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 that 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 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

Resumo

O objetivo deste trabalho é construir uma ferramenta capaz de integrar uma célula de combustível de óxido sólido (Solid Oxide Fuel Cell, SOFC) em um sistema de calor e energia combinada (CHP), e avaliar o desempenho econômico do projeto e a redução das emissões de CO2 lançadas no ar. O modelo foi desenvolvido no Microsoft Excel e a partir de poucos insumos é capaz de prever o consumo elétrico e térmico de um cliente no setor comercial. A arquitetura do modelo considera um SOFC alimentado com gás natural para fornecer o cliente com eletricidade e calor, enquanto a energia extra será absorvida a partir da grade quando a demanda ainda não está satisfeita pelo SOFC. Este estudo também compreende uma visão geral sobre os subsídios disponíveis italianos para financiar a integração do SOFC nos sistemas de CHP; e uma análise relacionada ao valor econômico do suprimento ininterrupto de energia elétrica, indicada como "valor da carga perdida" (Value of Lost Load, VOLL). Diversas análises de sensibilidade também são conduzidas para avaliar o peso de diferentes parâmetros no resultado final do estudo. Resultou que a implementação do SOFC dentro de um sistema de CHP produz economias consideráveis em termos de dióxido de carbono liberado no ar. Além disso, a partir dos dois exemplos de aplicações mostradas neste estudo, percebe-se como o preço atual dos SOFCs ainda é uma barreira para a disseminação dessa tecnologia, enquanto o preço-alvo investigado leva a cenários financeiros promissores.

Palavras-chave: Célula de combustível de óxido sólido, calor combinado e sistema de energia, Value of Lost Load, Sistema de subsídios italiano, ComSos

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Nomenclature

Greek symbols

Δ Difference

ε Efficiency

Roman symbols

$Base\ load$: Minimum yearly value of electric consumption of the customer

$Boiler\ efficiency$: Efficiency of the boiler

$CO_2\ density$: Carbon dioxide density

$CO_2\ reduction$: Carbon dioxide reduction between the reference case and the SOFC production

$Degradation\ rate$: rate of degradation of a SOFC

$\varepsilon_{e,rif}$: Average Italian efficiency to produce electricity separately equals to 0.46;

$\varepsilon_e\ replacement$: Electrical efficiency threshold of replacement of the stack of the SOFC

$\varepsilon_{th,rif}$: Average Italian efficiency to produce heat separately equals to 0.9;

$E_{covered}^{SOFC}$: Electricity produced by the SOFC feeding the customer

$Echp$: Yearly amount of electricity produced by the CHP system;

Ef: yearly amount of energy in the form of fuel introduced in the CHP system;

$Electric\ power$: Value of the electric power installed considering all the SOFC placed in series

$Elec_{price}$: Price of electricity

$Elec_{ratio}$: Ratio between the electric consumption of the customer and the database

Em_f: Italian emission electricity factor

$Energy_{SOFC}^{input}$: Energy in input to the SOFC

$h.maint$: Hours of maintenance performed every year

$Hchp$: Yearly amount of heat produced by the CHP system;

$Heat\ power$: Thermal power provided by the SOFC

$Hour\ of\ replacement$: Maximum number of hours per year of using the stack of the SOFC

$H_{covered}^{SOFC+storage}$: Thermal energy produced by the SOFC covering the user’s need including the storage i: inflation

K: Parameter to consider the size of the system installed for TEE

$N° \; of \; SOFC \; in \; series$: Number of SOFC to be placed in series

NG_{price}: Price of natural gas

$Nominal \; size$: Electric size of the conventional SOFCs

$O\mathrm{e}M_i$: Operation and maintenance cost at the year "i"

$LHV \; methane$: Low heating value of methane

PES: Primary energy saving

$RISP$: Amount of energy expressed in MWh saved by the CHP system;

$Ref \; CO_2$: Emission of carbon dioxide in the reference case

$SOFC \; CO_2$: Mass production of CO2 during the year

TEE: Number of white certificates

$Yearly \; electricity \; consumption \; customer$: Electricity expressed in kWh/y used by the customer

$Yearly \; electricity \; consumption \; database$: Electricity expressed in kWh/y as reported in the database

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. To tackle this trend is necessary to turn the tide and reduce the presence of GHG in the atmosphere. The production of electricity through the consumption of fossil fuels is among the main responsible for the increase of GHG over time, for this reason more sustainable processes of generating electricity are spreading around the World. On this regard, the European Union (EU) is taking steps in the direction of cleaner and more sustainable ways to obtain electricity. Among the various initiatives undertaken by the EU, this study will focus on the objective of the European project named ComSos. ComSos (Commercial-scale Solid Oxide Fuel Cell System) is a European funded project 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, *ComSos – Comsos*).

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. The analysis performed by the tool is based on the electricity and heat consumption data profiles available on the Unites States Department of Energy website and used as a framework for this study (United States Department of Energy, 2018). 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).

1.1 The ComSos project

Horizon 2020 is the biggest EU research and innovation program ever, with nearly €80 billion of funding available over 7 years (2014 to 2020) in addition to the private investment that this operation will attract. Horizon 2020 has the political backing of Europe's leaders and the Members of the European Parliament. They agreed that investment in research and innovation is essential for smart, sustainable and inclusive growth. Horizon 2020 is helping to achieve this by coupling research to innovation and focusing on three key areas: excellent science, industrial leadership, and societal challenges. The goal is to ensure Europe produces world-class science and technology that drives economic growth, with the objective of removing barriers to innovation and can making it easier for the public and private sectors to work together in delivering solutions to big challenges facing our society. The program covers a wide range of thematic areas: future emerging technologies, advanced materials, nanoelectronics, robotics, advanced computing, space, health, food security, demographic change, education, smart green, and integrated transport, secure clean and efficient energy (H.2020).

The ComSos - Commercial-scale Solid oxide fuel cell systems - project is framed within the last-mentioned category "Secure clean and efficient energy" which objective is to support the transition to reliable, sustainable and competitive energy systems, addressing energy efficiency and low carbon technologies. Aligned with this perspective the ComSos project is a 42-months project (2018-2020) with a budget of EUR 10.2 million, is 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, *Partners – Comsos*). This project is conducted by different partners focused on specific areas:

Table 1 Partners involved in the ComSos project (ComSos, *Partners – Comsos*)

VTT	VTT Technical Research Centre of Finland Ltd is a state-owned and controlled non-profit company operating under the ownership steering of the Finnish Ministry of Employment and the Economy. Its activities are focused on three areas: knowledge-intensive products and services, smart industry and energy systems and solutions for natural resources and environment
convion	Convion Oy is a leading supplier of fuel cell systems, focusing on the commercialization of products for decentralized power and heat generation. Convion's employees have more than 10 years of experience in the development and commercialization of energy-efficient and zero-emission fuel cell systems.

BlueTerra Energy Experts	BlueTerra is an independent energy consultancy specialized in energy savings and local energy solutions for the industry, agriculture and the built environment and with a lot of experience in the field of (micro-)CHP. Within their projects, an integral approach is combined with expertise ranging from technology and economics to legislation and policy.
sunfire	Sunfire GmbH develops and manufactures systems for renewable industrial gas and fuel production. These substitutes for mineral oil and natural gas, known as e-gas, e-fuel or e-chemicals, replace fossil fuels in existing infrastructures. The solid oxide cells (SOCs) used for the conversion process are also used as generators to provide electricity and heat.
SOLID POWER	The SOLIDpower Group is one of the world's leading companies in the field of high-temperature fuel cell technology (SOFC, solid oxide fuel cells). The Group develops, manufactures and markets fuel cell systems for generating power and heat in residential and commercial buildings at locations in Italy, Germany, Switzerland, and Australia.
	Politecnico di Torino, Department of Energy "Galileo Ferraris", STEPS – Synergies of Thermochemical and Electrochemical Power Systems – is a research group part of the Energy Department of Politecnico di Torino, focusing his research on thermo-chemical and electrochemical processes for hydrogen and synthetic fuels generation from renewable energy, CO_2 recycle and SOFC systems. STEPS group is involved in international and national research projects and collaborations.

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

2 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 and Kendall). 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 2.1 shows the basic working principle of a fuel cell (Office of energy efficiency & renewable energy)

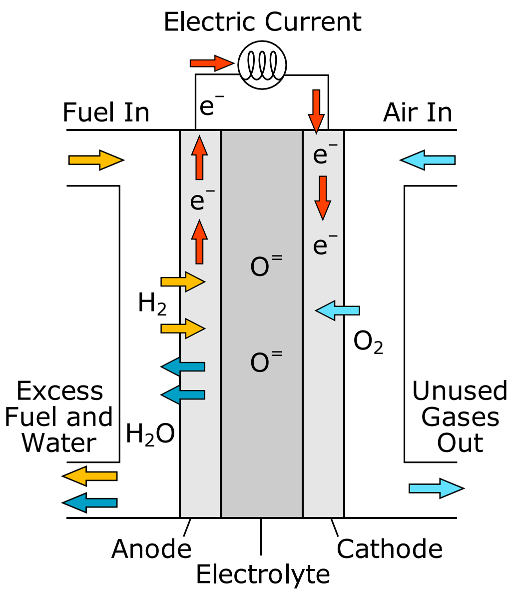

Figure 2.1 General diagram of a fuel cell (Office of energy efficiency & renewable energy, 2019)

There are different types of fuel cells, each of those composed by the different materials and involving different chemical reactions. The main types are here reported:

- SOFC (Solid Oxide Fuel Cell)
- MCFC (Molten carbonate Fuel Cell)
- PAFC (Phosphoric Acid Fuel Cell)
- PEMFC (Proton Exchange Membrane Fuel Cell)
- DMFC (Direct Methanol Fuel Cell)
- DEFC (Direct Ethanol Fuel Cell)

This study will be only focused on SOFCs and their applications. SOFCs are around 55-60% 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 and Kendall).

2.1 SOFC fuels

A SOFC can receive as input different substances:

- Hydrogen;
- Hydrocarbon gases such as methane (CH_4) and propane (C_3H_8);
- Biofuels such as methanol (CH_3OH) and formic acid ($HCOOH$);

Also other compounds can be utilized if opportunely pre-treated (Kendall and Kendall). When pure hydrogen is used, it is mostly employed with PEMFC (which maximum efficiency is around 50%) because it develops more power working at room temperature, which wouldn't happen with SOFC working at high temperatures. The main advantage of hydrogen applied to FC consists of the clean emissions after its usage. However, the difficulty related to a convenient way to store and transport pure hydrogen obstructs its diffusion. Hydrocarbons react well with steam or air to provide hydrogen useful for the cell, and carbon monoxide which then combine with oxygen ions at the anode interface. Also, hydrocarbon fuels give good energy storage compared to hydrogen, facilitating their diffusion and usage.

This study is aimed to explore the economic advantages and implication subsequent to the introduction of such devices in a system where electricity and heat are required. It is not, therefore, centered on the chemical and structural properties of a fuel cell, for this reason the SOFC 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 2.2

Figure 2.2 Simplified model a SOFC used in this study

Among the available fuels to feed a SOFC, natural gas is chosen since it is on average the most likely to be available in a specific local/national grid. Natural gas is a mixture of different gases where the main component is methane (CH_4), with minor presence of hydrocarbons gas such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}), as well as non-hydrocarbon gases (Speight). As the provenance of natural gas changes, the composition slightly differs from region to region, however, the presence of methane in most of the cases 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.

2.2 Anode

The anode is the electrode at which oxidation (loss of electrons) takes place. In a fuel cell, the anode is electrically negative. The basic requirement of an anode in any fuel cell is to provide sufficient active sites for the oxidation of the fuel, under operating conditions. The simplest oxidation reaction at an anode is:

$$H_2(g) \rightarrow 2H^+ + 2e^- \tag{2.1}$$

This equation illustrates that three phenomena are needed to meet in one place to produce a working anode: the entry of gas-phase H_2, production of the H^+ ions from the electrolyte and migration of the electrons to the circuit. This means a porous anode has to be made of ionic and electronic conductors. In order to have a long-expected lifetime, is crucial for the anode to remain stable even at high ranges of temperatures.
Significant progress has been made in SOFC anode development since the first version of a SOFC. Currently, the most conventional used materials are Ni and yttria stabilised zirconia (YSZ) even if they still face problems related to carbon coking and sulfur poisoning. Sulfur posinonig affects the cathode and the overall reaction because sulfur tends to replace oxygen in the reaction. Further studies are necessary to optimize these materials in terms of composition and microstructure, with emphasis on their electronic conductivity, electrocatalytic properties, chemical, and thermal stability. A catalyst is used to facilitate the oxidation of the hydrogen, platinum is generally deployed to improve the rate of the oxidation process (Kendall and Kendall). The use ose of catalysts is necessary to overcome the kinetic

2.3 Cathode

The cathode is the electrode at which reduction (gaining of electrons) takes place. In a fuel cell, the cathode is electrically positive. It is composed of platinum particles uniformly supported on carbon particles to act as a catalyst, increasing the rate of the reduction process. Also it is porous so that oxygen can pass through it (Office of energy efficiency & renewable energy). The reaction which takes place at the cathode is:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{2.2}$$

High-temperature operation of SOFC helps the electrode reaction to proceed without precious metal catalysis, which, however, does not mean any material can be used as the cathode. Properties required for cathode materials are:

- High catalytic activity;
- High electronic conductivity (preferably, electronic–ionic mixed conductivity);
- Chemical stability and compatibility with the other cell components;
- Morphological stability;
- Mechanical stability and compatibility.

Also, they must be achieved in a cost-effective manner. Over time different combinations of materials have been tested to find the perfect candidate as cathode. At this stage, MIEC (Mixed Ionic Electronic Conductor) Perovskite represents so far, the most promising material to be used, even if significant chemical improvement can still be done to increase its lifetime (Kendall and Kendall).

2.4 Electrolyte

The electrolyte for a solid oxide fuel cell must meet a very exacting combination of electrical, chemical and mechanical requirements in order to be suitable for practical application. Its objective is to allow the migration of ions through its structure while avoiding that of electrons. It has to be stable and must have sufficiently high ionic conductivity with low electronic conductivity at the cell operating temperature. In addition, it must be possible to form the material into a thin, strong gas-tight layer. The most usual oxides of choice for this application are those possessing the fluorite structure, such as yttria-stabilized zirconia (YSZ), the most common electrolyte for SOFC. YSZ is not among the most abundant materials on Earth, however it is not a scare resource.

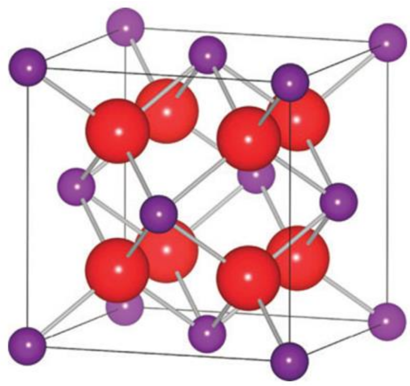

Figure 2.3 The cubic fluorite structure is the framework of the main used electrolytes (Kendall and Kendall)

Other fluorite oxide ion conductors, such as doped ceria, have also been proposed as electrolyte materials for SOFCs, especially to attain the goal of reduced temperature operation (600–800 °C). More recently, a number of other materials, including perovskites, brownmillerites, and hexagonal-structured oxides, have also been found to possess good ionic conductivity at these lower temperatures. Substantial oxide ion conductivity is a rare phenomenon in complex oxides, especially at low temperatures, and so the number of materials that display conductivity adequate for application combined with the restrictions of mechanical strength, high stability, ease of processing and low cost is extremely limited (Kendall and Kendall)

2.5 SOFC operating principle

SOFCs operate at very high temperatures—as high as 1,000°C. High-temperature operation removes the need for a precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system.

SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more sulfur than other cell types can. In addition, they are not poisoned by carbon monoxide, which can even be used as fuel. This property allows SOFCs to use natural gas, biogas, and gases made from coal. High-temperature operation has disadvantages. It results in a slow start-up and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology. Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 700°C that has fewer durability problems and cost less. Lower-temperature SOFCs have not yet matched the performance of the higher temperature systems, however, and stack materials that will function in this lower temperature range are still under development (Kendall and Kendall). The complete chemical reactions of the SOFC will be further explored in section 4.7.

