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Installation of fuel cell-based cogeneration systems in the commercial and retail sector: Assessment in the framework of the COMSOS project

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ABSTRACT

This work studies the technical and economic feasibility of the introduction of a SOFC-based cogeneration system to supply non-residential buildings with electricity and heat. The techno-economic evaluation is performed for the hotel and hospital sectors, by introducing real hourly load profiles (electrical and thermal) for the buildings. The analysis considers different countries in terms of energy intensity (and load profiles), cost of energy and regulations/incentives. Results are achieved by comparing the SOFC scenario with a benchmark one where electricity is supplied by the grid and heat by a natural gas fed boiler and evaluating the relative payback time between the two solutions.

The analysis showed that, despite the current high investment cost of the SOFC system, in countries such as Germany, Italy and UK (where electricity prices are among the highest in Europe), the option is yet advisable if supported by effective subsidies (already existing for cogeneration systems), and it could offer a competitive alternative to traditional systems, especially in the hospital sector, where the relative payback time is achieved in the 10th year for UK, and in the 14th year for Germany and Italy. A cost reduction scenario has also been analyzed: results show that the SOFC is the best option in most of the locations, both economically and in terms of environmental impact (pollutants emissions reduction).

1. Introduction

The adoption of distributed energy generation is nowadays strongly supported by national and EU initiatives. The growth of projects on the 'energy community' concept aims at reducing the energy load to be transferred through the grid and incentivizing the local production and use of energy [1,2].

The energy community concept always requires – to work fully independently from the national grid – the availability of a cogeneration system. A programmable electricity producer is indeed essential to match the end-users loads when renewable energy sources and available storage systems are not able to provide power. In this context, the replacement of traditional polluting Internal Combustion Engines (ICEs) with zero-emissions high efficiency Fuel Cell systems (FC) like SOFC could play a fundamental role in the reduction of pollutants emissions. This concept is even more important in urban areas, where concentration of NOx, SOx and Particulate Matter (PM) is creating damages to the health of citizens.

The use of fuel cell systems for residential and non-residential buildings has been studied in many literature works. The Horizon programme has funded two important project: the first one is the Ene.Field project (European-wide field trials for residential fuel cell micro-CHP, 2012–2017) where the goal of installing 1000 units in 10 EU countries has been reached [3]. Of these installed units, 603 were SOFC, while the others PEMFC. The activity of this consortium is now focused on a second project called PACE (Pathway to a Competitive European FC mCHP market, 2016–2021) where the goal is the installation of 2500

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Nomenclature

CAPEX	Capital Expenditure
BoP	Balance of Plant
CCF	Cumulated Cash Flow
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
CF	Cash Flow
EI	Energy Intensity
FC	Fuel Cell
FIT	Feed In Tariff
HVAC	Heating, Ventilating and Air Conditioning
ICE	Internal Combustion Engine
ITC	Investment in Tax Credit
LCOE	Levelized Cost Of Electricity
LHV	Lower Heating Value
NPV	Net Present Value
OPEX	Operating Expenditure
PBT	Pay Back Time
PEMFC	Proton Exchange Membrane
PES	Primary Energy Saving
PM	Particulate Matter
RPBT	Relative Pay Back Time
SOC	Solid Oxide Cell
SOFC	Solid Oxide Fuel Cell
TOE	Ton of Oil Equivalent

units throughout Europe [4]. For what concerning scientific literature, the use of SOFC for residential application has been studied under different perspectives. Al Moussawi et al. [5] investigated possible different operating strategies for the system operation, comparing load following (off-grid) with base load operation (on-grid): results show that base load operation leads to better energy, economic and environmental performances. Even if the possibility of regulating the system power output is an interesting option of FC systems, currently installed units are usually working in base load operation mode, in order to keep the system continuously running at a stable level and avoiding thermal stresses on the stacks with linked degradation effects. Furthermore, the SOFC module BoP should be designed properly to allow modulation of the set point. Fong et al. [6] also compared the operation in electrical load following with the thermal load one: their work shows that electrical load should be preferred as the key one to be satisfied since this configuration increases the primary energy savings more than the thermal-led operation. More complex solutions where the SOFC-CHP system is upgraded with a downstream turbine and a carbon capture section have also been analyzed by Hemmatabady et al. [7].

The authors of the presented work have also analyzed the technical and economic aspects of installing a FC system in a residential building, analysing the performance in different operating modes [8] and also coupling a heat pump system to increase the self-consumption in the winter period [9]. Other works are focused on the concept of CHP for an aggregation of houses: this solution reduce the peaks of the electrical load thus maximizing the load coverage from the FC system (if operated in base load) [10].

Even if residential building application is one of the most studied solution for small size stationary FC systems, the presented work is focused on non-residential buildings. The reason for this shift relies in the different shape of the electrical load among the two applications. The typical electrical load of a residential building has some peaks during morning and afternoon, a possible constant base load during the day and a near zero base load during the night. During the design phase this shape turns into a very low size system (700 kW was the optimal size from the Ene.Farm project in Japan, where 300′000 residential fuel cells systems were installed [11]). Furthermore, if the onsite produced electricity is exported when in excess (for example during night) an incentive should be available to make the investment profitable. Finally, a typical residential building can exploit the thermal production only during winter days [12].

Non-residential buildings are for example: supermarkets, malls, hotels, hospital, sport centres, etc. The interesting features of these application are the availability, in almost all the presented cases, of a constant base load thought all the year and a possible need for thermal power – not only for space heating – during the whole year. On the other side, reliability of the CHP system is central for these application and the FC should usually work 24/7 with a very high availability factor. Few scientific works have analyzed the installation of FCs in non-residential buildings. Hybrid systems with heat pumps where proposed for China public buildings by [13]. Jing et al. [14] analyzed both LCOE and payback time for SOFC installation (in CCHP mode, with an adsorption chiller) in different building types in China. From their analysis, hospital, hotel, and supermarket achieve more benefits than office and school when installing an SOFC; furthermore, warmer regions rank slightly higher than colder regions. From their analysis the authors also stated the SOFC system with adsorption chiller, could generate an average carbon emission reduction rate of 60% and over 85% of air pollution cost saving. An hybrid CCHP system was also proposed for an educational building in Iran by Mehrpooya et al. [15]: the systems again demonstrated optimal performance with a total efficiency of 60%: anyway, despite the high efficiency values and the significant reduction of the major contaminants, the payback time was estimated to be 8.3 years. Naimaster at al. [16] analyzed more widely the potential of SOFC installations in office buildings: the goal of their study was the evaluation of the annual cost and CO_2 reduction linked with the installation. Results shows that an optimized 175 kW SOFC CHP system successfully lowered annual utility costs by up to 14.5% (over a baseline HVAC system) and CO_2 emissions by up to 62% A similar study, on the potential of fuel cells for the Malaysian building sector, was also presented in [17]. Comparative technical analyses between commercial and residential buildings and among different operating modes and regulatory frameworks are also available in [18,19].

