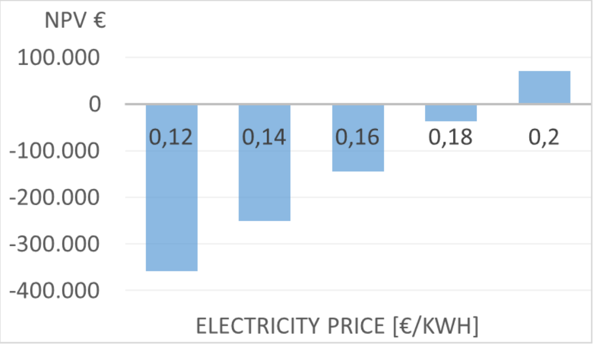

Figure 7 NPV vs electricity price

From the graph, it is possible to comprehend the great impact the price of electricity has on the convenience of the project. For the lowest price of 0.12 €/kWh the investment is not convenient. Same applies for the prices until 0.18 €/kWh, while for a corresponding price of 0.20 €/kWh the net present value appears to be positive.

NPV versus degradation rate

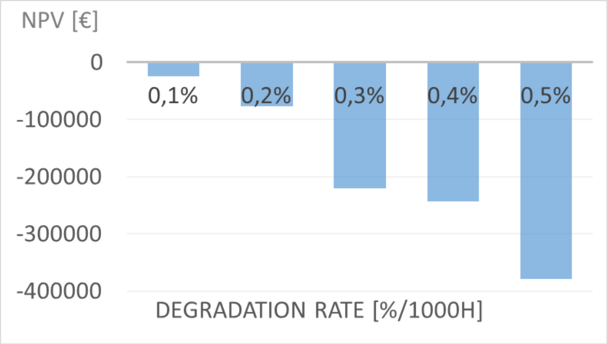

Figure 8 NPV vs degradation rate

It is interesting to notice the big difference between the values of 0.2 and 0.3 %/1000h: with 0.02 %/1000h no replacement of the stack of SOFC takes place during the period analyzed of 14 years and this benefits the final net present value considerably. More specifically, the relation between the degradation rate and the lifetime of the SOFC is reported in the following table:

Degradation rate [%/1000h]	**Lifetime [year]**
0.5	6.3
0.4	7.8
0.3	10.5
0.2	15.7
0.1	31.4

Table 4 Degradation rate and consequent value of lifetime of the SOFC

10. CONCLUSION

This study is focused on the analysis of solid oxide fuel cells for combined heat and power systems applied to the commercial sector. In order for the SOFC installation to be convenient it is necessary that beyond the need for electricity, there is a consistent demand of heat in order to utilize the thermal power produced by the SOFC. In this way, the effective efficiency of the SOFC reaches values around 85%. The internal use of the heat produced by the SOFC and the related savings in the purchasing of natural gas from the grid plays an important role in the final economic balance.

A crucial point regarding the spread of SOFCs is the current price to manufacture the module of 8000 $\frac{€}{kW}$. In fact, as shown in the first example, developing calculation considering the current price for this technology, the implementation is far from being convenient. However, with the technology becoming more mature and with advancements in the production methods and cheaper materials explored and used, there is a great chance for a future reduction of cost. The target scenario with an assumed price of 4000 $\frac{€}{kW}$ mentioned in this study, shows that the SOFC implementation in case the scenario’s conditions are met, is convenient and profitable: in spite of an initial investment of 1.384.300 €, at the end of the period of 14 years, it results in a profit of 1.019.672 €.

While the price to purchase the SOFC module is still too high, since fuel cells through the cogeneration of electricity and heat lead to a consistent reduction of emissions, national subsidies are available to incentive the introduction of these devices. In Italy, the Government is supporting the implementation of fuel cells through the system of the TEE. Also, in the rest of Europe there are similar incentives: in Germany these systems are supported through the Combined Heat and Power Act 2016 CHP (KWKG 2016), which objective is to reduce the overall production of greenhouse gases (BMWi - Federal Ministry for Economic Affairs and Energy, 2019). The subsidy in these cases can make the difference not only on the economic balance of a single project, but also in helping the diffusion and consequently the future development of these devices, attracting the attention of the scientific community.

Regarding the emissions of carbon dioxide, while producing electricity SOFCs are promising devices: the CO_2 emission factor of the conventional SOFC analyzed in this study is 0.355 $\frac{kgCO_2}{kWh}$ and it is lower than the average CO_2 emission factor in Italy equals to 0.466 $\frac{kgCO_2}{kWh}$ (ISPRA, 2018). Moreover, the SOFC together with electricity produces heat which would otherwise require to be absorbed by the grid implying other CO_2 emissions related to the dispatch of heat. The 2 cases investigated in this study leads to a reduction of CO_2 emissions equals to 25% for the supermarket and 32% for the hospital. A further possible step to improve the model would be to size the SOFC differently. It is possible to evaluate an increase in the installed power by doing a study that takes into account three factors and related economic implications:

- The amount of extra user load covered
- Selling the extra electricity of the SOFC on the grid to not to modulate the output of the SOFC, evaluating the sale price on the network
- The amount of extra heat user covered

From this variation, it may result that it is more convenient to assume a larger size of the SOFC.

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