3 Load profiles database

This study aims to develop an economic evaluation of an investment which is as close as possible to the reality. Having the E&H consumption profiles of every customer of last few years, would allow a targeted and precise evaluation about the convenience related to the introduction of a SOFC. However, most of the time this information is not available. Hence, the elaborated 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, formerly known as commercial building benchmark models. These models, divided in 16 different building types represent approximately 70% of the commercial buildings in the U.S (U.S DOE). The 16 categories are:

Table 2 The sixteen different categories adopted in the database (U.S DOE)

BUILDING TYPE NAME	FLOOR AREA (m^2)	NUMBER OF FLOORS
Large Office	46320	12
Medium Office	4982	3
Small Office	551	1
Warehouse	4835	1
Stand-alone Retail	2319	1
Strip Mall	2090	1
Primary School	6871	1
Secondary School	19592	2
Supermarket	4180	1
Quick Service Restaurant	236	1
Full-Service Restaurant	511	1
Hospital	2262	5
Outpatient Health Care	3804	3
Small Hotel	4013	4
Large Hotel	11345	6
Midrise Apartment	3135	4

These building types when applied in different climatic areas of the U.S have different values of the electric and heat consumption. From the website, is then possible to download the hourly values of E&H consumptions (kW) for most of the cities in the Unites States for a whole year. 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:

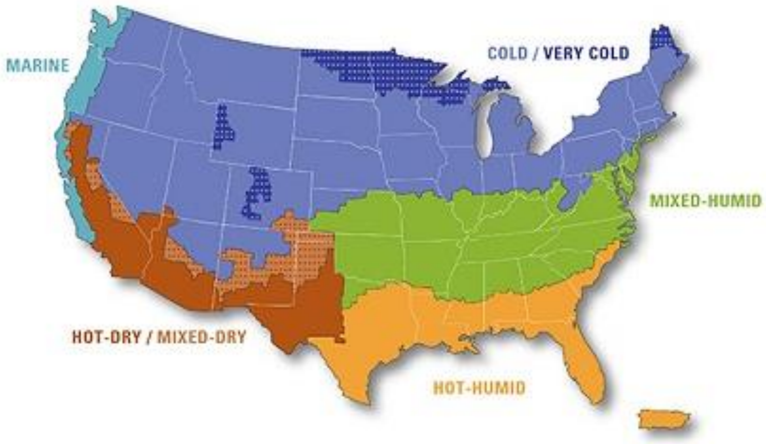

Figure 3.1 United states different climatic areas

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

For each of these 5 States, 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 for one of the combinations is here reported:

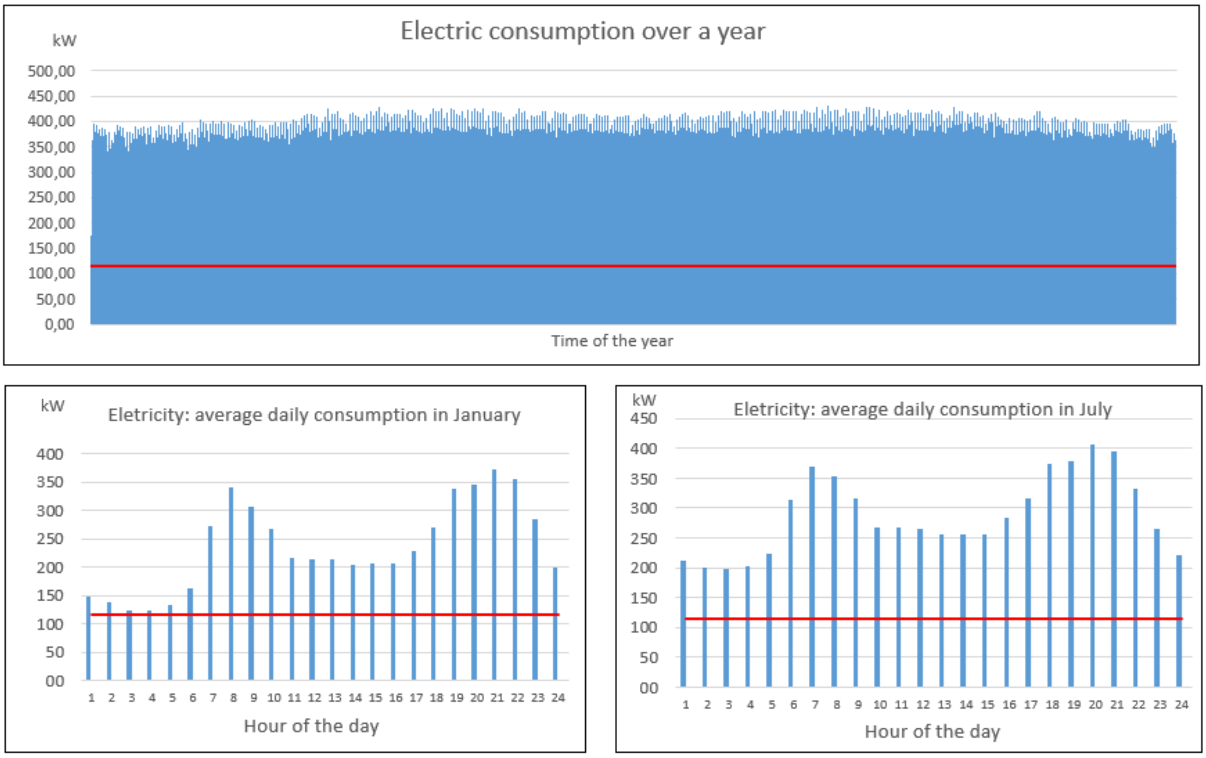

Figure 3.2 Hourly electric consumption profile of a large hotel in Colorado on different time windows

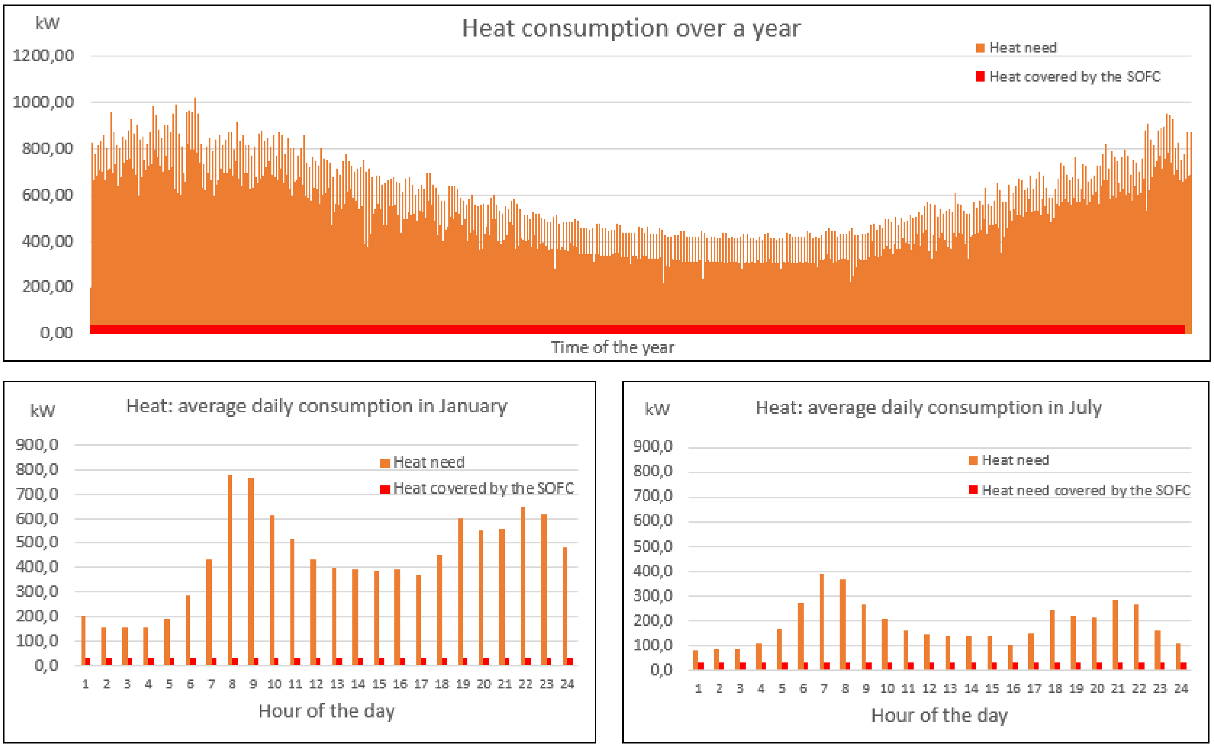

Figure 3.3 Hourly heat consumption profile of a large hotel in Colorado on different time windows

Figure 3.2 represents the electric consumption profile of a large hotel in Colorado. During the year the profile keeps the same trend even over different seasons. The daily representation shows a major consumption during the morning and the evening.

An important aspect is the constant base load the profiles show: from the daily graphs it's actually possible to notice the presence of constant load required during the whole day. The annual spectrum of consumption might be deceptive on this regard: the base load appears to be higher. However, a more detailed look at the values confirms the trend of the daily profiles. In the rest of this study the term "base load" will refer to the minimum value of electric consumption expressed in kW registered during the year, which will be a key figure to size the SOFC system.

Figure 3.3 in orange shows the heat consumption profiles. From the yearly graph we can notice the reduced consumption in the central region of the graph, corresponding to the summer months. The daily graphs have the same trend; however, the values of July are considerably inferior as expected. It is also interesting to notice how hospitals have a considerable heat demand also during the night.

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: the SOFC in order to be profitable needs a consistent minimum base load during the whole year which some building types didn't show. It was chosen to have at least 10 kW as base load, since this study was meant to focus on the commercial sector which is characterized by higher consumption levels compared to the residential sector which comprises a lower range of power values. The following table shows the acceptable and not acceptable types of building with their corresponding base load.

Table 3 Acceptable and not acceptable types of building.

ACCEPTABLE TYPES OF BUILDING	BASE LOAD [KW]
Large Office	211.1
Medium Office	18.8
Primary School	40
Secondary School	87
Supermarket	75.3
Full-Service Restaurant	14.6
Hospital	466.2
Outpatient Health Care	40.8
Small Hotel	31.9
Large Hotel	101.4
Midrise Apartment	14.7
NOT ACCEPTABLE TYPES OF BUILDING	
Small Office	1.9
Warehouse	6.5
Stand-alone Retail	3.7

Strip Mall	3.2
Quick Service Restaurant	9.5

The green row values correspond to the acceptable types of building, while the red ones to the not acceptable types which will not be taken into account for the rest of the study.

Analysing all the graphs deducted from the data, it was possible to notice that the curves of a same building type, even if it shows different values for the consumptions (kW), always maintains approximately the same shape also in different regions of the U.S. An example of it is reported below: the graphs show the electric consumption [kW] (average of the days in January), of an hospital in the 5 considered countries in the U.S. It is possible to notice that the shape of the curves is approximately the same.

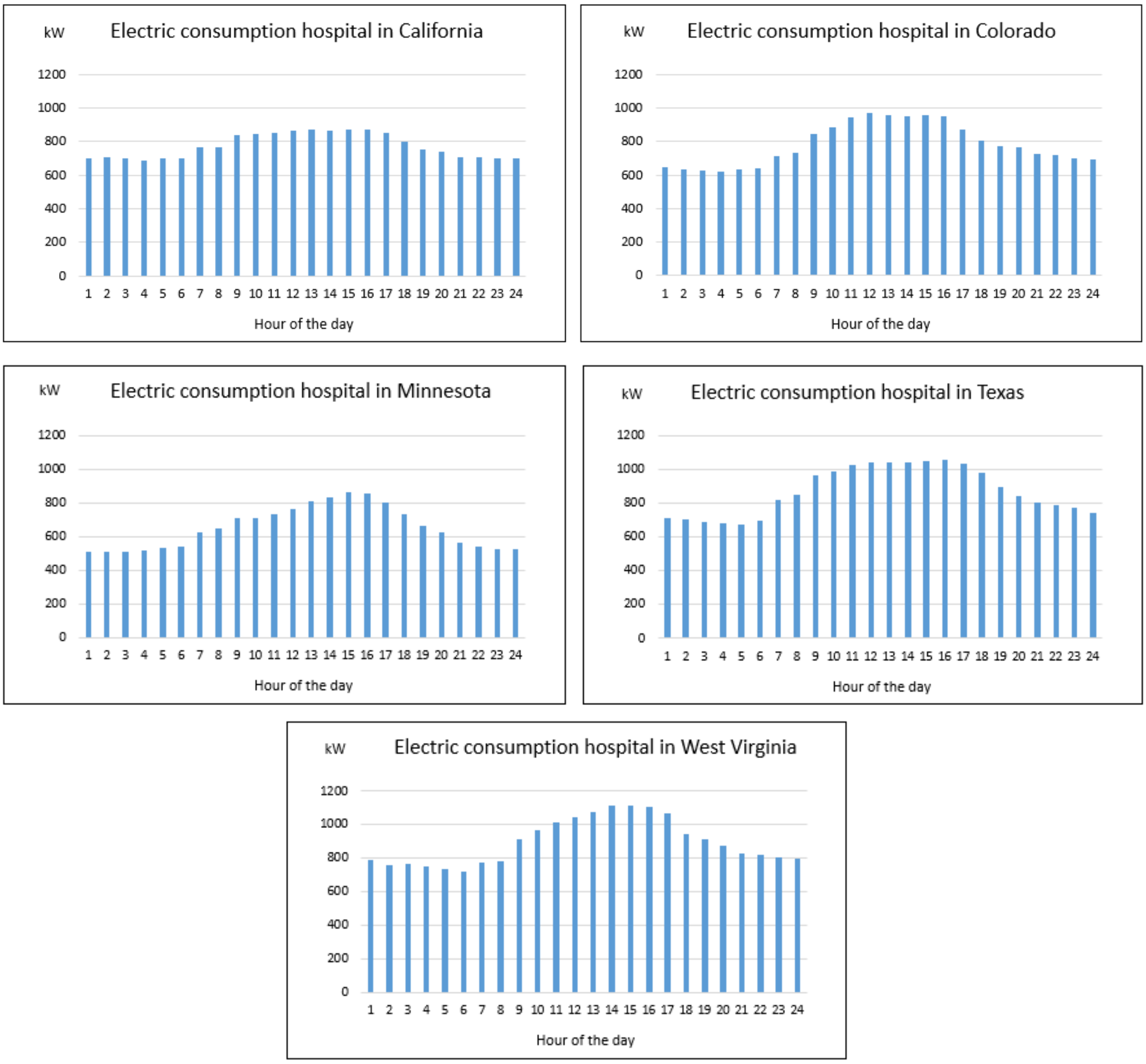

Figure 3.4 Average of the days in January electric consumption expressed in kW of a hospital in California, Colorado, Minnesota, Texas, West Virginia

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 and it will be further explained in paragraph 4.2.

4 Methodology

This chapter constitutes the core of the study. It is dedicated to the description of the Excel tool utilized to evaluate the convenience of the introduction of a SOFC in a combined heat and power system, including equations used and their significance. The main purpose of this tool is to furnish an overall economic evaluation as much precise as possible. To achieve this result, the model re-creates the electrical heating and consumption profiles starting from the values of their total energetic annual consumption in terms of electricity and heating. In this chapter the equations of the model are often shown minimizing the use of acronyms to facilitate the comprehension of the meaning of each term. With the same purpose units of measurement are introduced in some of the equations. Screenshots of the model are reported in this chapter to offer a close look at the tool, together with the explanation of the main entries.

4.1 Architecture of the system

A solid oxide fuel cell is basically a device that fed with natural gas (or other fuels) produces electricity and heat. Consequently, the ideal customer for a convenient introduction of such devices has a consistent need for electricity and heat over the year. In the following illustration the system of an ideal customer is represented: in this example the customer runs a hotel which has a need for electricity and heat, both absorbed by the grid. The heat is obtained through a boiler, supplied with natural gas from the grid. The yellow, blue and red lines represent respectively electricity, natural gas, and heat.

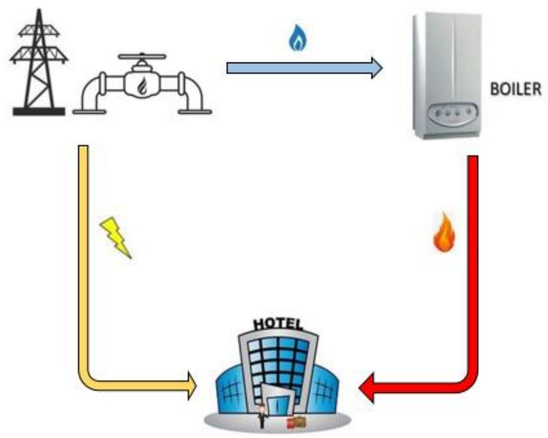

Figure 4.1 General scheme of an ideal customer before the introduction of the SOFC

The following illustration shows the general scheme of the system after the introduction of a SOFC:

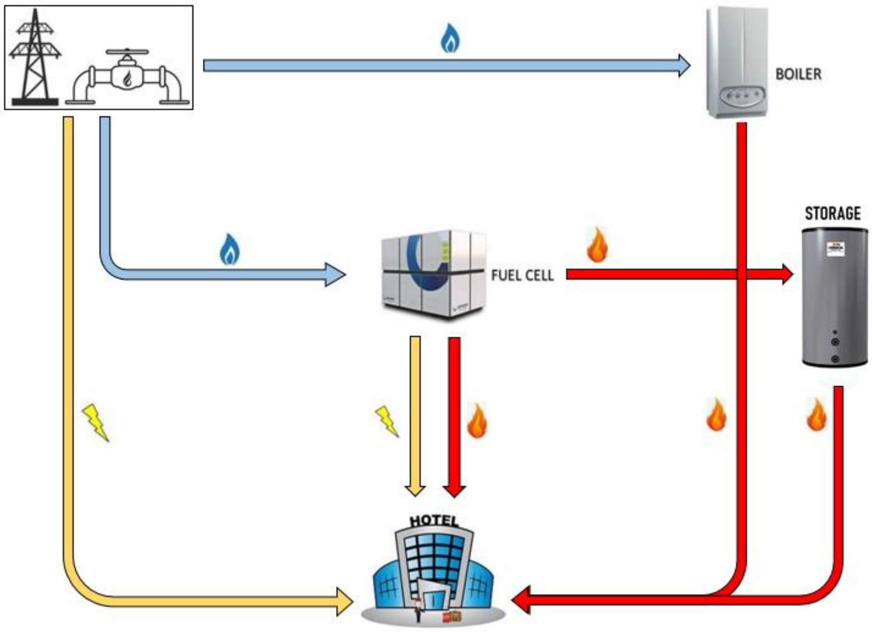

Figure 4.2 General scheme of the system after the introduction of the SOFC

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 into 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. Part of the heat produced by the SOFC will be wasted because the heat might be produced when is not required by the customer and in that case, just a part of it will be used. In fact, a storage unit is considered in this study with the hypothesis that is able to save 5% of the extra heat produced. This concept is explained in more detail in paragraph 4.5 "Energy flows". In the face of a certain consumption of natural gas to feed the SOFC, its introduction would lead to a reduction of electricity and heat absorbed by the customer from the grid. The convenience of the introduction of a SOFC relies, despite the electrical efficiency, on the average lower price of natural gas compared to the electricity price. In addition, part of the heat is covered by the SOFC and this leads to an overall reduction of expense for the consumptions.