Another possible use of fuel cells within the building sector is the use of reversible SOC which are able to store renewable energy into hydrogen and then re-use the fuel when power is needed by the group of buildings or micro-grid. The application of a reversible SOC in the island of Procida in Italy has been studied by Lamagna et al. [20]: these solutions are particularly interesting in remote locations where fuel supply is expensive due to transport costs. Recently, Acha et al. [21] developed an analysis similar to the one presented in this work for the supermarket sector: the authors highlighted a payback time of 4.7–5.9 years with subsidies and 6–10 years without (slightly higher than the combustion engine CHP solution which is used a reference case for the comparison). The presented work aims at analysing the installation of commercial SOFC systems (with real system data from the manufactures) in two non-residential buildings: hospitals and hotels. Supermarkets have also been analyzed, only in terms of load shape, and will be discussed in future works. The main goal of the analysis is to evaluate the technical, economic and environmental feasibility of the installation of SOFC-CHP systems in non-residential buildings under different scenarios for what concerns geographical location (energy intensity and energy prices will vary), system performance and costs scenarios (current and target). Energy consumption profiles have been retrieved from real data available for US buildings [22] and rescaled to match all the countries analyzed. A simplified market potential analysis is also presented to show the size of the potential market for similar installations.

The novelty of this work relies in the high-quality and high-reliability of input data, which are referred to real SOFC systems (data from manufacturers) and real energy consumption profiles (hourly basis); furthermore, the analysis was carried out in a 'general' way, and not analysing a single case study, in order to point out the drivers and the limitations for this application. Market potential analysis is also provided as a novel instrument – for this specific application – to quantify the possible replications.

The entire work has been developed in the framework of the COMSOS project (Commercial-scale SOFC systems, 2018–2022 [23]). The project aims to validate and demonstrate fuel cell based combined heat and power solutions in the mid-sized power range of 10–60 kW, totalling 450 kWe. The project will implement the installation of 25 SOFC-technology based power around the world, to prepare manufacturers for developing capacity for serial manufacturing, sales and marketing of mid FC CHP products. The consortium includes the coordinator VTT, the 3 key EU-manufactures Convion Oy, Sunfire GmbH and SOLIDpower SpA, and 2 research institutes for data analysis, Politecnico di Torino and Blueterra. The SOFC modules which will be installed within the COMSOS project are 12 kW (Solidpower), 20 kW (Sunfire) and 58 kW (Convion).

2. Market description

The potential markets are analysed: number of hospitals and hotels for each country is reported, and their thermal and electric need is matched with the size of the SOFC system. For all the case studies here presented, hourly load profiles have been retrieved from a collection of real consumption data available in a database from the US Department of energy [22]. In this database, load profiles are provided for different sites (16 building types are available) in 1020 different US locations and with different sizes and energy intensities. The key element in analysing a market for the SOFC installation is the need of a base load, able to guarantee a smooth operation of the SOFC-CHP systems without interruptions or thermal cycles, which would cause degradation effects on the stacks.

2.1. Hospitals

The hospital sector needs a constant, stable and reliable electric supply in order to keep the instruments continuously in operation and to maintain optimal environmental conditions, both for patients and staff. Hospitals are usually occupied 24/7, all year round, and they require both electric and thermal power to support the activities. The analysis has shown a similar trend in the daily load profiles of many types of hospitals. Both for big and small structures, the energy consumption has a time dependent behaviour that does not vary with the size (usually expressed in terms of hospital area, m^2). Power supply based on a fuel cell system could constitute an optimal option for health centres, due to its high efficiency and continuity of operation, with negligible polluting emissions.

2.1.1. Hospitals distribution

It is possible to recover the number of hospitals, in the year 2015, in EU and US from the World Health Organization Database [24] and the American Hospital Association [25]. Appendix A (Figure A1) shows the sector distribution: countries with high population have usually a big number of health centres, as US and Russia.

The analysis on the hospital sector focuses only on specific EU countries: Germany, UK and Italy are chosen (the choice is mainly driven by the available data in literature on Energy Intensity). Germany is where the greatest number of SOFC tested units exist, market creation efforts have been most intense, electricity prices are among the highest in Europe, and where customers are more accepting residential fuel cell products and their high early costs [26]. Italy is instead one of the European countries with the highest share of CHP in gross power generation (20% [27]), so the introduction on a commercial scale of a SOFC-CHP system could have a great impact on the market, and on the entire national energy sector. Finally, UK is the last country chosen for the analysis, due to the presence of the necessary data in literature.

Table 1
Average energy intensity indexes for hospitals in the selected countries.

Location	EI_{el} [kWh/m^2]	EI_{gas} [kWh/m^2]	Reference
Colorado	376	160	[22]
Maryland	441	200	[22]
Minnesota	395	225	[22]
Washington	393	200	[22]
Germany	100	180	[29]
Italy	130	225	[29]
UK	105	505	[30]

US has more than 6′000 hospitals: it is the biggest market among those analysed, and it is the one monitored more in depth. Indeed, from the database provided by the US Department of Energy [22], it is possible to recover the hourly based load profiles for specific US hospital buildings. Data are divided by cities, and the electricity and gas consumption are specified in the various terms (cooling, heating, fans, water treatment system, etc.). From the database, four US cities are chosen for the analysis: Boulder (Colorado), Baltimore (Maryland), Minneapolis (Minnesota) and Seattle (Washington). They are selected because they are in different climatic zones.

2.1.2. Energy intensity

Specific indexes, as the energy intensity EI (kWh/m^2), allow to compare structures that are very different in dimensions. The number of analyzed cases is limited in a range with similar electric intensity EI_{el} and gas intensity EI_{gas}, both expressed in kWh/m^2.

A comparison is made between the energy consumption in different hospitals in the world. This index could depend on the technology used in the structure: as an example, IEO (Istituto Europeo di Oncologia, Milano) has one of the highest index ($EI_{el} = 452$ kWh/m^2 [28]), probably because it is an innovative and modern hospital equipped with more electronic instrumentation.

Parameters are completely variable, also in the same country: EI_{el}, in Italy, varies in the range between 183 kWh/m^2 [29] for AOB (Azienda Ospedaliera Brotzu, Cagliari) and 452 kWh/m^2 for IEO. Indeed, buildings can be totally different depending on the year of construction, extension or final destination, parameters which affect the related energy consumption. In order not to focus only on single specific cases which could be not representative of the entire national hospital sector, a deeper literature research was performed to obtain average parameters, able to represent the entire country. In literature it is possible to find, for the hospital sector, the average national EI_{el} and EI_{gas} only for a limited number of countries: for the analysis, indexes of UK are taken from the report provided by the Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET, [30]), whereas indexes of Colorado (Boulder), Maryland (Baltimore), Minnesota (Minneapolis) and Washington (Seattle) are taken from EIA database [22]. This choice was made because the US indexes provided by the CADDET are far from the value calculated from the hourly consumption, which is the most accurate energy assessment in literature, and on which this work is based. Finally indexes for Germany and Italy are taken from [29].

In Table 1 the specific indexes chosen for this analysis are shown. High values of EI_{el} and EI_{gas} indicate that, on average, the analysed country has energy-intensive buildings. USA countries show the highest electrical consumption per floor area, because, in average, American buildings in the non-residential sector have a good level of innovation and technologies.

2.1.3. Electricity and heat demand profiles

Energy profiles are different for each analysed hospital. Electricity

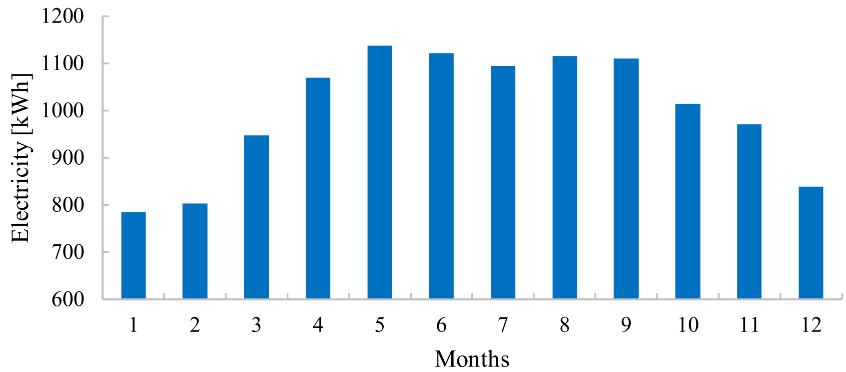

Fig. 1. Average monthly electricity consumption for an hospital (Minneapolis, US).

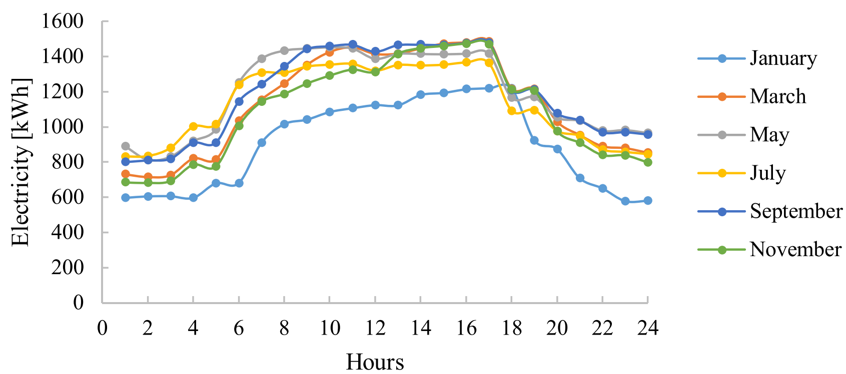

Fig. 2. Daily electricity profile for an hospital in Minneapolis (US).

consumption reaches its maximum in summer, due to the ambient cooling, which is energy-intensive, particularly for countries with a hot climate (Colorado, Italy). On the contrary, thermal energy needed is minimum from June to September, because it is strongly related to the space heating. The seasonal trend is also confirmed from data available on the Cagliari hospital [29]. Fig. 1 shows the average monthly consumption for a typical hospital in Minneapolis (US).

Electricity can be exploited to feed several equipment: cooling, heating, fans, water treatment system, medical and other devices. Consumption mainly depends on both the technological level of these instruments and on the activities carried out in the structure, as well as on the climatic characteristics of the location. Heating, Ventilation and Air Conditioning system (HVAC) is composed of all systems dedicated to air conditioning in the building, as refrigerating unit, air handling unit, heat generators, fans and pumps. Indeed, HVAC alone constitutes more than 40% of the total, because all these machines are turned on for many hours every day. Illumination, that typically depends on daylight hours, and medical equipment are the remaining part. The last one is the item with the greatest number of devices, which can be very different for operating hours or technology. Indeed, diagnostic imaging equipment are very energy-intensive, instead computers or alarms do not need much electricity. Thus, depending on the hospital and on the used technology, medical equipment can be a relevant fraction of the electricity consumption.

However, total electricity consumption is highly reduced in months in which there is the absence of the air conditioning, and there is good ambient light (Spring and Autumn). Both for big and small hospitals this trend is replicated, varying with the annual weather, confirmed by literature data for Italy [28] and Minnesota [22] hospitals. In terms of average monthly values, winter months (December, January and February) show the lowest values of electrical energy consumption of the year, because despite being the period in which greater illumination is required, the absence of HVAC supplied by electricity leads to a significantly lower energy consumption.

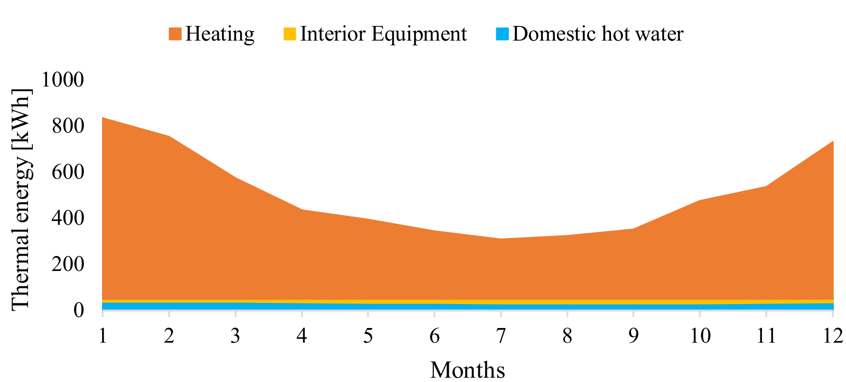

Fig. 3. Monthly average thermal energy consumption for an hospital in Minneapolis (US).