4.2 Input data and load profiles definition

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);

The meaning of the mentioned inputs is here explained:

- <u>Country</u>: corresponds to the location where the customer is located and according to it the price of electricity and natural gas might change together with the available national subsidies, as further discussed in paragraph 4.6 “Energy prices”.

- <u>Type of customer</u>: corresponds to the type of activity the customer runs, the categories available are those expressed in chapter 3: full-service restaurant, hospital, large hotel, large office, medium office, midrise apartment, outpatient, primary school, secondary school, small hotel, supermarket. It’s necessary to pick the right category to have an accurate shape for the profiles.

- <u>Annual electricity and heat consumption</u>: 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.

The concept behind the re-creation of the profile considers the assumption according to within a specific category the E&H profiles have approximately the same shape and characteristics. Then, depending on the annual electric and heat consumptions the curves can be scaled to lower or higher values.
Firstly, to scale the curves to obtain those of the customer was necessary to calculate the total electric and heat consumption of every type of building of the database, this was done by summing all the hourly consumptions within the year both for electricity and heat for all the 5 countries considered. Then, to avoid specificities, for each type of building was calculated an average profile among the 5 different locations. The following table could then be compiled:

Table 4 Part of the summary table related to the profiles of the database from DOE

Database customers								
	Large office		Small hotel		Supermarket		Full service restaurant	
Electric yearly consumption	5.905		588		1.653		317	
Heat yearly consumption	1.084		203		792		278	
Date and time	Large office electricity	Large office heat	Small hotel electricity	small hotel heat	Supermarket electricity	Supermarket heat	Full service restaurant electricity	Full service restaurant heat
01/01 01:00:00	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
01/01 02:00:00	256	244	40	25	83	5	23	82
01/01 03:00:00	253	204	41	30	87	14	15	0
01/01 04:00:00	257	276	36	30	90	18	15	0
01/01 05:00:00	253	209	36	31	92	24	15	0
01/01 06:00:00	269	282	38	28	98	22	15	0
01/01 07:00:00	290	212	43	33	96	22	23	75
01/01 08:00:00	342	303	62	32	129	412	39	76
01/01 09:00:00	344	227	76	40	135	380	45	65
01/01 10:00:00	316	267	96	58	161	332	42	62
01/01 11:00:00	275	132	81	49	135	312	34	67
01/01 12:00:00	228	157	57	45	169	270	42	71
01/01 13:00:00	225	112	55	41	200	247	43	63
01/01 14:00:00	229	136	55	40	208	220	42	53
01/01 15:00:00	227	94	55	35	206	208	34	53
01/01 16:00:00	229	116	55	37	202	200	34	53
01/01 17:00:00	227	87	55	36	198	202	34	57
01/01 18:00:00	290	133	61	20	202	213	43	60
01/01 19:00:00	356	130	73	23	181	264	46	66
01/01 20:00:00	367	197	88	28	188	289	46	68
01/01 21:00:00	339	157	89	28	169	293	39	67
01/01 22:00:00	342	214	95	34	159	295	39	62
01/01 23:00:00	314	170	92	32	145	260	39	75
01/01 24:00:00	294	238	69	39	82	0	39	78

The screenshot reports just a part of the table which in reality comprises all the acceptable types of building mentioned previously and the 8760 values of the year. Therefore, the following ratios were calculated:

$$Elec_{ratio} = \frac{Yearly\ electricity\ consumption\ customer}{Yearly\ electricity\ consumption\ database} \quad (4.1)$$

$$Heat_{ratio} = \frac{Yearly\ heat\ consumption\ customer}{Yearly\ heat\ consumption\ database} \quad (4.2)$$

Then the 8760 values of the E&H hourly consumptions of the database were multiplied by the ratios just found in order to have the new 8760 values of the E&H consumptions of the customer. In this way, the E&H consumption profiles of the customers are built.

4.3 Conventional SOFC characteristics

To perform this study and the calculation it implies, 3 different conventional SOFC have been used. These 3 different size-based fuel cells are not produced by any particular manufacturer. They represent average values deducted from those of the manufacturers involved in the project. Once a specific SOFC has been selected for a certain application, its values and features can be inserted in the model so that a more punctual evaluation of the investment can be obtained. The assumed values are summarized in the following table:

Table 5 Characteristic of the assumed conventional SOFCs

CHARACTERISTIC OF THE SOFC	TYPE 1	TYPE 2	TYPE 3	UNIT
Nominal size	6	60	300	KW
Electrical efficiency	55%	55%	55%	
Thermal efficiency	30%	30%	30%	
Hours of maintenance per year	72	72	72	h/year
Electrical efficiency threshold of replacement	40%	40%	40%	
Degradation rate	0.4%	0.4%	0.4%	%/1000h
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	€/year
Commissioning and installation cost	2000	4000	6000	€
Margin of the SOFC manufacturer	20%	18%	15%	
CO_2 emissions	1.78	1.78	1.78	$kg/m^3_{methane}$
Lifetime	68182	68182	68182	h

Some of the items of tables will be here explained:

- Nominal size: it corresponds to the installed electric power that the SOFC is able to provide to the customer.

- Degradation rate: while the SOFC is operated, its electrical efficiency reduces over time: for every 1000 hours of usage a reduction of 0.4% of the initial value of the electrical efficiency occurs.

- Electrical efficiency threshold of replacement: consists of the minimum acceptable value of electrical efficiency to keep the SOFC running. The SOFC should be substituted when 40% of efficiency is reached.

4.4 Sizing of the SOFC system

The solid oxide fuel cells show certain stability and an increase in lifetime if they operate in the condition of constant output electric load. Hence, varying the electric demand requested from a SOFC has a negative influence on the overall lifetime duration of the cell. Therefore, to be sure the SOFC operates at constant load during the year, in the model the cell is sized according to the minimum value of electricity consumed by the customer expressed in kW, referred as 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:

$$N° \; of \; SOFC \; in \; series = ROUNDDOWN\left(\frac{Base \; load \; [kW]}{6 \; [kW]}\right) \tag{4.3}$$

ROUNDDOWN is the Excel function that rounds down a decimal number to the closest inferior integer number.
If Base load < 300 kW Type 2 SOFCs will be used using following the same concept:

$$N° \; of \; SOFC \; in \; series = ROUNDDOWN\left(\frac{Base \; load \; [kW]}{60 \; [kW]}\right) \tag{4.4}$$

Similarly, if Base load > 300 kW, then:

$$N° \; of \; SOFC \; in \; series = ROUNDDOWN\left(\frac{Base \; load \; [kW]}{300 \; [kW]}\right) \tag{4.5}$$

For example, if the base load of the customer is 138 kW, 2 Type 2 SOFCs will be considered to perform the study.
No cumulative solutions of different types of SOFC working unitedly have been considered in this study.
Once the Type of SOFC is known and the so N° of SOFC in series, it is possible to calculate the electric and heat power to be installed:

$$Electric \; power \; [kW] = N° \; of \; SOFC \; in \; series * Nominal \; size \; [kW] \tag{4.6}$$

$$Heat \; power \; [kW] = \frac{Electric \; power \; [kW]}{Electrical \; efficiency} * Thermal \; effiency \tag{4.7}$$

The electric power consists of the total amount of electric power the SOFCs can provide. The heat power is the amount of heat expressed in kW which is released by the SOFCs during its operation which can be used to supply useful heat to the customer using a system of heat exchangers.

4.5 Energy flows

At this point knowing the information related to the SOFCs and of the E&H consumption profiles, it's possible to find more specific information regarding the system and the flows of energy which occur every year. The values are different among the years because the electrical efficiency of the cell 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. To clarify:

$$\Delta\varepsilon_e = -\,\Delta\varepsilon_{th} \tag{4.8}$$

$$\varepsilon_e + \varepsilon_{th} = \varepsilon_{tot} = constant \tag{4.9}$$

Where:

ε_{tot} is the total efficiency of the cell;

ε_e is the electric efficiency of the cell;

ε_{th} is the thermal efficiency of the cell.

The following image is a screenshot from the Excel tool, it gives an overview regarding the type of information extracted by the model:

Table 6: First part of the Excel tool in the "Energy flows" section. Case of a Midrise apartment with E&H consumptions equal to 1400 MWh/y and 800 MWh/y

Energy flows										
Years	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Electricity needed by the customer [kWh]	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000	1.400.000
Heat needed by the customer [kWh]	800.000	800.000	800.000	800.000	800.000	800.000	800.000	800.000	800.000	800.000
Input energy in the SOFC [kWh]	947.782	947.782	947.782	947.782	947.782	947.782	947.782	947.782	947.782	947.782
SOFC gas input [m^3/y]	104.038	104.038	104.038	104.038	104.038	104.038	104.038	104.038	104.038	104.038
Hour of replacement induced by degradation [h]	68182									
Operating hours stack	8688	17376	26064	34752	43440	52128	60816	8688	17376	26064
Replacement of the stack								Here		
Electrical efficiency at the end of the year	53,09%	51,18%	49,27%	47,35%	45,44%	43,53%	41,62%	53,09%	51,18%	49,27%
Average electrical efficiency during the year	54,04%	52,13%	50,22%	48,31%	46,40%	44,49%	42,58%	54,04%	52,13%	50,22%
Electric need covered by the SOFC [kWh]	512.222	494.107	475.991	457.876	439.760	421.645	403.529	512.222	494.107	475.991
Electric coverage of the need	37%	35%	34%	33%	31%	30%	29%	37%	35%	34%
Electric need left uncovered by the SOFC [kWh]	887.778	905.893	924.009	942.124	960.240	978.355	996.471	887.778	905.893	924.009

In this section the items reported on the rows of the Excel table will be explained:

- Electricity needed by the customer: this value of electricity expressed in kWh per year, is the amount of yearly electricity the customer needs to run its activity. It corresponds to the input value chosen at the beginning and it is assumed to be the same every year.

- Heat needed by the customer: it is the same concept expressed above, but here it is related to the consumption of heat.

- Input energy in the SOFC: This corresponds to the amount of energy in the form of natural gas that is fed into the fuel cell. This and the next values of this study expressed in kWh are evaluated for each year. $Energy_{SOFC}^{input}$ depends on the initial size of the SOFC, and it is found with the following relation:

$$Energy_{SOFC}^{input}\ [kWh] = \frac{Initial\ size\ of\ the\ SOFC\ [kW]}{\varepsilon_e\ at\ year_0} * (8760 - h.maint.)[h] \quad (4.10)$$

  The sizing of the SOFC is performed just considering the electrical optimal size, while the thermal load which can be provided is consequent and dependent on the electricity need of the customer.
  The value of “Input energy in the SOFC” doesn’t vary over the years because the reduction of electrical efficiency is going to affect the outputs produced by the SOFC, and it doesn’t regard the inlet.

- SOFC gas input: expresses the amount of gas in m^3 which is fed into the SOFC. This value is also constant over the years and it is regulated by the following equation:

$$SOFC\ gas\ input\ [m^3] = \frac{Energy_{SOFC}^{input}\ [kWh]}{LHV\ methane\ \left[\frac{kWh}{m^3}\right]} \quad (4.11)$$

  The low heating value is the amount of useful energy which can be developed by 1 cubic meter of methane, it is assumed to be 9.11 $\frac{kWh}{m^3}$ (WNO).

- Hour of replacement induced by degradation: according to the initial electrical efficiency, the rate of degradation, and the electrical efficiency threshold of replacement introduced in previous chapters, the total number of working hours can be calculated:

$$Hour\ of\ replacement = \frac{(\varepsilon_e\ at\ year\_0 - \varepsilon_e\ replacement)}{\varepsilon_e\ at\ year\_0 * degradation\ rate} * 1000 \quad (4.12)$$

- Operating hours stack: it is the cumulative number of hours of usage of the SOFC. This number takes into account the assumed 72 hours of maintenance per year.

- Replacement of the stack: This row reports with the caption "here" if and when the substitution of the stack cell is necessary. If nothing appears in this row it implies there is no substitution of the SOFC during the analysed window time.

- Electrical efficiency at the end of the year: At the beginning of the year the value of the electrical efficiency is higher respect to that at the end of the year, due to the degradation rate:

$$\varepsilon_e \; end \; of \; the \; year_i = \varepsilon_e \; at \; year_0 * \left(1 - \frac{operating \; hours \; stack}{1000} * degradation \; rate\right) \tag{4.13}$$

- Average electrical efficiency during the year: since the electrical efficiency is decreasing over the year, an average value was considered to perform the calculation. The value was obtained simply calculating the average between the value of electrical efficiency at the beginning and at the end of the year

- Electric need covered by the SOFC($E_{covered}^{SOFC}$): the SOFC was sized concordantly to the minimum value of electricity consumption registered throughout the year (base load). For this reason, the cell is not able to cover the whole of the electricity consumption profile of customer. Here it is reported the amount of energy expressed in kWh actually covered by the SOFC. This value is decreasing over the years because of the reduction of electrical efficiency. The value is calculated according to the following relation:

$$E_{covered}^{SOFC} = Energy_{SOFC}^{input} * Avg.\varepsilon_e \; during \; the \; year \tag{4.14}$$

- Electric coverage of the need: it expresses the share of energy covered by the fuel cell within each year:

$$Electric \; coverage \; of \; the \; need \; [\%] = \frac{Electricity \; needed \; by \; the \; customer \; [kWh]}{Electric \; need \; covered \; by \; the \; SOFC \; [\, kWh]} \tag{4.15}$$

  This value follows the trend of the "Electric need covered by the SOFC".

- Electric need left uncovered by the SOFC: it is the amount of electrical energy that cannot be covered by the SOFC and consequently has to be absorbed from the grid.

In the next table, the values related to the thermal load will be shown and discussed:

Table 7: Screenshot of the second part of the Excel tool in the "Energy flows" section. Case of a Midrise apartment with E&H consumptions equal to 1400 MWh/y and 800 MWh/y

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Average thermal efficiency during the year (complement)	30,96%	32,87%	34,78%	36,69%	38,60%	40,51%	42,42%	30,96%	32,87%	34,78%
Total thermal energy produced by the SOFC [kWh]	293.392	311.508	329.623	347.739	365.854	383.970	402.085	293.392	311.508	329.623
Thermal need covered by the SOFC [kWh]	265.718	279.931	293.622	306.979	320.074	332.834	345.069	265.718	279.931	293.622
Thermal need covered by the SOFC + storage [kWh]	267.101	281.510	295.423	309.017	322.363	335.391	347.920	267.101	281.510	295.423
Thermal need covered by the SOFC + storage %	33%	35%	37%	38%	40%	42%	43%	33%	35%	37%
Thermal need left uncovered by the SOFC + storage[kWh]	532.899	520.069	506.378	493.021	479.926	467.166	454.931	534.282	520.069	506.378
Thermal need left uncovered by the SOFC + storage %	67%	65%	63%	62%	60%	58%	57%	67%	65%	63%
Input energy for the boiler [kWh]	579.238	565.292	550.410	535.892	521.658	507.789	494.490	580.742	565.292	550.410
Boiler efficiency	92%									
Energy saved by the storage unit [%]	5%									
Cost of the storage unit [€]	2.000	€								
Heat directed to the storage unit [kWh]	27.675	31.577	36.001	40.760	45.780	51.136	57.017	27.675	31.577	36.001
Heat to the storage unit / Heat produced by the SOFC [%]	9%	10%	11%	12%	13%	13%	14%	9%	10%	11%
Energy saved by the storage unit [kWh]	1.384	1.579	1.800	2.038	2.289	2.557	2.851	1.384	1.579	1.800
Savings achieved by the storage unit [€]	64	73	84	95	106	119	133	64	73	84

Following the same idea, the values for thermal power were calculated:

- <u>Average thermal efficiency during the year</u>: it follows the same concept of the electrical efficiency expressed previously, the only difference lies in the increase of thermal efficiency over the years.

- <u>Total thermal energy produced by the SOFC</u>: it consists of the total amount of energy produced by the SOFC within each year:

$$T.thermal\ energy\ produced\ by\ the\ SOFC = Energy_{SOFC}^{input}\ [kWh] * Avg.\varepsilon_{th}\ during\ the\ year \quad (4.16)$$

  It is noticeable how this term increases over the years because of the greater thermal efficiency until the year of the replacement of the cell is reached and the values of electrical and thermal efficiency are restored.

- <u>Thermal need covered by the SOFC [kWh]</u>: This term consists of the amount of energy produced by the SOFC feeding the customer. When the thermal production of the SOFC is lower than the customer's need, all the thermal energy will be directed to the customer. Otherwise, the thermal need of the customer will be covered, and the extra energy will be directed to the storage unit where it will be partially saved. For example, if the SOFC is producing 10 kW of heat while the customer needs 6 kW, 4kW will be directed to the storage unit, where the 5% will be saved. The functioning of the storage unit is explained later on in this chapter.

- <u>Thermal need covered by the SOFC + storage [kWh]</u>: ($H_{covered}^{SOFC+storage}$)This value differs from the previous because the energy saved through the storage unit is here added.

- Thermal need left uncovered by the SOFC + storage [kWh]: This term expresses the amount of thermal energy the customer still needs to purchase from the grid to meet its demand. It is calculated as a difference between the thermal energy the customer needs and the energy effectively supplied to the customer by the SOFC, also including the contribution of the storage unit.