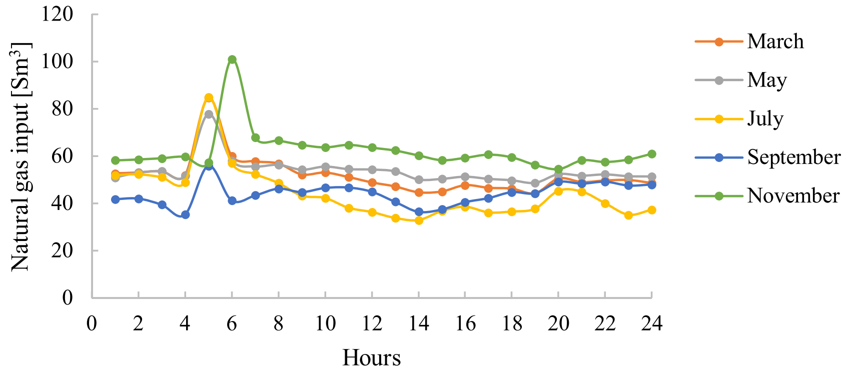

Fig. 4. Daily natural gas consumption profile for an hospital in Minneapolis (US).

Table 2
Average energy intensity indexes for hotels in the selected countries.

Location	EI_{el} [kWh/m^2]	EI_{gas} [kWh/m^2]	Reference
Colorado	212	263	[22]
Maryland	260	244	[22]
Minnesota	235	320	[22]
Washington	210	247	[22]
Finland	230	189	[33]
Germany	135	150	[34]
Spain	124	144	[33]

Since the daily activities are quite similar and they do not depend on the period of the year, daily electricity profile of a hospital shows a trend which is replicated every day. The curves follow a common evolution: their trend is rather flat in the central hours of the day, from 10:00 a.m. to 18:00p.m., with a peak in the afternoon and the minimum during the night [22]. Lowest point represents the base load, which is the minimum electricity needed to satisfy the hospital facilities, when most of the equipment is not in operation. Fig. 2 shows the daily trend of electricity consumption in different days of the year.

For what concerns the thermal load, the heat provided by the combustion of methane is exploited in various components: environment heating, interior equipment and water heater. Natural gas consumption (calculated by the LHV of natural gas, 9.27 kWh/Sm^3 [31]), depends on the climatic conditions, on the scope of the hospital facilities (kitchens, showers…) and on building capacity, age and insulation.

Thermal energy consumption shows a constant value for hot water and interior equipment, which does not depend on the season. The gas consumption for space heating varies indeed with the season with a minimum request in summer. Thermal energy thus demand strongly depends on the use of heating: it constitutes more than 64% of the total (for US locations, [22]), and in some cases even more than 80% (for Cagliari hospital [29]). Fig. 3 shows the monthly average thermal energy request for an hospital in Minneapolis (US). Fig. 4 shows the daily gas consumption profile for five different months. Gas profile shows a similar behaviour among different months, with a thermal demand peak located at 5:00 or 6:00 am: this is probably the hour of the day in which heating and equipment are started.

2.2. Hotels

In a hotel, electricity is the primary energy source and it is used for HVAC, lighting, lift and all the equipment, while natural gas is used mostly for heating and cooking.

2.2.1. Hotels distribution

The same US locations (data available from US Department of Energy [22]) were chosen for the analysis as in the hospital case.

In Europe, the number of hotels and similar accommodations in each country are provided by Eurostat database for 2019 [32]. Due to the lack of data in the literature, it was necessary to choose among those countries that could offer reliable consumption data. Final choice is therefore to analyse Finland (794 hotels), Germany (32′182 hotels) and Spain (19′683 hotels).

2.2.2. Energy intensity

In Table 2 all the countries included in this analysis were reported, with relative national average values of EI in kWh/m2. The consumption per square meter is lower compared to hospitals. Indeed, hospitals are more energy-intensive, due to the presence of the equipment, which often have a high technological level (in the chosen countries).

2.2.3. Electricity and heat demand profiles

A typical full service American hotel [35] has a restaurant, a coffee shop, an on-site laundry, offices and conference rooms. This type of hotel has a very high occupancy rate, so there is no difference between

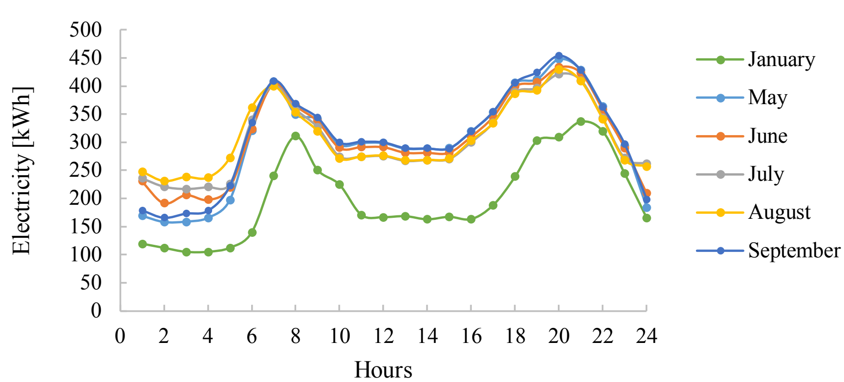

Fig. 5. Daily electricity profile for a typical hotel in Minneapolis (US).

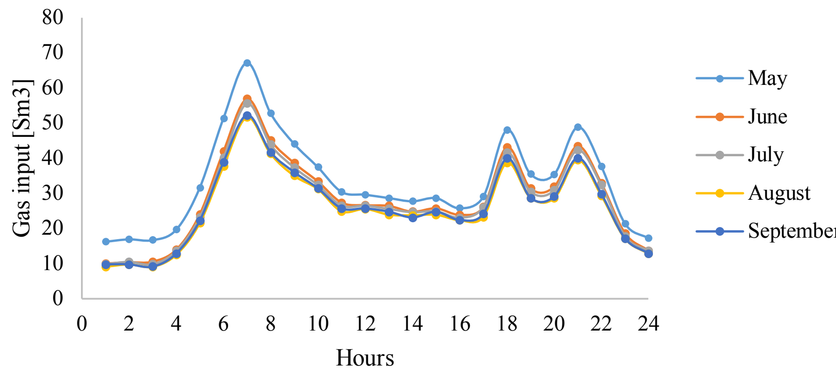

Fig. 6. Daily natural gas consumption profile for a typical hotel (Minneapolis, US).