- Input energy for the boiler [kWh]: The "thermal need left uncovered by the system SOFC + storage" has to be supplied from the grid. However, to calculate the total amount of energy directed to the boiler first and then to the customer, the efficiency of the boiler has to be considered:

$$Input\ energy\ for\ the\ boiler = \frac{Thermal\ need\ left\ uncovered\ by\ the\ SOFC + storage}{Efficiency\ of\ the\ boiler} \quad (4.17)$$

- Boiler efficiency: It quantifies the efficiency the boiler achieves converting the chemical power of natural gas in input into available heat for the customer. In this study, the model "THW-I NT E, 23/15" manufactured by Hoval, is a suitable device for the range of power of the types of buildings analysed. The efficiency of the boiler varies between 91.3% and 93.3% according to the operating condition (Walker and Blaen). An efficiency of 92% has been assumed for this study.

- Energy saved by the storage unit [%]: In order to not waste all the excess heat produced by the SOFC, a storage unit is installed to save part of the energy and re-utilize it when it is needed. The model is applied to different types of building characterized by different consumption curves and values; it is not, therefore, possible to define a unique operating procedure for the storage system adaptable for every case, because this would imply a simulation with every type of building, as well with different combinations of inputs.
For this reason, to evaluate the advantages brought from such device, it is assumed the storage system leads to saving a certain portion of the excess heat the unit receives. According to the study "The financial viability of a SOFC cogeneration system in single-family dwellings" between 4% and 8% of energy can be saved through the operation of a storage system (Alanne et al.). Concordantly, in this model the percentage of energy saved by the storage unit is assumed to be 5%.

- Cost of the storage unit [€]: It corresponds to the estimated price for a storage unit suitable for this application. The assumed value of €2000 has been deducted from the manufacturer "Hasson tanks" (Hasson Tanks). However, a variation on this value has a very low impact in the final economic balance, since the other amounts involved are considerably higher.

- Heat directed to the storage unit [kWh]: As already clarified before in the section related to "thermal need covered by the SOFC [kWh]", This term sums all the energy conveyed to the storage unit within a year.

- Heat to the storage / Heat produced by the SOFC [%]: This ratio expresses the percentage of the total heat produced actually directed to the storage unit. It is calculated to better comprehend the potential advantage brought by the storage unit to the system.

- Energy saved by the storage unit [kWh]: According to the percentage of the wasted energy re-used, this value expresses, in fact, the amount of energy saved. It is obtained by multiplying "heat directed to the storage unit" by "storage, percentage of wasted energy re-used".

- Savings achieved by the storage unit [€]: It consists of the economic value of the heat saved due to the introduction of the storage unit. The value is calculated following the formula here presented:

$$Savings\ achieved\ by\ storage\ unit = \frac{Energy\ saved\ by\ the\ storage\ unit}{Boiler\ efficiency} * Elec_{price} \tag{4.18}$$

Where $Elec_{price}$ stands for electricity price.

4.6 Energy prices

On the first page of the model is possible to choose the country where the customer is located. This selection affects 2 key factors of the study: the price of electricity and the price of natural gas. According to the yearly consumption, electricity and natural gas have different categories of price. The higher the yearly consumption, the lower is the price per kWh of energy. The application of a SOFC is more attractive in those countries where the difference between price of electricity and price of natural gas is higher. In fact, the SOFC is able provide electricity to the customer even if receives natural gas at the inlet. Its convenience is also obviously affected by the electrical efficiency of such a device, which balances the amount of energy in the natural gas actually converted into electricity. The values for most of the European countries are obtained from the Eurostat website (Eurostat). The following two images report the tables for electricity and natural gas utilized in the tool.

Table 8: Excel tool screenshot of the electricity price table (Eurostat, 2019)

Electricity			
Electricity prices source			
Excluding VAT and other recoverable taxes and levies			
Unit: € / kWh			
	Electric yearly consumption up to [MWh]		
	50	2.000	20.000
	Type 1	Type 2	Type 3
Belgium	0,15	0,11	0,09
Denmark	0,10	0,08	0,08
Germany	0,18	0,15	0,13
Estonia	0,10	0,09	0,08
Ireland	0,15	0,13	0,11
Greece	0,14	0,12	0,10
Spain	0,14	0,13	0,11
France	0,14	0,13	0,11
Croatia	0,14	0,14	0,11
Italy	0,14	0,14	0,11
Lithuania	0,14	0,15	0,12
Luxembourg	0,14	0,15	0,12
Hungary	0,14	0,15	0,12
Netherlands	0,14	0,16	0,12
Austria	0,14	0,16	0,13
Poland	0,14	0,17	0,13
Portugal	0,14	0,17	0,13
Slovenia	0,14	0,17	0,13
Finland	0,14	0,18	0,14
Sweden	0,14	0,18	0,14
United Kingdom	0,14	0,19	0,14

Table 9: Excel tool screenshot of the electricity price table (Eurostat, 2019)

Natural gas			
Gas prices source			
Excluding VAT and other recoverable taxes and levies			
Unit: € / kWh			
	Heat yearly consumption up to [MWh]		
	278 Type 1	2.778 Type 2	27.778 Type 3
Belgium	0,04	0,03	0,02
Denmark	0,06	0,06	0,04
Germany	0,04	0,04	0,03
Estonia	0,03	0,03	0,03
Ireland	0,05	0,04	0,03
Greece	0,04	0,04	0,03
Spain	0,04	0,04	0,03
France	0,05	0,04	0,04
Croatia	0,03	0,03	0,03
Italy	0,06	0,04	0,03
Lithuania	0,04	0,03	0,03
Luxembourg	0,04	0,04	0,03
Hungary	0,03	0,03	0,03
Netherlands	0,06	0,06	0,03
Austria	0,05	0,04	0,03
Poland	0,04	0,03	0,03
Portugal	0,06	0,04	0,03
Slovenia	0,05	0,04	0,03
Finland	0,06	0,06	0,05
Sweden	0,07	0,06	0,05
United Kingdom	0,05	0,03	0,03

4.7 Emissions

As mentioned in chapter 2, the solid oxide fuel cell can be fed by different types of fuel. When the cell is directly fed with hydrogen, the reactions which take place at the anode and the cathode are the following:

Anode:

$$H_2 + 0^{2-} \rightarrow H_2O + 2e^- \tag{4.19}$$

Cathode:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{4.20}$$

Multiplying by a factor of 2 the reaction at the anode, the overall reaction is:

$$2H_2 + O_2 \rightarrow 2\,H_2O \tag{4.21}$$

From the relations, it is possible to notice the only product of the reaction would be water. In fact, the process of generating electricity happens without releasing polluting substances. Moreover, if the hydrogen is produced with the process of electrolysis fed by renewable energy, the overall process of electricity production would have a very low environmental impact. Despite that, most of the time it is more likely to have available natural gas from the grid rather than hydrogen. For this reason, this study is centered on the usage of natural gas. Assuming methane as the only active component in the natural gas conveyed in the SOFC as explained in chapter 2, the reaction which will take place at the anode and cathode will be:

Anode:

$$CH_4 + 4O^{2-} \rightarrow CO_2 + 2H_2O + 8e^- \tag{4.22}$$

Cathode:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{4.23}$$

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

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4.24}$$

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:

$$SOFC\ CO_2 \left[\frac{ton}{y}\right] = SOFC\ gas\ input \left[\frac{m^3}{y}\right] * CO_2\ density \left[\frac{kg}{m^3}\right] * \frac{1}{1000} \left[\frac{ton}{kg}\right] \tag{4.25}$$

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:

$$Ref\ CO_2 = \frac{\left(E_{covered}^{SOFC} * Em_f\right)}{1000} + \frac{H_{covered}^{SOFC+storage}}{LHV\ methane * CO_2\ density * 1000} \tag{4.26}$$

Where:

- $Ref\ CO_2$ is the number of tons of CO_2produced over in a year in the reference case;
- $E_{covered}^{SOFC}$ is the energy produced by the SOFC which covers the load of the customer;
- $H_{covered}^{SOFC+storage}$ 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 with respect to the reference case:

$$CO_2\ reduction\ [\%] = \frac{(Ref\ CO_2 - SOFC\ CO_2)}{Ref\ CO_2} * 100 \qquad (4.27)$$

4.8 Cash flow

The cash flow section is the one dedicated to the calculation of the benefits, costs and consequently the possible profit. Here is reported a screenshot from the Excel tool and the elements will be commented below:

Table 10: Screenshot of the cash flow section.

Cash flow										
Inflation	2%									
Discount rate	5%									
								Years		
Input energy flows	1	2	3	4	5	6	7	8	9	10
Electricity and heat not bought from the grid:										
Electricity [kWh]	512.222	494.107	475.991	457.876	439.760	421.645	403.529	512.222	494.107	475.991
Heat [kWh]	290.328	305.989	321.111	335.888	350.395	364.555	378.174	290.328	305.989	321.111
Costs:										
SOFC module manufacturing	240.000									
Commissioning and installation	2.000									
Stack replacement								96.000		
Manufacturer profit	43.560							17280		
Storage unit	2.000									
Operation and maintenance cost (+ i)	500	510	520	531	541	552	563	574	586	598
Cost of the fuel to the SOFC (+ i)	40.541	41.352	42.179	43.023	43.883	44.761	45.656	46.569	47.501	48.451
Total	328.601	41.862	42.699	43.553	44.424	45.313	46.219	160.424	48.087	49.048
Benefits:										
VOLL	388	396	404	412	420	429	437	446	455	464
Electricity not bought from the grid (+ i)	72.432	71.268	70.028	68.710	67.311	65.829	64.261	83.202	81.864	80.440
Heat not bought from the grid (+ i)	13.499	14.511	15.533	16.573	17.634	18.714	19.801	15.506	16.669	17.843
Subsidy	14.624	14.624	14.624	14.624	14.624	14.624	14.624	14.624	14.624	14.624
Total	100.943	100.799	100.589	100.319	99.990	99.596	99.124	113.777	113.612	113.371

The values of discount rate and inflation are assumed to be respectively 5% and 2% (*Inflation Forecasts*).

Input energy flows:

- Electricity and heat produced by the SOFC: those values expressed in kWh are the amounts of electricity and heat expressed in kWh produced by the SOFC and supplied to the customer in 1 year. They correspond to the amount of energy that the customer will not need to buy from the grid, as they are provided by the SOFC.

Costs:

- SOFC module manufacturing cost: As seen in chapter 4.3 the manufacturing of the SOFC has a cost expressed in $\frac{€}{kW}$, therefore according to the size of the SOFC, it will result in a different cost. This value constitutes an up-front cost for the customer during year 1.

- Commissioning and installation cost: it is the initial cost the customer has to face to have the power system installed. It is paid at beginning in one solution.

- Stack replacement: It refers to the cost of the substitution of the stack of the cell. This cost occurs when the substitution of the cell is needed because the electrical efficiency threshold of replacement has been crossed. The cost will appear accordingly to the year of the substitution. However, it is not necessary to substitute the whole system. In fact, the only part that needs to be replaced is the stack of the SOFC which is assumed to correspond to 40% of the initial cost.

- Margin of the company: This item constitutes the margin of the company over the selling of the SOFC module. It is applied at the beginning of the time period, it corresponds to a certain percentage of "SOFC module manufacturing" and "Commissioning and installation" costs. The share was assumed equal to 20% according to the information provided by partners of the project. The total price the final customer has to pay upfront to have the whole system installed is logically the sum of "SOFC module manufacturing cost", "commissioning and installation cost", and "margin of the company"

- Storage: It corresponds to the cost of the storage unit in order to save the extra heat produced by the SOFC. Playing with the model it's possible to verify that the employment of the storage unit is always convenient considering its initial reduced cost compared to the saving which can be achieved.

- Operation and maintenance cost (+i): This term corresponds to the economic cost to sustain operation and maintenance the SOFC needs during a year and the value is assumed to be 500 $\frac{€}{year}$. Inflation is also considered during the time frame according to the following formula:

$$OeM_i = OeM_0(1+i)^{(y-1)} \tag{4.28}$$

  Inflation is considered every time a cash flow occurs in a year different from year 1.

- Cost of the fuel to the SOFC (+ i): As already explained the SOFC is fed with natural gas to be bought from the grid. This cost is one of the major contributors to the final balance.

$$Cost\ of\ Natural\ gas\ [€] = Energy_{SOFC}^{input}\ [kWh] * price\ of\ natural\ gas\ \left[\frac{€}{kWh}\right] \tag{4.29}$$

  Also this time, inflation is taken into account.

Benefits:

- VOLL: Value of lost load. Its value and meaning will be discussed in chapter 7

- Electricity not bought from the grid (+ i): This figure generally is the major economic benefit introduced by the fuel cell. It can be calculated according to the following equation:

$$Electricity\ saving[€] = Electricity\ produced\ by\ the\ SOFC\ [kWh] * price\ of\ electricity \left[\frac{€}{kWh}\right]$$

- Heat not bought from the grid: Similarly, to the previous value, the mathematical relation is reported below:

$$Heat\ savings\ \ [€] = \frac{Heat\ fed\ to\ the\ customer\ by\ the\ SOFC[kWh] * \mathrm{NG}_{price} \left[\frac{€}{kWh}\right]}{Boiler\ efficiency} \tag{4.30}$$

  Where NG_{price} stands for natural gas price.

  It is necessary to mention that the boiler efficiency has to be considered since, according to it, the amount of energy actually purchased from the grid is always superior to the heat received by the customer.

- Subsidy: Subsidy is the amount of public funding the SOFC plant is entitled to. This value strongly depends on the country where the specific application of the SOFC is evaluated. Subsidy concept is explored in more detail in chapter 5 "Subsidy system"

Once all the costs and benefits have been introduced it is possible to calculate the economic balance as shown in the next figure:

Table 11: Final economic balance of the plant

Final balance										
	Years									
	1	2	3	4	5	6	7	8	9	10
Cash flow	-227.659	58.937	57.889	56.765	55.565	54.283	52.904	-46.646	65.526	64.322
Discounted cash flow	-227.659	56.130	52.507	49.036	45.714	42.532	39.478	-33.151	44.350	41.463
Cumulative discounted cash flow	-227.659	-171.528	-119.021	-69.985	-24.271	18.261	57.739	24.589	68.939	110.402
Net present value	216.303									

- Cash flow: it's possible to calculate the cash flow for every year, as the difference between benefits and costs.

- Discounted cash flow: while the cash flow is just the sum of costs and benefits for every single year, the discounted cash flow takes also into account the discount rate, according to the next relation:

$$Discounted\ cash\ flow\ year_i = \frac{Discounted\ cash\ flow\ year_0}{(1 + discouunt\ rate)^{(year\ -\ 1)}} \tag{4.31}$$

- Cumulative discounted cash flow: This is the cumulative sum over the years of the calculated "Discounted cash flows"

$$Cumulative\ DCF\ year_i = Cumulative\ DCF\ year_{i-1} + DCF\ year_i \tag{4.32}$$

  Where DCF stands for Discounted Cash Flow.

- Net present value: or NPV is the crucial value to be obtained. It corresponds to the "Cumulative discounted cash flow" in the last year of the analysed time period. It expresses the profitability of a specific project. If this value is positive means the implementation of the SOFC is convenient, otherwise its integration would lead to an economic loss.

The lifetime considered in this study is equal to 14 years. It's useful and intuitive to graph the pace of the "discounted cash flow" over the years, as shown in the Figure 4.3:

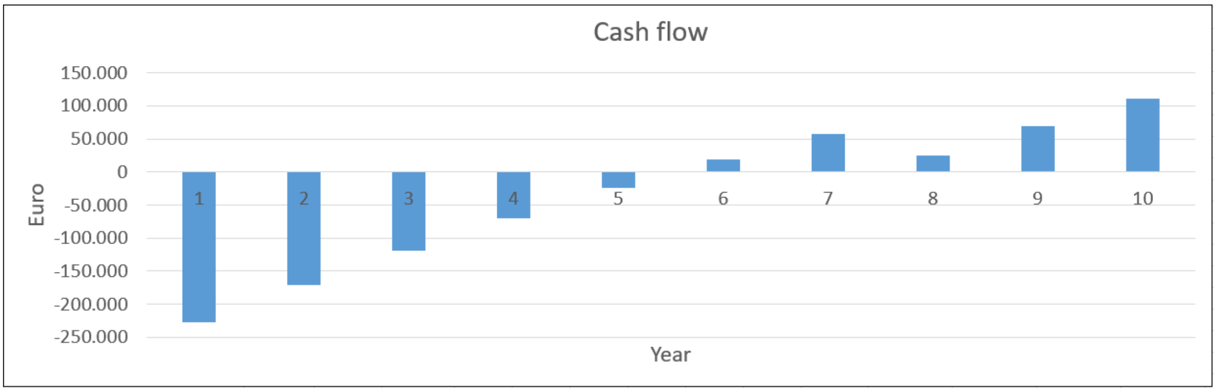

Figure 4.3 Example of the graph of the "discounted cash flow"

From the example reported is possible to derive the payback time of the project, in this case almost 6 years. The last column represents the value of the "net present value": in this case, the investment would lead to a profit around 216000 Euro.

5 Subsidy system

In order to evaluate the economic feasibility of the introduction of a SOFC to feed the electrical and thermal need of a utility, it's necessary to perform a techno-economic analysis which comprises a number of factors which leads to a satisfactory level of detail. Subsides and economic supports from the government or any other external institutions to promote renovation and greater efficiency are key factors to be considered for an accurate economic evaluation. SOFCs constitute a high-efficiency system that has the qualification to access this funding. In this study the regulation of Italy has been analysed in detail.