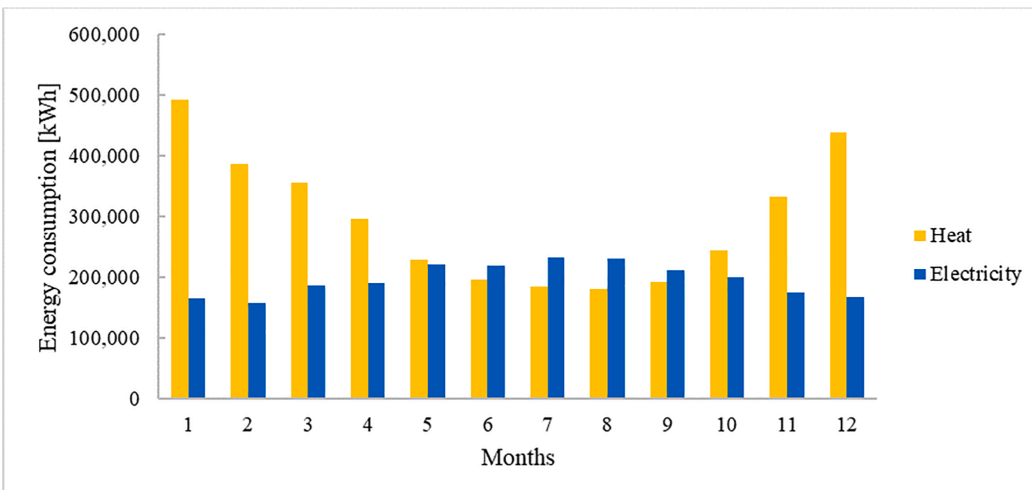

Fig. 7. Monthly energy consumption for a typical hotel in Minneapolis (US).

weekdays and weekends. Unlike hospitals, hotels show a bigger variation in their load profiles, obviously depending on the activities performed by the customers. Electricity, in all analysed cities, has two demand peaks (Fig. 5), one in the morning between 7:00 and 8:00 am, and one in the evening between 8:00 and 9:00 pm. Gas consumption has instead three peaks (Fig. 6).

In both cases, load profiles have a daily trend which is quite constant over the different months and seasons, so the assumptions made for hospitals are still valid.

Electricity and natural gas demand has also a seasonal variation. As reported in Fig. 7, electricity consumption is quite constant over the year, with lower values in winter months, while heat profile shows a bigger variation, with its minimum value in summer. Both profiles depend on the HVAC system, but the impact is more evident in the heat profile.

3. Methodology

A mathematical model has been developed to evaluate the techno-economic feasibility of the installation of an SOFC system in a commercial building. The economic analysis has been performed over a period of 15 years. Evaluation of the economic convenience of the investment is based on several factors: building size, energy consumption and fuel cell performance, capital expenditure, operational costs and economic data, that vary with the chosen location. These parameters have a large variability range, so the model is built to work in different configurations, in order to obtain a more in-depth analysis. It is also possible to compare the economic and environmental impact that arise from the substitution of a typical power supply system (reference scenario: electricity from the grid and heat from a natural gas fed boiler) with an SOFC cogeneration system.

3.1. *Model description*

The model has been developed using Excel® as the main tool. It consists of four sections:

1. Input settings
2. Load profiles evaluation
3. SOFC model
4. Cash flow evaluation

3.1.1. *Input settings*

This is the dashboard of the model. Here input data can be chosen from a list. User can choose:

- Building type (hospital or hotel)
- SOFC technology
- Location
- Price scenario

3.1.1.1. SOFC technology. There are different technical and economic parameters depending on the fuel cell producer. In this analysis, five different technologies are studied, but only the two last cases are

Table 3
Fuel cell technical and economic information.

	Unit	Value
SOFC module nominal size, $P_{el,rated}$	kW	25
Electrical efficiency @ nominal size, $\eta_{el,rated}$	%	55
Thermal efficiency @ nominal size, $\eta_{th,rated}$	%	27
Average system availability	%	98
Technical lifetime of the module	h	43′000
Degradation rate, ε_{deg}	% / kh	0.5
NOx emission	mg/kWh	40
Manufacturing cost stack current	€/kWe	4′900
Manufacturing cost stack target	€/kWe	1′200
Manufacturing cost BoP current	€/kWe	5′000
Manufacturing cost BoP target	€/kWe	1′500
Operational cost	€/y	1′700
Commissioning and installation cost	€/kW	100
Company profit percentage	%	10

Table 4
Energy prices for chosen locations.

Location	Electricity Price [€/kWh]	Gas Price [€/kWh]	Reference
Hospitals			
Colorado	0.08	0.02	[39]
Maryland	0.10	0.03	[39]
Minnesota	0.09	0.02	[39]
Washington	0.08	0.02	[39]
Germany	0.12	0.03	[37,38]
Italy	0.12	0.03	[37,38]
UK	0.13	0.03	[37,38]
Hotels			
Colorado	0.09	0.02	[39]
Maryland	0.10	0.03	[39]
Minnesota	0.09	0.02	[39]
Washington	0.08	0.02	[39]
Finland	0.07	0.06	[37,38]
Germany	0.15	0.04	[37,38]
Spain	0.11	0.04	[37,38]

reported, which show average data. The first three are the Comsos commercial systems: Sunfire, SOLIDpower and Convion products (not shown here for confidentiality reasons). The fourth named "*SOFC*" is a fictitious model, that represents the typical parameters of a generic SOFC available on the market (average values from Comsos data). Results between the "SOFC" generic model and the three SOFC systems are anyway not too different and results presented here can be representative of an SOFC system available in the European market. Parameters used for the SOFC model are presented in Table 3.

The fifth case study, called the "*Best performing module*" represents and SOFC system with the same economic costs, but with better technical performance compared to the previous one. In particular, this scenario is used to evaluate the effect of the following technical parameters:

- η_{el} = 55–65%
- ε_{deg} = 0.2–0.5%
- Lifetime = 43′000-69′000 h (5–8 years)
- Availability = 98–99%

3.1.1.2. Location. Each location shows different load profile, based on the average consumption of its country. For hospitals the following countries are available: Colorado, Maryland, Minnesota and Washington for US, Germany, Italy and UK for Europe. Instead, hotels show the same US locations plus Finland, Germany and Spain.