5.1 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, *Certificati Bianchi*). The system is administrated by the institution called "Gestore Servizi Energetici" (GSE). TEE are negotiable securities that certify energy savings achieved in the final uses of energy, obtained carrying out interventions to increase energy efficiency. The TEE system is an incentive mechanism based on a mandatory primary energy saving scheme addressing electricity and natural gas distributors with more than 50,000 end customers (large distributors). For each year from 2017 to 2020, the savings targets that large distributors must achieve through the implementation of energy efficiency interventions have been set. The results to be achieved for the following years are:

- 2017: 7.14 million TOE (Ton Oil Equivalent, 1 TOE = 11.63MWh);
- 2018: 8.32 million TOE;
- 2019: 9.71 million TOE;
- 2020: 11.19 million TOE.

The obligatory entities, or large distributors, can fulfil the obligation share of savings in two ways:

- realizing directly or through the companies they control, energy efficiency projects allowed to the mechanism;
- purchasing the securities from other parties admitted to the mechanism: other distributors, certified Energy Service Company (ESCO), or public or private end-users who have appointed a certified Expert in Energy Management (EGE). (GSE, *Certificati Bianchi*)

ESCO are companies enabled to carry out energy efficiency interventions and recognized by GSE to access the exchange platform to sell certificates. The platform where these certificates can be sold and bought is handled by the institution called "Gestore dei mercati energetici" (GME). More specifically the entities allowed to access the exchange platforms of TEE are reported in the following table:

Table 12: Entities entitled to exchange TEE on the dedicated platform

Classification	Detail
Obligatory entities	Large distributors with more than 50.000 end customers
ESCO	Energy Service Companies
DE and DG	Distributors of electricity and gas
SEM	Company with an appointed energy manager
EMV	Companies with responsibility for conservation and rational use of energy
SSGE	Company with a management energy system
SEGE	Companies with an expert in energy management

More specifically the entities allowed to access the exchange platforms are regulated by the normative: ISO 50001, UNI CEI 11352, UNI CEI 11339. (GSE, *Certificati Bianchi Chiarimenti Operativi per La Presentazione Dei Progetti*). For each TOE of savings achieved thanks to the realization of energy efficiency interventions, a TEE is recognized for the entire useful life of the new system installed (from 3 to 10 years). Voluntary entities (ESCOs, EGEs) and the obligatory entities exchange TEE on the market platform managed by GME or through bilateral negotiations. (GME, 2019).

5.2 Applicability to fuel cells

Cogeneration is the combined production, in a single process, of electrical or mechanical energy and heat. In the Italian Ministerial Decree (DM) 04/08/2011 is reported the condition to determine if an electricity production system can be considered as cogenerative:

"The production of electricity from combined power and heat production units with counterpressure steam turbine, thermal recovery gas turbine, internal combustion engine, microturbines, Stirling engines and fuel cells is to be fully deem electricity that can be qualified as cogenerative if these units have an annual first principle efficiency of at least 75%" (D.M. 4 August 2011).

Solid oxide fuel cells have as input energy in the form of gas to produce electricity and heat. Their total efficiency is the sum of the electrical and thermal efficiency:

Figure 5.1 Basic SOFC scheme

$$\varepsilon_{tot} = \varepsilon_e + \varepsilon_{th}$$

The conventional SOFC adopted in this study has the following features:

- $\varepsilon_e = 55\%$
- $\varepsilon_{th} = 30\%$

So that corresponds to:

- $\varepsilon_{tot} = 85\%$

Which subsequently means the whole electricity production can be considered as cogenerative. This achievement influences the evaluation of the CHP system as “High-performance cogeneration” (CAR): if a cogenerative system is recognized as CAR it is entitled to access the mechanism of the TEE and it also accesses other benefits which are not explored in this study.

According to the D.M 4/8/2011 (D.M. 4 agosto 2011), to evaluate if a cogenerative unit is a CAR it’s necessary to calculate the Primary Energy Saving (PES) index according to the following formula:

$$PES = 1 - \frac{Ef}{\left(\frac{Echp}{\varepsilon_{e,rif}} + \frac{Hchp}{\varepsilon_{th,rif}}\right)} \tag{5.1}$$

Where:

- PES is the yearly amount of energy-saving as input of the CHP system;
- Ef is the yearly amount of energy in the 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;

As explained before, the term $Echp$ can be inclusive of the whole yearly electricity produced by the CHP system just if the total efficiency ε_{tot} is higher than 75%.

If the value of PES is higher than 10% the CHP system is recognized as CAR. The amount of saving in terms of energy (RISP, [MWh]) achieved by the introduction of the CHP system can be calculated with the following formula:

$$RISP = \frac{Echp}{\varepsilon_{e,rif}} + \frac{Hchp}{\varepsilon_{th,rif}} - Ef \tag{5.2}$$

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:

$$TEE = RISP * K * 0.086 \tag{5.3}$$

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. TEE are distinguished into the following types, according to **DM 11/01/2017**:

- Type I: certifying the achievement of primary energy savings through projects reducing final electricity consumption;
- Type II: certifying the achievement of primary energy savings through projects reducing natural-gas consumption;
- Type III: certifying the achievement of savings of forms of primary energy other than electricity and natural gas and not used for transport;
- Type IV: certifying the achievement of savings of forms of primary energy other than electricity and gas in the transport sector.

Systems like SOFC which consume gas as input can access white certificate of type II. White Certificates cannot be combined with other types of state incentives required for the same project. However, they are compatible with European, local or regional incentives for energy efficiency. They are also compatible with the on-site exchange mechanism (selling electricity on the grid). (GSE, *Condizioni Generali Di Cumulabilità*)

5.3 Price variation over time of TEE

The price of TEE on the platform does not have a value by fixed GSE, it can rather vary and fluctuate according to the market offer and demand. However, over the years the price of TEE has been registering a constant positive trend. The increase in price is obviously beneficial for who is willing to improve the efficiency of specific end-user and then sell the TEE. Over the last 5 years the value has increased from approximately €100 to the actual assumed value for this study of €300.

5.4 Process to require the TEE

The GSE will recognize the CAR operation for the cogeneration units that require it, carrying out verification and inspection to determine the number of TEEs to which these units are entitled. The GSE will also review requests for preliminary evaluation (preventive) for units not yet in operation, aimed at the subsequent access to the White Certificates. If the project submitted is not compliant with the legislation, the shortcomings identified and any changes to be made will be indicated. Finally, the GSE carries out the activities of verification and control on the incentive plants by informing the Minister of Economic Development (MISE) and the manufacturer of the final outcome of the inspections. All the requests must be submitted exclusively through the RICOGE Portal, which allows uploading all the data and documents needed at the start of the practice. (GSE, *Cogenerazione Ad Alto Rendimento*).

5.5 Correlation between SOFC and parameters and TEE

The equations 6.2 and 6.3 regulate the number of TEE and consequently the value of the yearly subsidy a certain CHP plant can receive. The term K has a fixed value once the sized of the application has been determined. The term RISP is the main factor affecting the TEE, it depends on $Echp$, $Hchp$, and Ef. Considering:

- $Echp = Ef * \varepsilon_{e,chp}$
- $Hchp = Ef * \varepsilon_{th,chp}$

It is possible to write:

$$RISP = \frac{Ef * \varepsilon_{e,chp}}{\varepsilon_{e,rif}} + \frac{Ef * \varepsilon_{th,chp}}{\varepsilon_{th,chp}} - Ef \tag{5.4}$$

$$RISP = Ef * (\frac{\varepsilon_{e,chp}}{\varepsilon_{e,rif}} + \frac{\varepsilon_{th,chp}}{\varepsilon_{th,chp}} - 1) \tag{5.5}$$

$$RISP \propto Ef * \varepsilon_{tot} \tag{5.6}$$

From the relation is possible to notice how the term RISP is affected by the terms Ef, and ε_{tot}. However, while a greater value of Ef makes RISP increase, it also increases the expenses to afford the primary energy bought. Increasing ε_{tot} leads to an increase of RISP, however, it comes also with a reduction of Ef, which means a reduction of costs which translates into an overall increase in profit.

6 Value of Lost Load

One of the features of fuel cells is the ability to supply electricity without interruptions. This chapter presents a few methods on how to economically evaluate this aspect. To supply uninterrupted power corresponds to avoid power outages and its costs. Its value corresponds then to the so-called Value of Lost Load. Value of Lost Load (VOLL) is defined as the value attributed by consumers to unsupplied energy. It represents the maximum price that consumers are willing to pay to be supplied with energy. The economic literature has developed some interesting approaches for a ex-ante evaluation of power outage costs. In the literature, a general distinction is made between direct and indirect costs. Direct costs are losses in asset value, for example, due to computer crashes or damages to other sensitive equipment. Indirect costs comprise all consequences of the absence of electricity as a factor of production and consumption. Over the years, a range of evaluation methods has been proposed and applied. Based on the kind of data used, they can be broadly classified into three categories (Wolf and Wenzel):

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

6.1 Survey-based approaches

The first method that was developed intends to determine the willingness of electricity users to pay to avoid the occurrence of blackouts. Survey-based attempts to seek to ascertain this willingness in a direct manner by means of questionnaires. For instance, some articles related to this are:

- A study based on hypothetical scenarios are used by Beenstock (Beenstock)
- The research of Carlsson and Martinsson referred to households (Carlsson and Martinsson)
- Surveys undertaken after outages in Chile (Serra and Fierro)

6.2 Market-based approaches

Market-based approaches instead judge the value of supply security based on actual market behaviour. Brown and Johnson (1969) were the first to suggest an estimate of consumer surplus on the electricity market as a proxy for outage costs. This requires estimating demand functions by observing demand sensitivities in response to changes in electricity prices. An alternative method in this direction is to observe expenditures for precautionary measures. Beenstock (1991) suggests evaluating outage costs based on investment in back-up generators (Wolf and Wenzel).

6.3 Production-function approaches

To determine costs at the firm level, electricity is viewed as an input in local production. By postulating a certain functional relationship, production losses in response to power shortages are estimated in terms of capacity declines. Similarly, to account for outage costs of households, electricity is seen as an input in the generation of utility during leisure time. To cope with existing data limitations, very simple functional forms for these input-output relationships are commonly adopted in the literature. The assumption of a simple proportional relationship prevails, as it merely requires calculating the ratio between the economic output (or utility/leisure output for households) and electricity consumption at an annual level. Based on this framework, De Nooij et al. and Growitsch et al. calculate outage costs for regions in the Netherlands and Austria, respectively (de Nooij et al.), (Growitsch et al.). By drawing on time profiles of electricity use, they determine time-specific costs. More complex production-function approaches incorporating the role of input-output linkages and resilience measures have been implemented by (Rose et al.). Reichl, et al. have developed and implemented a mixed method combining macroeconomic data with expert and consumer surveys, which can so far be considered the most advanced approach for evaluating power outages (Reichl). It has culminated into an online tool (www. blackout-simulator.com), which offers the possibility to simulate losses from regional power outages for European countries.

6.4 Examples of Production function approach

One example of Production-function approach is developed by Wolf & Wenzel (Wolf and Wenzel). Their study analyses the relation between power outages and its cost. The study takes into account several parameters (Duration of the outages, day of the week, the hour of the day, etc.) and assumptions given the scarcity of punctual information. The output of the study is the value of lost load expressed in €/kWh for different regions in Germany. Every firm will have a different VOLL, however, to generalize, a study per sector can be conducted. Here is reported the VOLL for the manufacturing and mining sectors in different regions of Germany.

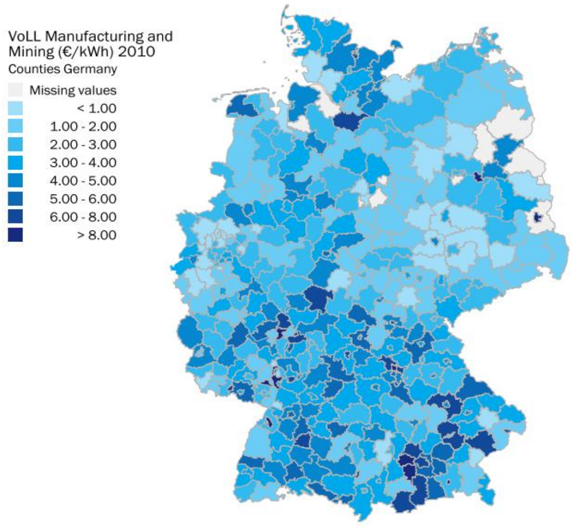

Figure 6.1 Spatial distribution of the VoLLs for the manufacturing sector in Germany (Wolf and Wenzel)

In the following table the global VOLL per region is presented:

Table 13: Distribution of regional VOLL in Germany, 2010 (Wolf & Wenzel, 2016)

Federal state	Ø VoLL firms	Highest VoLL firms	Lowest VoLL firms
Baden-Württemberg	6.63 €/kWh	Baden–Baden (City) (9.97)	Waldshut (3.10)
Bavaria	6.48 €/kWh	Starnberg (10.74)	Altötting (0.91)
Berlin	9.23 €/kWh	–	–
Brandenburg	6.13 €/kWh	Cottbus (City) (10.45)	Oder-Spree (2.03)
Bremen	6.54 €/kWh	Bremerhaven (7.83)	Bremen (City) (5.26)
Hamburg	6.49 €/kWh	–	
Hessen	7.18 €/kWh	Main-Taunus-Kreis (10.05)	Hersfeld-Rotenburg (3.49)
Lower-Saxony	5.61 €/kWh	Harburg (9.13)	Salzgitter (City) (1.48)
Mecklenburg-Vorpommern	6.62 €/kWh	Rostock (City) (8.99)	Nordwestmeckl. (3.67)
North Rhine-Westphalia	5.17 €/kWh	Bonn (City) (9.49)	Duisburg (City) (1.53)
Rhineland-Palatinate	6.03 €/kWh	Zweibrücken (9.60)	Ludwigshafen (City) (1.37)
Saarland	4.65 €/kWh	St. Wendel (5.77)	Saarlouis (2.34)
Saxony	5.13 €/kWh	Leipzig (City) (8.11)	Meißen (2.89)
Saxony-Anhalt	4.10 €/kWh	Halle (City) (9.83)	Saalekreis (1.16)
Schleswig–Holstein	7.33 €/kWh	Kiel (City) (9.71)	Dithmarschen (2.07)
Thuringia	5.09 €/kWh	Weimar (City) (9.50)	Saalfeld-Rudolstadt (1.90)

Doing the average among the presented values 6.15€/kWh is obtained. This means that for every kWh of electricity the firm is not receiving, it represents a loss of 6.15€ for the firm. From other studies similar values are deducted:

- Austria: 8.60 €/kWh (Growitsch et al.)
- The Netherlands: 8.56 €/kWh (de Nooij et al.)
- Spain: 6.35 €/kWh (Linares and Rey)

Adapting this research to the case of fuel cells in CHP systems and trying to quantify the ability of these systems to furnish an uninterrupted supply, some considerations are here presented. Assuming the introduction of a fuel cell-based system will lead to reliability of 100% in terms of electric consumptions (no power outages), we can calculate the economic benefit for the firm:

$$Benefit\ \left[\frac{€}{year}\right] = VOLL\ \left[\frac{€}{kWh}\right] x\ Yearly\ energy\ lost\ \left[\frac{kWh}{year}\right] \tag{6.1}$$

Where:

$$Yearly\ energy\ lost\ \left[\frac{kWh}{year}\right] = Avg.hours\ of\ outage \left[\frac{h}{year}\right] x\ Annual\ consump. \left[\frac{kWh}{8760h}\right] \tag{6.2}$$

For example, if we consider a company with an average annual consumption of 50’000 kWh, in Austria (VOLL=8.60 €/kWh), where an average of 20 hours per year of outage is expected we have an economic loss of 982 €/year which will turn into a benefit with the introduction of a fuel cell-based system.

7 Model applications

This chapter is devoted to the analysis of 2 different cases in order to evaluate the results obtained by the model. Both examples are placed in Italy where the subsidies, which contribute significantly to the economic balance, have been integrated scrupulously. The model requires in input the values of the yearly electric and heat consumption of the customer over a year. In these 2 examples these values will be assumed to be close at the yearly E&H consumption values of the database to avoid generating unreal case studies. Moreover, in this section screenshots of the Excel tool are often reported to effectively expose the model functioning and peculiarities.

7.1 Supermarket

The case consists of the analysis of a supermarket in Italy, with the following assumed E&H consumptions:

Table 14: Inputs of the model

Input		
Type of user	Supermarket	
Country	Italy	
Electric yearly consumption	1400	MWh
Heat yearly consumption	600	MWh

As explained before, 1400 and 600 MWh are values of example close to the corresponding to the database value equal to 1653 MWh and 752 MWh. In the model, it is possible to choose the preferred value of the SOFC module manufacturing cost among the two values reported in. The current scenario has been chosen (SOFC module manufacturing cost = 8000 $\frac{€}{kW}$). Comparing the E&H consumptions with those of the corresponding reference type of building (supermarket, respectively 1653 MWh and 752 MWh), the following ratios can be calculated:

Table 15: E&H ratios calculated from the yearly consumptions of the customer and the database

Electricity Ratio: Elec_Consumpt_Customer / Elec_Consumpt_Database	85%
Heat ratio: Heat_Consumpt_Customer / Heat_Consumpt_Database	76%

The found values, lower than the unit, have led to a reduction of the 8760 hourly consumption values of the reference supermarket, in order to build the consumption profiles of the customer. As an example, the first day of the year is reported below:

Table 16: First day of the year of E&H consumption of the customer deducted by the model

Date/Time		Customer	
		Electricity need	Heat need
		[kW]	[kW]
1	01/01 01:00:00	70,20	4,03
2	01/01 02:00:00	73,78	10,27
3	01/01 03:00:00	76,12	13,52
4	01/01 04:00:00	78,10	18,20
5	01/01 05:00:00	83,38	16,64
6	01/01 06:00:00	81,23	16,62
7	01/01 07:00:00	109,44	312,41
8	01/01 08:00:00	113,99	287,80
9	01/01 09:00:00	136,48	251,45
10	01/01 10:00:00	114,00	236,60
11	01/01 11:00:00	143,25	204,57
12	01/01 12:00:00	169,60	187,35
13	01/01 13:00:00	176,29	166,77
14	01/01 14:00:00	174,37	157,59
15	01/01 15:00:00	171,33	151,61
16	01/01 16:00:00	167,94	153,44
17	01/01 17:00:00	170,97	161,44
18	01/01 18:00:00	153,49	199,94
19	01/01 19:00:00	159,36	219,02
20	01/01 20:00:00	142,81	222,13
21	01/01 21:00:00	135,10	223,49
22	01/01 22:00:00	122,52	197,32
23	01/01 23:00:00	69,50	0,36
24	01/01 24:00:00	100,21	1,78

According to the minimum value of electricity registered during the year, it was possible to optimally size the SOFC among the types available chosen for this study:

Table 17: Screenshot of the overview section of the model

Overview		
Electric base load of the user	65,1	kW
Yearly average electric load of the user	159,8	kW
Yearly average thermal load of the user	68,5	kW
Input power in the FC	109,1	kW
Electricity produced by the FC @Year 0	60,0	kW
Heat produced by the FC @Year 0	32,7	kW
Select a year	Year 1	
Electricity produced by the FC	59,0	kW
Heat produced by the FC	33,8	kW

It's worth to mention, as explained in chapter 4, that the analysis conducted on the database ensures that the minimum electric consumption value registered during the year is not a sporadic and unbound from the rest of the values, quite the opposite. The tool allows, through the cell in orange in Figure 1.4, to select a specific year, to visualize which area of the electric and heat needs are covered. In the following graph relative to the first year of usage, the blue area corresponds to the electric consumption profile of the customer, while the yellow area is representative of the portion of the load covered by the electricity produced by the SOFC. The first of these 3 graphs, corresponds to a whole year, instead the others refer to an average day during January and July, in order to represent a typical winter and summer day. The average day is calculated performing the average for every hour of the day taking into account all the days of the month. It is possible to notice how the yellow area does not cover the blue area on the lower right corner of the first graph: the reason is ascribable to the 72 yearly hours of maintenance when the SOFC is not operative.

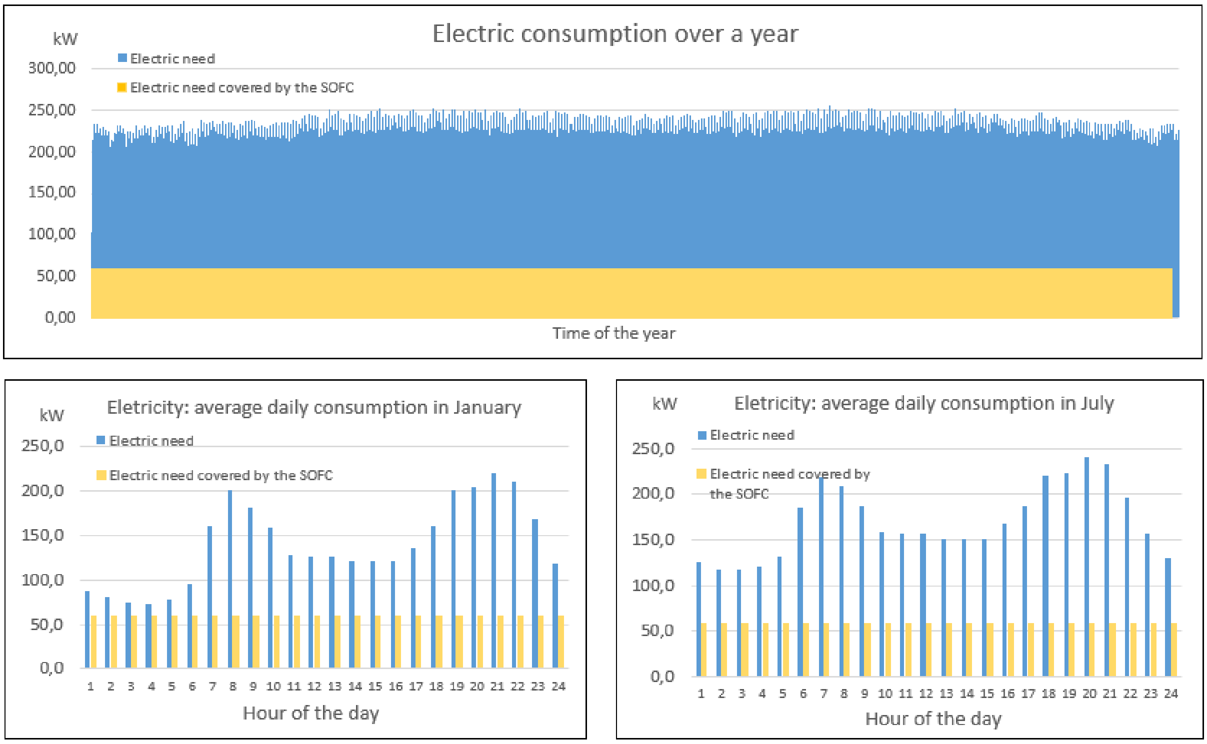

Figure 7.1 Supermarket electrical consumptions profile and the energy produced by the SOFC during the 1st year

It is interesting to notice how the demand for electricity in a supermarket is consistent also during the night. This attributable to the fridges/freezers or lights. Selecting a different year, while the profiles represented in blue do not change according to the assumption of no variation on the need of the customer for the whole 14 years considered, the areas in yellow are affected by the modification of the electric efficiency of the cell over time. In fact, a reduction in efficiency leads to a minor amount of available electricity output for the customer.

By way of example, the same graphs related this time to the 7th year of usage of the SOFC are here presented:

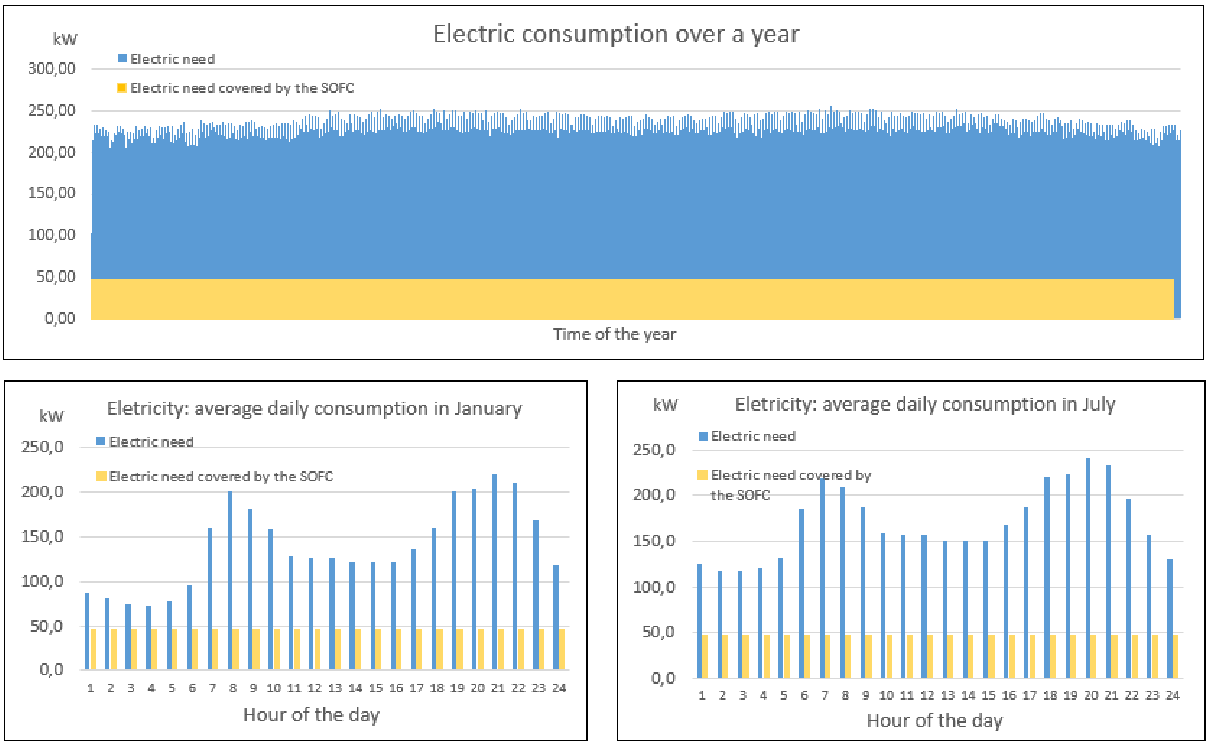

Figure 7.2 Supermarket electrical consumptions profile and the energy produced by the SOFC during the 7th year

Contrary to the first year, this time the electric load provided by the SOFC is equal to 47 kW, therefore lower the initial value of 59 kW. Logically this implies that the savings achieved by the introduction of the SOFC after the first year, are lower compared to the performances registered at the beginning.

The same concepts apply for the next graphs related to the heat, where the red surface is the thermal power produced by the SOFC covering the customer heat profile instead represented in orange:

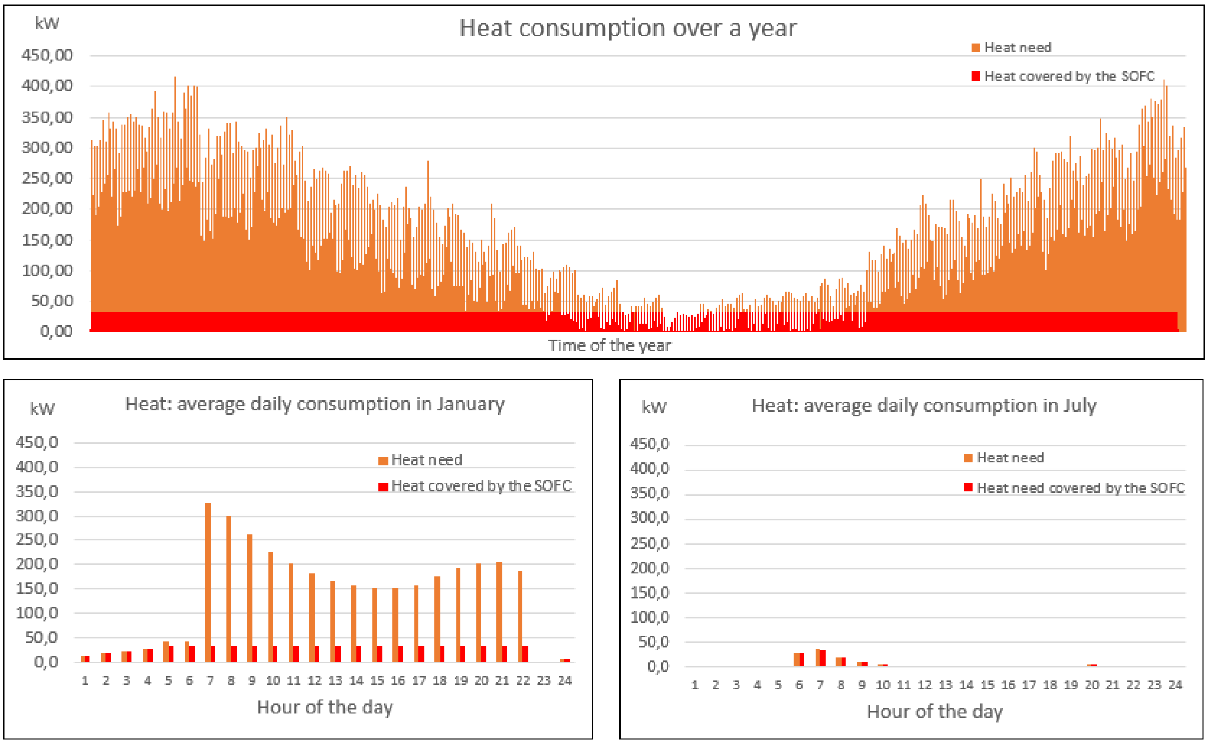

Figure 7.3 Supermarket heat consumptions profile and the energy produced by the SOFC during the first year

As expected, the demand for heat during the summer is inferior. It is remarkable to observe the different scale of values between the average day in January and in July: in the second case, the values are below 40 kW. Another function of the tool is to visualize the energy flows within a specific year. For example, these are the energy flows during the first year.

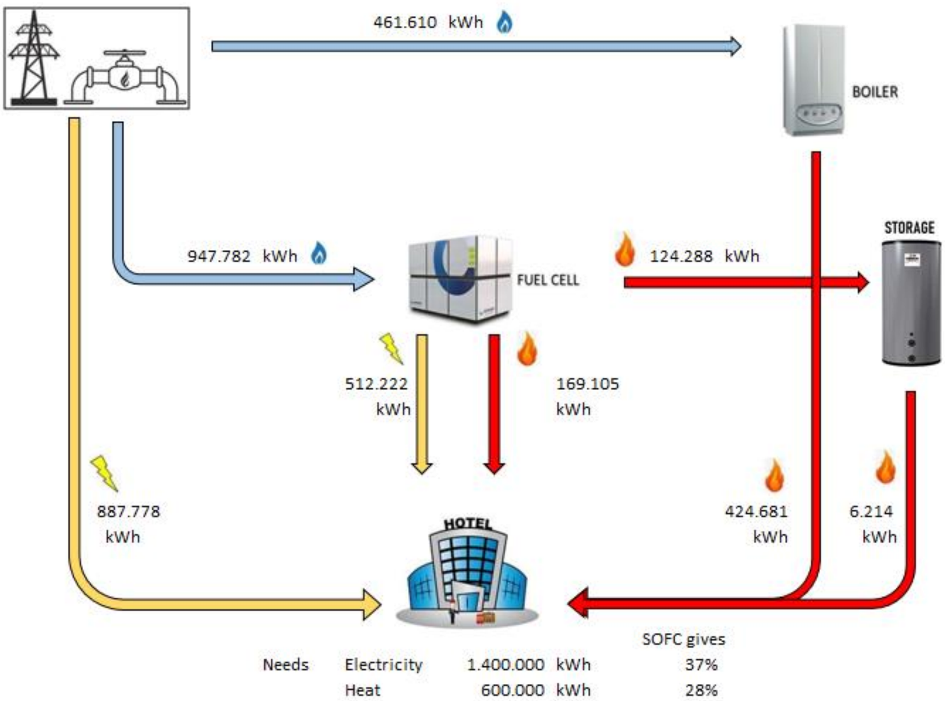

Figure 7.4 Energy flows of the whole system

The emissions produced by the system implementing the SOFC are calculated in comparison with the emissions produced if the same amounts of electricity and heat had to be entirely absorbed from the grid (electricity taken from the grid and heat produced by a boiler fed by natural gas from the grid) and consequently produced according to the Italian reference emission rate:

Table 18: Emission section of the model, supermarket case

Emissions		
CO_2 density	1,78	kg/m3
CO_2 factor electricity generation Italian grid	0,446	kg/kWh_e
Reference CO_2	247	ton CO_2/y
CO_2 emissions produced by the SOFC	185	ton CO_2/y
CO_2 savings	62	ton CO_2/y
CO_2 savings	25%	

It is interesting to notice how the system allows cutting off one-fourth of the emissions of CO_2. This percentage is not related to the overall consumption of the customer, but it is enclosed to the electricity and heat produced by the SOFC. The energy prices are deducted from the tables shown in paragraph 4.6 according to the range of consumptions. The following table reports the tariffs applied in this case:

Table 19: Energy prices section of the model, supermarket case

Energy prices		
Country	Italy	
Electric yearly consumption	1400	MWh
Corresponding SOFC type	Type 2	
Electricity price	0,14	€/kWh
Heat yearly consumption	600	MWh
Corresponding SOFC type	Type 2	
Gas price	0,04	€/kWh

At this point, the costs of the system can be calculated, and they are shown in the following graph:

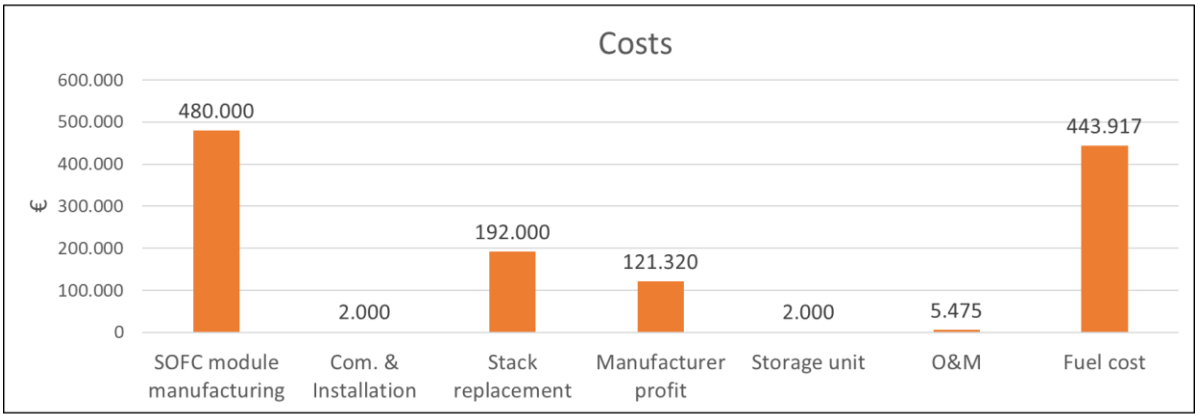

Figure 7.5 Cost structure of the supermarket case

While "Commission & installation", "storage unit" and "operation and maintenance" are negligible costs, "SOFC module manufacturing" constitutes the main expense to be faced by the customer to utilize the system. "Fuel cost" is another large cost to be sustained in order to run the system over time. It is necessary to mention that the "manufacturer profit" is here reported apart from the "SOFC module manufacturing" and "Com.& Installation" to have a better look at the cost structure, while the final customer will be presented just the sum of these three items.