Every country has different energy prices (Table 4), which depend on the different supply and demand conditions, including the geopolitical situation, the national energy mix, import diversification, network costs, environmental protection costs, adverse weather conditions or levels of taxation and excise duties [36]. Furthermore, prices vary according to

Table 5
Scaling coefficients for the chosen locations.

Location	SC_{el}	SC_{gas}
Hospitals		
Colorado	0.94	0.81
Maryland	1.10	1.02
Minnesota	0.98	1.15
Washington	0.98	1.02
Germany	0.25	0.92
Italy	0.32	1.15
UK	0.26	2.58
Hotels		
Colorado	0.92	0.98
Maryland	1.14	0.91
Minnesota	1.02	1.19
Washington	0.91	0.92
Finland	1.00	0.71
Germany	0.59	0.56
Spain	0.54	0.46

the type of consumer: the greater the energy consumption, and therefore the energy purchased, and the lower the specific price. Hospitals fall into the category of non-household consumers, and those analysed have a yearly electric consumption in the range of 2′000−20′000 MWh, and a yearly gas consumption in the range of 10′000–100′000 GJ according to Eurostat database [37]. Hotels have electric consumption in the range of 500–2′000 MWh, and gas consumption between 1′000–10′000 GJ. For EU locations, prices were taken from Eurostat [37,38], whereas for US cities they were taken from the US Energy Information Administration (EIA) [39].

Spark Spread (SS) is a common metric for estimating the profitability of natural gas-fired electric generators, and it is calculated as the difference between the wholesale market price of electricity (p_{el}) and its cost of production using natural gas (which is depending on the gas price p_{gas} and the electrical efficiency of electricity production and supply system η_{el}) [40].

$$SS = p_{el} - \frac{p_{gas}}{\eta_{el}} \quad (1)$$

In countries with a high spark spread, the revenues related to the electricity production are maximized, because electricity is sold at a higher price (or in any case it is not purchased, it is a saving), and natural gas needed for the operation has a lower impact on the costs.

3.1.1.3. SOFC price scenario. SOFC costs scenarios provides costs at current market situation and target values, which should be achieved in the short term, within 5–10 years. Total manufacturing cost is given by the sum of the module and the BoP costs, and at current market situation they amount to about 11′000 €/kW. Considering CAPEX reductions with increasing production volumes, due to the economies of scale, target costs will be over 70% smaller: 3′000 €/kW (see Table 3).

3.1.2. Load profiles

Energy consumption data from different sites are analysed on a yearly, daily and hourly basis, since this is strongly affecting the operation of the SOFC system. Detailed hourly data are present in the literature only for US cases. Starting from the average electric and gas intensity for each country (see Tables 1 and 2), load profiles from the US cities have been scaled for the EU ones. Scaling the US consumption, a new load profile is obtained. Electric (SC_{el}) and gas scaling coefficients are calculated for each location, as the ratio between the chosen location ($EI_{el,location}$) index and the US index (average value between the 4 cities, $EI_{el,US}$):

$$SC_{el} = \frac{EI_{el,location}}{EI_{el,US}} \quad (2)$$

A coefficient greater than 1 indicates that the analysed EU country needs more energy (on average) than the US. European countries usually show lower average electric consumption compared to the US ones, so the scale coefficients are lower than one. Table 5 shows electricity and gas scaling coefficients for hospitals and hotels in the chosen locations.

3.1.3. SOFC model

Continuous modulation (load following) is not always recommended for an SOFC system because working at high temperature (about 800 °C) the system will suffer thermal cycles and fast modulation. Therefore, a continuous operation is preferred, to avoid faster degradation of the stacks, to keep the system at its maximum efficiency and to avoid using working hours to turn off and on the system. For this reason, in this analysis, in accordance with the Comsos SOFC manufacturers, the SOFC is considered continuously working at full load throughout the year, except the time when it is turned off for maintenance.

Each fuel cell has an average system availability (expressed in working hours per year), when the system is considered fully running. In the model, SOFC production is set to zero during the unavailability time: the hours of the year in which the energy demand is minimum have been chosen as the maintenance period. Looking at the electricity consumption (Figs. 1 and 7) the minimum energy requirement is located in winter months, during the first days of January. Therefore, in that period, SOFC is considered turned off for maintenance.

SOFC electric capacity has been chosen by calculating the number of modules able to satisfy the minimum required power value (base load) from the consumption profile. In this way the system can continuously work at its maximum efficiency and load (Fig. 9 shows an example for a German hospital).

Once the minimum power value has been found (P_{base}), this is then divided by the power of the single module (P_{mod}), rounding to the lower integer. Then, the installed capacity ($P_{el,rated}$) is calculated.

$$N_{mod} = int\left(\frac{P_{base}}{P_{mod}}\right) \tag{3}$$

$$P_{el,rated} = N_{mod} * P_{mod} \tag{4}$$

The fuel cell module has the technical characteristics provided by the producer, shown in Table 3. Module is subject to degradation over time, so the produced electric and thermal power vary, and consequently also the electric and thermal efficiency. A constant total efficiency is assumed over time, given by the sum of the electric and thermal efficiency (e.g. when electrical efficiency will decrease due to degradation, thermal efficiency will increase).

$$\eta_{sys} = \eta_{el} + \eta_{th} \tag{5}$$

The electrical power produced (P_{el}) decreases as a function of time, according to the degradation rate ε_{deg}, a parameter that expresses the percentage reduction in the production of electric power, as a function of the working hours.

$$P_{el} = P_{el,rated} \cdot (1 - \varepsilon_{deg} \cdot h) \tag{6}$$

Hourly electric efficiency (η_{el}) is given by the ratio between the current (P_{el}) and the nominal power ($P_{el,rated}$), multiplied by the nominal electric efficiency ($\eta_{el,rated}$). In this way it is possible to consider how the degradation of the module affects the SOFC efficiency.

$$\eta_{el} = \eta_{el,rated} * \frac{P_{el}}{P_{el,rated}} \tag{7}$$

Keeping constant the total efficiency, the thermal one can be calculated.

$$\eta_{th} = \eta_{sys} - \eta_{el} \tag{8}$$

To simplify the calculations, average electric and thermal efficiency are used throughout the year in calculating the power produced by the fuel cell. This is the average between the efficiency at the beginning of the year and at the end.

$$\eta_{avg} = \frac{\eta_{begin} + \eta_{end}}{2} \tag{9}$$

Therefore, thermal power produced ($\dot{Q}_{th}$) shows a variation in time, but, unlike the electric power, it grows with the degradation of the module, like the thermal efficiency η_{th}.

$$\dot{Q}_{th} = P_{el} * \frac{\eta_{th}}{\eta_{el}} \tag{10}$$

To calculate the electric and thermal efficiency for the years following the first one (when they are equal to rated values), the reduction (due to degradation) is applied. As done for the first year, for each following year the average is calculated in the same way as in Eq. (9).