In the same way, the benefits introduced by the system can be deducted:

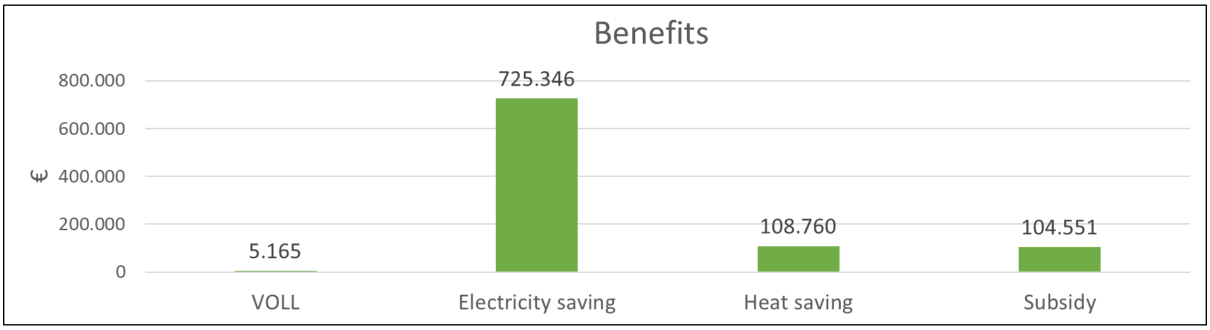

Figure 7.6 Benefits structure of the supermarket case

The largest benefit as expected is the amount of electricity not bought directly from the grid since produced by the SOFC. A similar consideration applies to the heat. The subsidies obtained by the system have a remarkable contribution to the total balance. The impact of VOLL is nearly unimportant. The following graph shows the cash flow trend over the years:

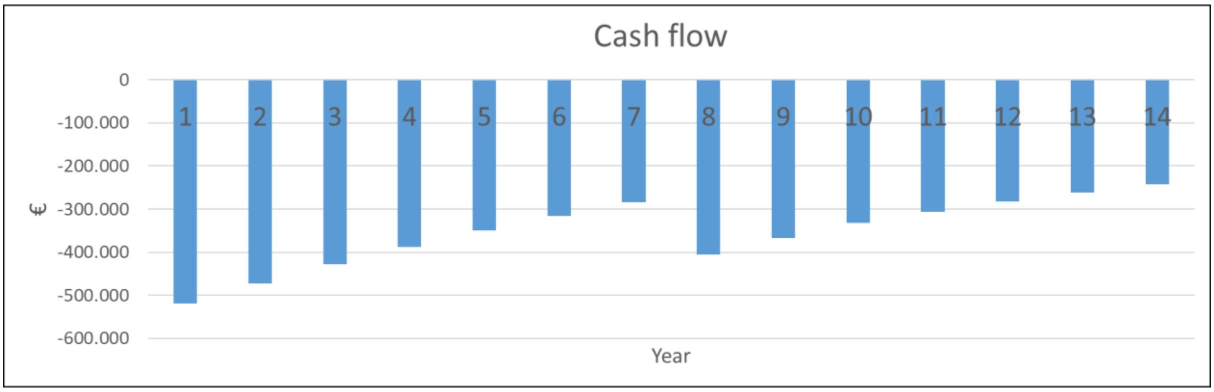

Figure 7.7 Cash flow of the supermarket case

In this case, the investment appears to be not convenient because at the end of the period it leads to a considerable loss of 243 k€. The result obtained is in major part attributable to the high cost deputed to the manufacturing cost of the SOFC, in fact, the cost of 8000 $\frac{€}{kW}$ leads to a final loss for every combination of type of building and E&H consumption tested. In other words, the high initial cost does not allow the system to re-pay the investment.

7.2 Hospital

In this second example the target cost of 4000 $\frac{€}{kW}$ has been considered. This time the structure analysed is a hospital placed in Italy. The assumed values of E&H consumption over the year follows the same logic as before and are respectively 6500 MWh and 3000 MWh. The calculations performed follow exactly the procedure shown in the previous example and only the salient results will be here illustrated and discussed. The base load of the application is equal to 429 kW, consequently the SOFC installed will be of type 3 with a corresponding power of 300 kW. The graphs related to the electric and heat coverage are here reported:

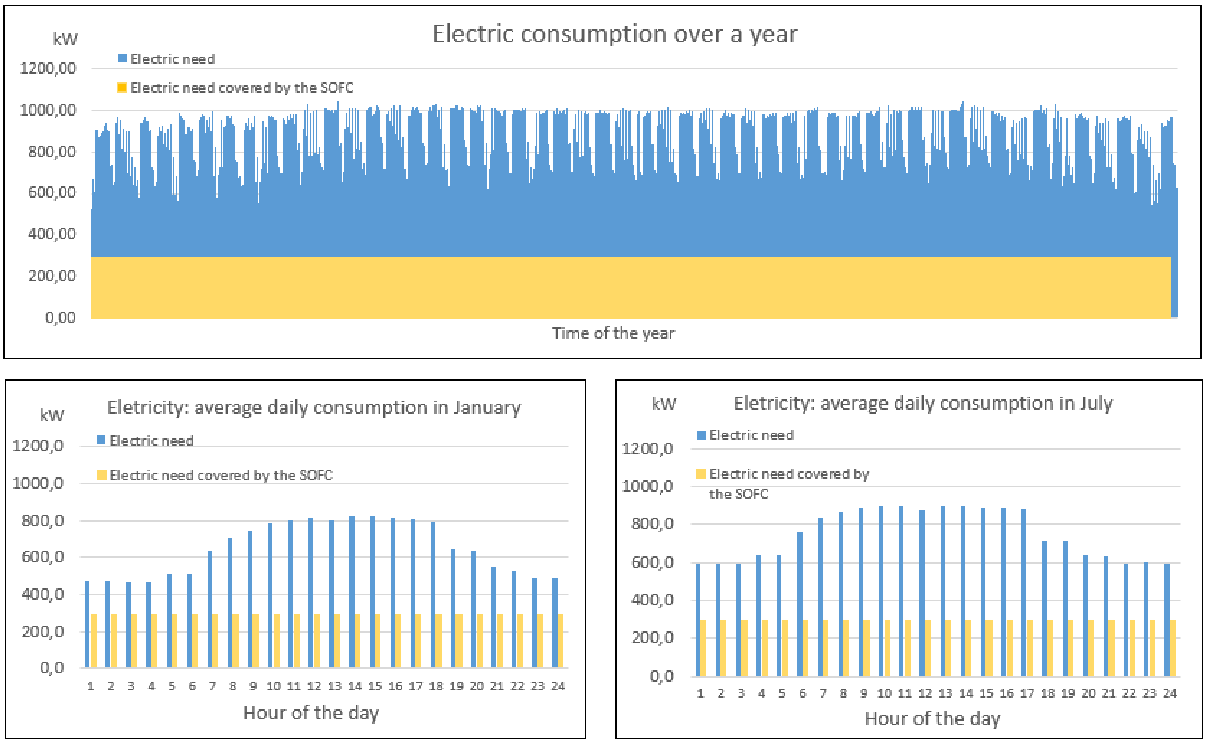

Figure 7.8 Hospital electric consumptions profile and the energy produced by the SOFC during the 1st year

We can notice how a hospital has a constant need for electricity during the year. The shape of the consumption profile in winter and summer is almost the same. The next graph shows the heat demand of the customer and the heat provided by the SOFC according to its installed power.

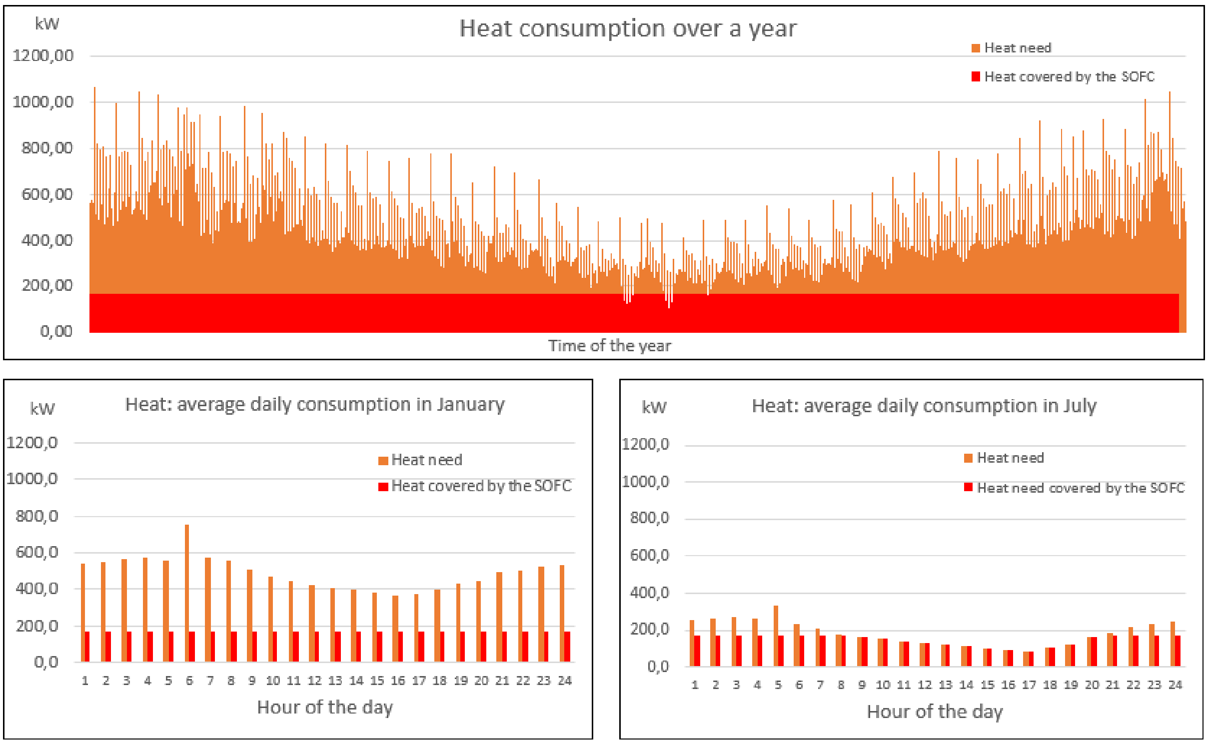

Figure 7.9 Graphs of the hospital heat consumptions profile and the energy produced by the SOFC during the 1st year

As expectable the need for heat is lower during summer. While in the cold months of the year the SOFC is not able to fully cover the need for heat of the customer, therefore inducing large amount of heat to be withdrawn from the grid, during summer thanks to SOFC, the amount of extra heat taken from the grid is quite little.
Regarding the emissions, the introduction of the SOFC leads to a reduction of emission approximately of 32%

Table 20: Emission section of the model, hospital case

Emissions		
CO_2 density	1,78	kg/m3
CO_2 factor electricity generation Italian grid	0,446	kg/kWh_e
Reference CO_2	1.363	ton CO_2/y
CO_2 emissions produced by the SOFC	926	ton CO_2/y
CO_2 savings	437	ton CO_2/y
CO_2 savings	32%	

The next graph shows the cost structure for this application:

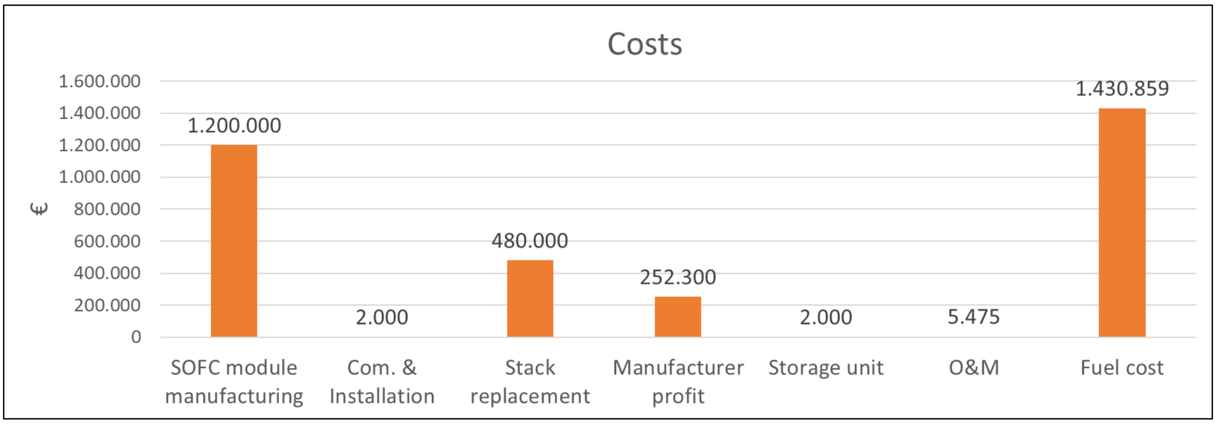

Figure 7.10 Cost structure of the hospital case

This time the major expense is represented by the fuel cost, immediately followed by the SOFC module manufacturing cost. The stack replacement together with the manufacturer's profit consists also of a not negligible cost. The benefits introduced by the system are:

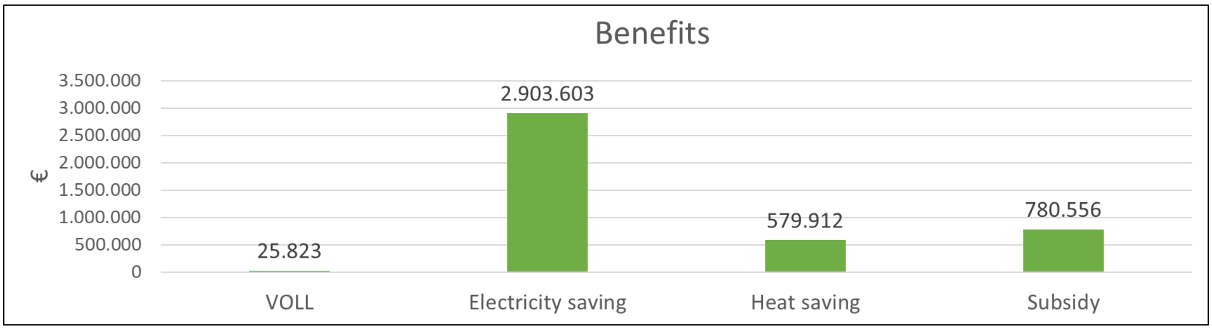

Figure 7.11 Benefits structure of the hospital case

Again, also in this case, the electricity not bought from the grid is the major source of savings. The subsidy in this case consistently helps the system to be economically sustainable in this case. The overall cash flow picture over the year:

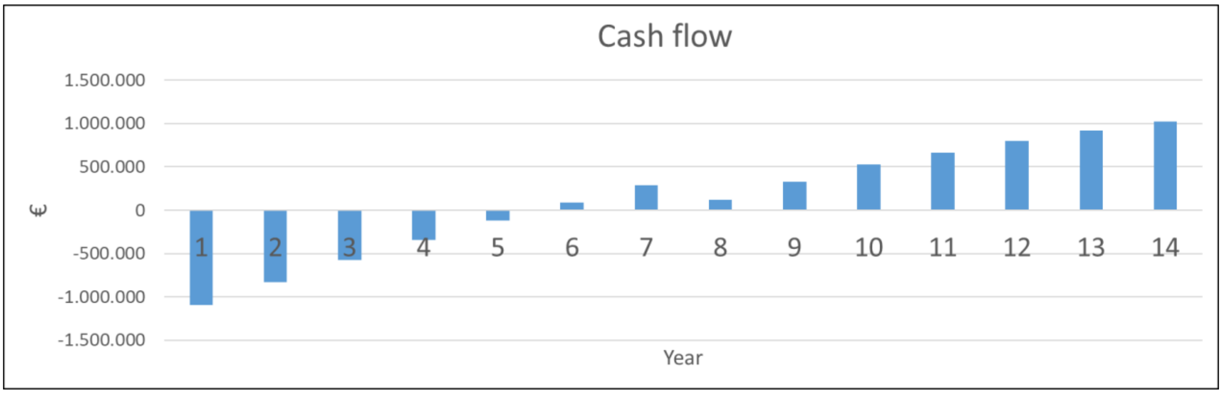

Figure 7.12 Cash flow of the hospital case

The reduced value of the SOFC module manufacturing (target scenario) is one of the main actors for the total balance of the system. In fact, this time the breakeven point is reached before the sixth year of usage and the profit of the system is considerably high: in spite of a heavy initial investment it leads at the end of the 14 years analysed, to a profit of about 1.02 M€.

8 Sensitivity analysis

This section is intended to evaluate how the different parameters involved in the study affects the result produced by the model. Understanding which the most significant parameters are is useful to define the key factors to be improved and their effects on the project. The analysis shown in this chapter is based on the first application example shown in the previous chapter, therefore a supermarket based in Italy with E&H consumptions respectively equal to 1400 MWh/y and 600 MWh/y. This type of building has been chosen to illustrate which kind of improvement can be brought to the system in order to make the net present value increase.