Energy savings are calculated, considering that the savings are different year to year, due to the SOFC stack degradation. Indeed, η_{el} and η_{th} change with time, and consequently electricity and heat produced by the SOFC will change. Year by year, the energy productions are therefore calculated as the previous year's production multiplied by the ratio between the actual efficiency over the previous one (average values between the initial and final efficiency calculated for every year). Current values are indicated with the subscript *i*, those of the previous year with subscript *i-1*.

$$E_{eli} = E_{eli-1} * \frac{\eta_{el\_avgi}}{\eta_{el\_avgi-1}} \tag{11}$$

$$E_{thi} = E_{th\ i-1} * \frac{\eta_{th\_avgi}}{\eta_{th\_avgi-1}} \tag{12}$$

The SOFC system needs inlet natural gas ($\dot{V}_{gas}$) to make the electrochemical reactions occur (a 100% methane flow rate is assumed). This is calculated as the ratio between the produced electric power (P_{el}) and the product of the current electric efficiency (η_{el}) and the lower heating value of methane (LHV_{gas}).

$$\dot{V}_{gas} = \frac{P_{el}}{\eta_{el} * LHV_{gas}} \tag{13}$$

Since the decrease in η_{el} corresponds to the same decrease in the produced electricity, the ratio is constant with time, hence the gas volume flow is the same for all the hours of the year. Yearly gas entering the fuel cell is therefore calculated by multiplying the volumetric flow rate by the working hours of the module in a year.

$$Gas_{SOFC} = \dot{V}_{gas} * h \tag{14}$$

Fuel cell has lower emissions than other conventional energy production systems, both in terms of CO_2 and NO_x. NO_x is calculated from the parameter provided by the producer (see Table 3), expressed in mg of NO_x per kWh of produced electricity. E_{el_avg} used in Eq. (15) is the average value between the electricity produced by the new and the degraded SOFC module.

$$\dot{m}_{NOx} = NOx_{emissions} * E_{elavg} \tag{15}$$

Instead CO_2 is calculated starting from the produced CO_2 by the reactions inside the module. Reactions show that the molar ratio between the methane sent to the cell and the CO_2 produced is 1:1. Consequently this is also the relationship between volumes and volumetric flow rates, hence the carbon dioxide mass flow rate is calculated by multiplying $\dot{V}_{gas}$ by the density of CO_2 ($\rho_{CO_2} = 1.87\ kg/m^3$).

$$\dot{m}_{CO_2} = \dot{V}_{gas} * \rho_{CO_2} \tag{16}$$

The emissions from the SOFC system were then compared with the average emissions factor for the national electricity production. Greenhouse gases and other atmospheric pollutants emission factors for Italian power sector have been calculated from ISPRA [41]. These factors

Table 6
Emission factors related to the Italian production of electricity and heat [41].

Pollutant	Type of production	Unit	Value
CO_2	Electricity	g/kWh	446
	Heat	g/kWh	215
NO_x	Electricity + Heat	g/kWh	0.23

express the quantity of emitted CO_2 and NOx in the Italian production of electricity and heat. Emission factors for the year 2017 (Table 6) were taken.

For the following calculation the yearly energy produced by the SOFC system is considered, which is the one that is not purchased from the grid, and therefore the one that would have involved the emission of pollutants if it had been produced with a conventional system.

$$\dot{m}_{CO2\_Conv} = E_{el}*CO_{2el} + E_{th}*CO_{2th} \quad (17)$$

$$\dot{m}_{NOx\_Conv} = (E_{el} + E_{th})*NO_{xConv} \quad (18)$$

3.1.4. Cash flow evaluation

The cashflow analysis is performed to understand how costs and savings, related to the installation of an innovative system for energy production, are structured, and when it will be possible to recover the investment.

The sum of all the investment costs (CAPEX) consists of various terms: manufacturing cost of the stack (k_{stack}) and of the BoP (k_{BoP}), commissioning & installation cost ($k_{C\&I}$) and company profit (k_{profit}).

Eq. (19) shows the evaluation of the total stack costs, the same methodology is applied to the BoP and C&I costs, while the profit is fixed as a percentage of the others. The CAPEX will be a negative term in the cashflow analysis.

$$k_{stack} = p_{stack}*P_{rated} \quad (19)$$

$$k_{BoP} = p_{BoP}*P_{rated} \quad (20)$$

$$k_{C\&I} = p_{C\&I}*P_{rated} \quad (21)$$

$$k_{profit} = 10\% \cdot (k_{stack} + k_{BoP}) \quad (22)$$

$$CAPEX = k_{stack} + k_{BoP} + k_{C\&I} + k_{profit} \quad (23)$$

The SOFC stacks are characterised by a technical lifetime, after which a replacement should occur. The replacement cost k_{rep} is assumed equal to the manufacturing cost of the stack (k_{stack}). Obviously, this cost must be considered only in the years in which the replacement takes place: in the analysed 15 years it happens 2–3 times, depending on the selected SOFC technology case study.

The $OPEX_{tot}$ is the sum of costs related to manage the system and to take the replacement of the stack. It also includes the cost of remaining electricity k_{el} and gas k_{gas} to satisfy all the electric and thermal load. $OPEX_{SOFC}$ is a cost provided by the suppliers in €/y: it includes maintenance to the SOFC module (e.g. air filter change, catalyst reformer change, etc.).

$$OPEX_{tot} = OPEX_{SOFC} + k_{el} + k_{gas} + k_{rep} \quad (24)$$

The evaluation of the $OPEX_{tot}$ needs in input the costs for the electricity and gas purchased from the grid, which are depending on the prices for the energy vectors (p_{el} and p_{gas}), the consumption of electricity (El_{load}) to cover the load not supplied by the SOFC system and the consumption of gas (Gas_{load}), which is the sum of the gas required to feed the SOFC system (Gas_{SOFC} from Eq. (14)) and the gas fed to the auxiliary boiler to supply the remaining thermal load not covered by the SOFC system.