8.1 NPV versus SOFC manufacturing cost

The first analysis conducted regards the cost of SOFC module manufacturing expressed in $\frac{€}{kW}$, in relation to the net present value at the end of the period of 14 years. As it was possible to notice from the 2 applications discussed before, the price for manufacturing the SOFC has a considerable influence on the economic feasibility of the implementation of the fuel cell in the system. In fact, the current price of 8000 $\frac{€}{kW}$ is at the moment one of the greatest barriers to the diffusion of such devices. The next graph shows the sensitivity analysis of this parameter in relation to the NPV:

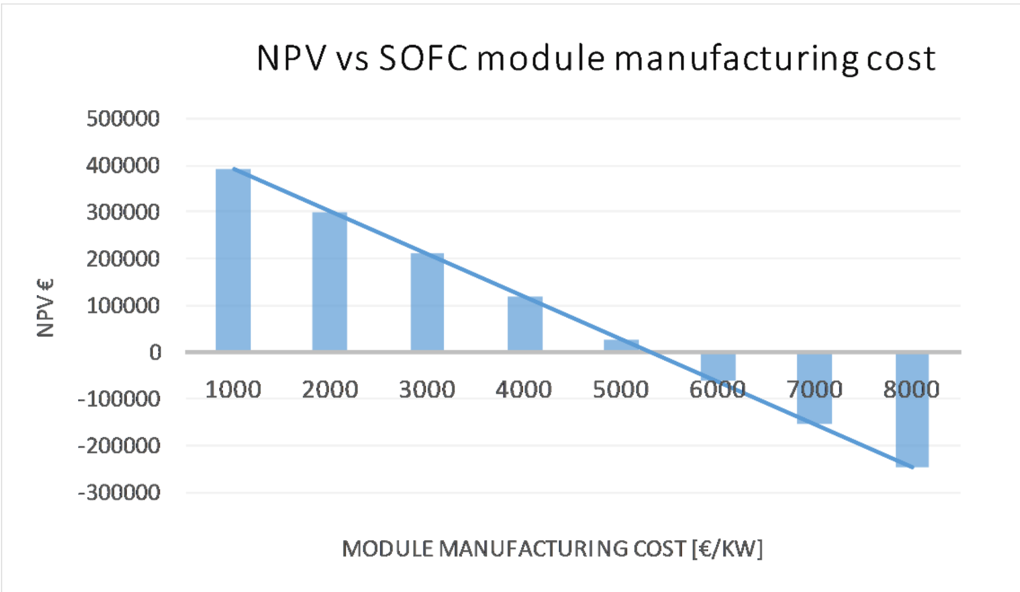

Figure 8.1 NPV vs SOFC module manufacturing cost

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 $\frac{€}{kW}$ the implementation of the SOFC is still not profitable. The application becomes positive with a SOFC module manufacturing cost equals to 5317 $\frac{€}{kW}$. Starting from a cost of the module from 4000 $\frac{€}{kW}$, the introduction of the SOFC appears to be largely profitable.

8.2 NPV versus electricity price

In this section, the effect of the electricity price will be evaluated respect to the net present value of the project:

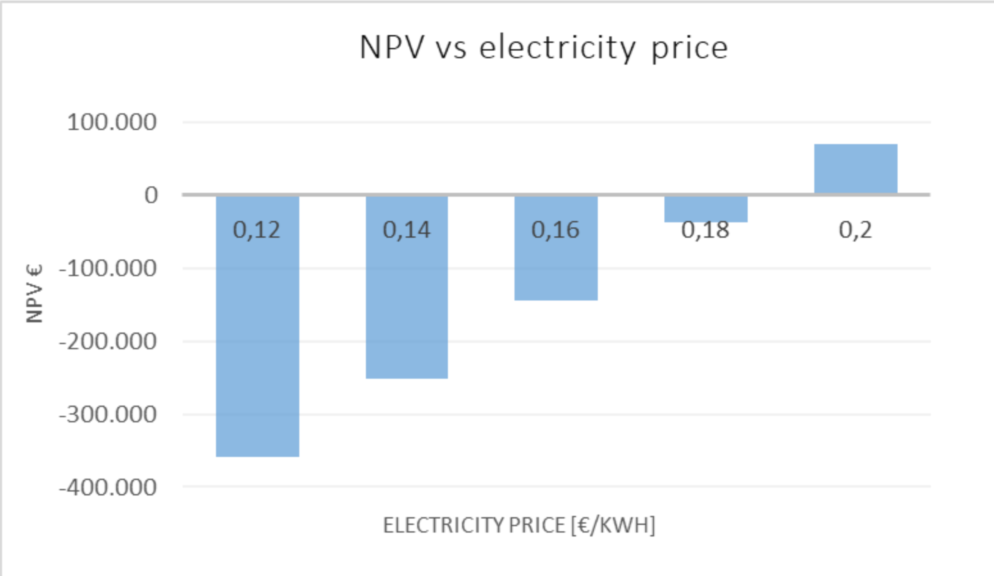

Figure 8.2 NPV vs electricity price

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 $\frac{€}{kWh}$ the investment is not convenient. Same applies for the prices until 0.18 $\frac{€}{kWh}$, while for a corresponding price of 0.20 $\frac{€}{kWh}$ the net present value appears to be positive. Since the SOFC consumes natural gas in order to save electricity purchased from the grid, it is logical to have the NPV growing organically with the price of electricity. The actual price of electricity in Italy is 0.14 $\frac{€}{kWh}$ and it leads so far to a negative NPV, approximately of -243 k€.

8.3 NPV versus natural gas price

The same logic has been followed and also the effects of the natural gas price have been screened:

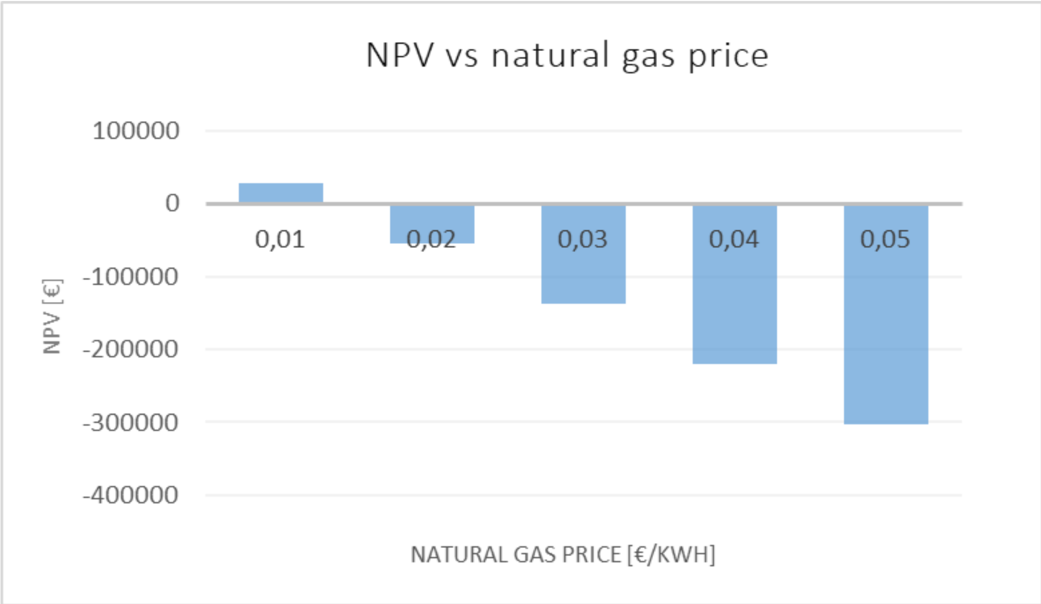

Figure 8.3 NPV vs natural gas price

From the graph, it is possible to notice how the actual price of natural gas equal to 0.05 $\frac{€}{kWh}$ leads to a negative net present value. The price of natural gas has also a large impact on the final result because it represents the fuel the SOFC is receiving. The cases analysed in this study belong to the category of the commercial sector, characterized by large values of E&H consumptions. Hence, the SOFCs adopted in this sector are deputed to process large amounts of fuel and consequently small variations on the fuel price have a considerable impact on the financial balance. More in detail, if a reduction of natural gas price lowers the "cost of the fuel to the SOFC" item and so increasing the NPV, at the same time it decreases the benefit named "Heat not bought from the grid". However, the "cost of the fuel to the SOFC" has a greater influence on the NPV and a reduction of the natural gas price leads to the overall growth of the net present value. Reduction on the price of natural gas makes the NPV more favourable, but the NPV becomes positive just for a price of 0.01 $\frac{€}{kWh}$., which is quite distance from the current market value.

8.4 NPV versus degradation rate

It is interesting to analyze to what extent the degradation rate is a limit for the SOFC and which is its impact on the NPV. The actual value of 0.4% of degradation every 1000 hours of usage has varied from 0.1% to 0.5%, the corresponding value of the NPV is shown in the next graph:

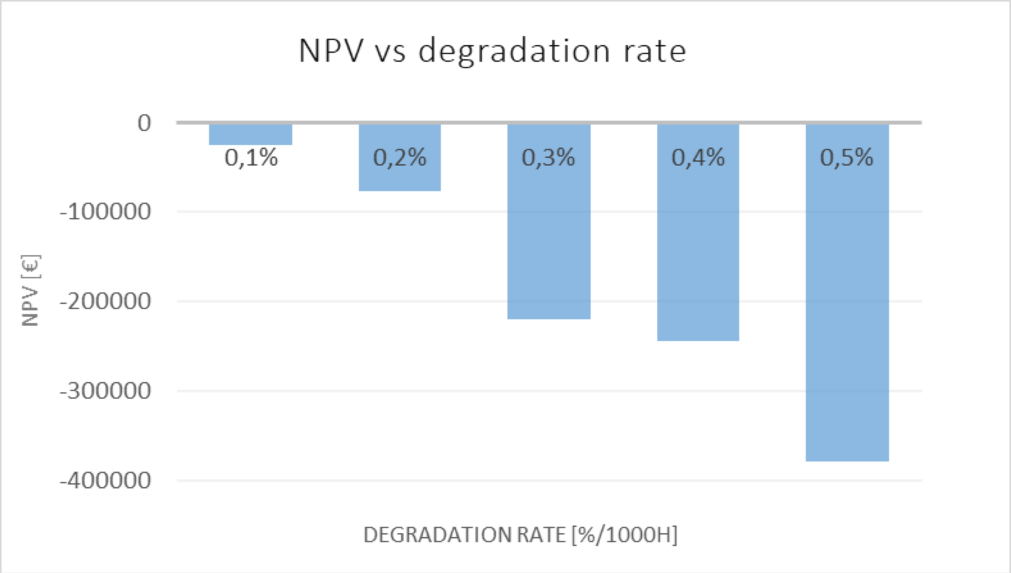

Figure 8.4 NPV vs degradation rate

The actual degradation rate of 0.4 %/1000h implies a negative value of the NPV. It's obvious that the higher value of 0.05 %/1000h makes the balance worse. 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 analysed 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:

Table 21: Degradation rate and consequent value of lifetime of the SOFC

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

8.5 NPV versus the total efficiency of the SOFC

Another analysis conducted in this study is the variation of the NPV in relation to the actual overall efficiency of 85%. Firstly, keeping the thermal efficiency fixed at 30% the electrical efficiency will be increased. Secondly, the thermal efficiency will be made to vary without this time altering the electrical efficiency.

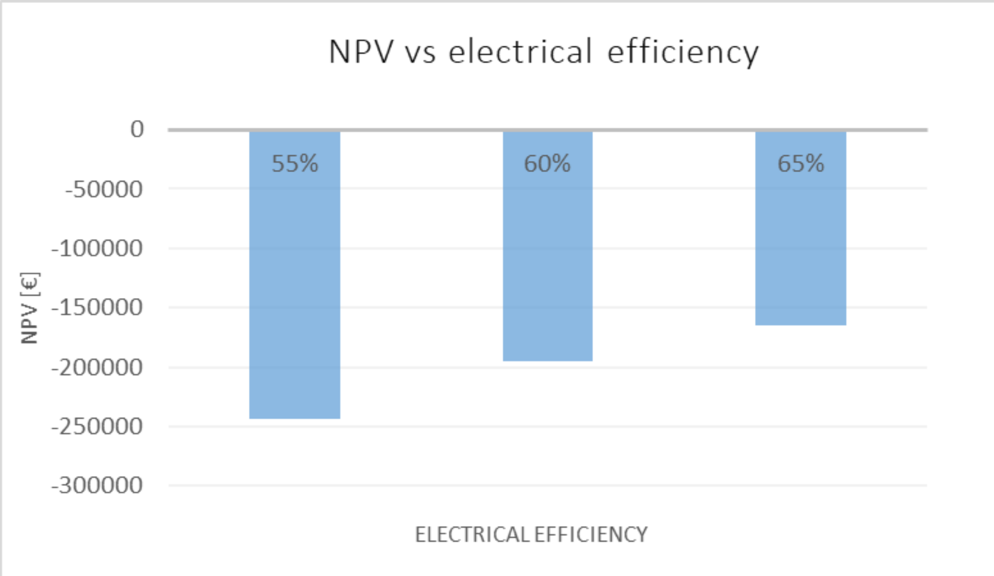

Figure 8.5 NPV vs electrical efficiency

As expected, a rise of the electrical efficiency of the cell results from 55% to 65% leads to an increase of the electrical energy produced in output by the SOFC, which increases the NPV of 32.2%. In spite of the linear growth of the NPV, even with an electrical efficiency of 65% the final balance of the plant is still negative. It's worth to remind that an electrical efficiency of 65%, together with a thermal efficiency of 30% consist in an overall efficiency of 95%, which is realistically the superior reachable limit.

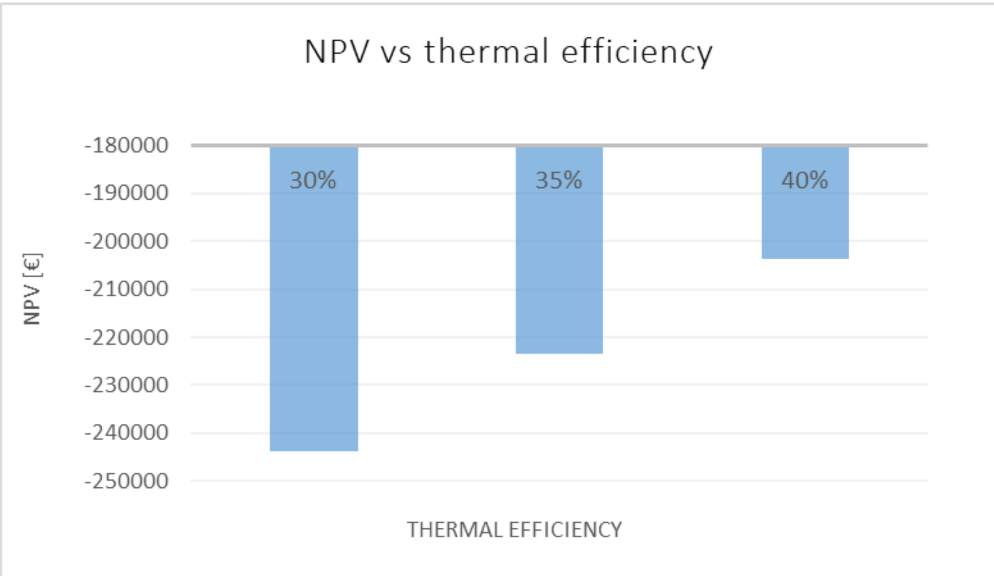

Figure 8.6 NPV vs thermal efficiency

The same trend occurs for an increase in thermal efficiency which has a direct positive effect on the NPV. However, for a value of 40% of the electrical efficiency, the investment on a SOFC is still not profitable.

9 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%. In case the heat is totally released and not exploited, the overall efficiency of the cell would drop to the only electrical one, around 55%. 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 €.

Regarding the evolution of prices in the future, many academic and industrial believe the cost of future mass-produced fuel systems at around $1000 per kW, while the study conducted by Staffell and Green reports that the target of $3000–5000 for micro-CHP is more realistic (Staffell and Green). The study here conducted shows, following a conservative approach, that the assumed target price of 4000€/kW is already sufficient to obtain a profitable investment.

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: for example, 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 analysed 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). 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.

The degradation rate is also a factor that heavily economically affects the implementation of SOFCs. Hence, it leads to the substitution of the stack of SOFC and this consistently weights on the potential profit of the installation. Reducing the degradation rate through research and improvement would allow the SOFC to keep an almost constant electrical efficiency with a consequently increased amount of electrical energy produced which is economically convenient, as shown in the sensitivity analysis. The tool created is available at https://it.scribd.com/document/438278295/Excel-Tool-SOFC-Integration-in-CHP-System .

9.1 Future development

Besides the Excel model developed in this study tries to reduce as much as possible the grade of approximation in re-creating the electricity and heat consumptions profiles of a certain customer for every day of the year, there is still room for improvement and further steps can be taken in order to optimize the calculation and subsequently the deducible conclusions. To increase the quality of the output of the tool, the thermal storage functioning can be explored more in detail: the assumed quota of heat saved equals to 5% is quite conservative, while a deeper investigation may reveal the amount of thermal energy saved can be superior.

In the case the E&H consumptions profiles of a certain customer are available, they can be inserted directly in the model, so obtaining a precise and customized evaluation on the performance of the SOFC applied to the need of the customer. A further possible step to improve the model would be to size the SOFC differently. Sizing the cell on the base load keeps it safe from modulations. However, it leaves most of the user's electrical load uncovered. Then, 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.

Another aspect which could be explored to increase the level of detail of the model would to also consider the reduction of the excises on the purchase of methane, together with a complete inspection of national subsidy available in each country to individuate the most convenient region to implement such devices.

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