Energy prices are assumed constant over time: this assumption has been confirmed after performing a sensitivity analysis on electricity and natural gas prices, based on historical trends at EU and single country level. Variations in the energy prices of +/- 0.5–2% (which are the average values for the last decade in Europe) are generating a LCOE variation lower than 1% in all cases and are no changes in the RPBT. The impact of the energy prices can be considered negligible, and this is the reason why the prices have been assumed constant in the analysis.

Electricity and gas costs depend only on the load profile, which is assumed unchanged every year.

$$k_{el} = El_{load}*p_{el} \quad (25)$$

$$k_{gas} = Gas_{load}*p_{gas} \quad (26)$$

$$Gas_{load} = Gas_{SOFC} + Gas_{boiler} \quad (27)$$

The last term of the cashflow analysis are the revenues (R) which are related to the savings for the end-user for the electricity and heat not bought from the grid (respect to the current scenario) to cover the loads. This is the positive term of the cashflow analysis. If the SOFC system covers the base load, a part of electricity (E_{el}) and gas ($E_{th,gas}$) is indeed not bought from the grid: this saving is calculated as the product of the produced energy by the electricity and gas price. Savings are considered the revenues (R_{el} and R_{th}) of the analysis.

$$R_{el} = E_{el}*p_{el} \quad (28)$$

$$R_{gas} = E_{th,gas}*p_{gas} \quad (29)$$

$$R = R_{el} + R_{th} \quad (30)$$

$E_{th,gas}$ is calculated from the thermal power ($\dot{Q}_{th}$) dividing by the boiler efficiency (η_{boiler} = 90%), because in case of absence of the FC system, thermal power should be produced with a traditional boiler.

$$E_{th,gas} = \dot{Q}_{th}*h*\frac{1}{\eta_{boiler}} \quad (31)$$

The difference between the OPEX and the revenues is the net costs for the load coverage in the SOFC system case study. The annual cash flow (CF) is then calculated: it is the algebraic sum of all analysed costs (negative) and revenues (positive).

$$CF = CAPEX + OPEX_{tot} + R \quad (32)$$

In this analysis, Annual Cash Flow is always negative, because only a fraction of the total energy demand is covered by the SOFC, and this saving, lower than total costs, is the only positive term in the evaluation.

Cumulative cash flow (CCF) is then calculated as the sum of the Annual Cash Flow for all the years analyzed. The investment is considered as 'recovered' when the cumulated cashflow in the 'SOFC scenario' starts to be lower than the cumulated cashflow in the reference scenario.

$$CCF = \sum_{i=1}^{15} CF_i \quad (33)$$

The Levelized Cost of Energy ($LCOE$) is a measure of the average cost of the kWh produced from the SOFC system, which includes all the money spent to build and operate a power-generating asset over its lifetime. It is weighted over the total energy output produced during the lifetime. The LCOE allows a comparison between different technologies for electricity generation and also between distributed technologies and the electrical grid. If LCOE is higher than the price at which electricity is purchased by the grid, the system does not lead to a cost effectiveness, and it is more convenient to procure energy directly from the grid. LCOE is calculated with the following equation where d is the discount rate, assumed equal to 7% [42].

$$LCOE = \frac{\sum_{n=1}^{15} \frac{CAPEX + OPEX_{SOFC} + k_{rep} + Gas_{SOFC,n}*p_{gas}}{(1+d)^n}}{\sum_{n=1}^{15} \frac{P_{el,n}}{(1+d)^n}} \quad (34)$$

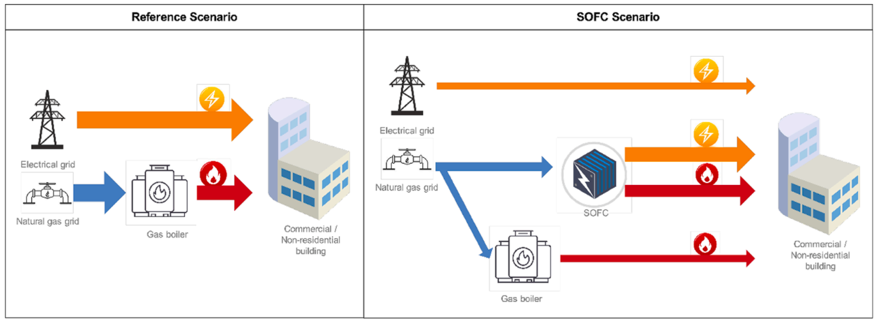

Fig. 8. Layout of the reference traditional power supply system and the SOFC cogeneration system.

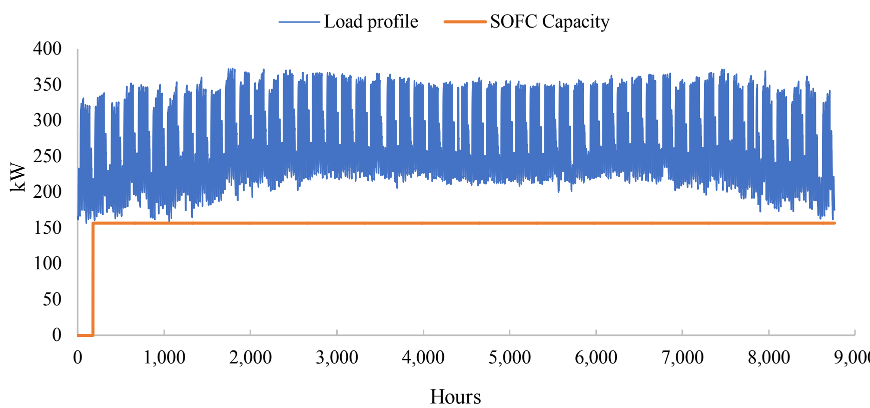

Fig. 9. Fuel cell sizing according to the minimum power required by an hospital (Germany).

3.2. Scenarios description

The analysis compared two scenarios (see Fig. 8): one in which the SOFC system is installed to satisfy the building base load consumption, and the other (reference scenario) in which the electricity and thermal demands are met by purchasing natural gas and electricity from the grid. In the reference scenario, the only equipment installed is a traditional natural gas boiler.

The comparison aims to discover if, in a period of 15 years, net expenditures (expressed by the *CCF*) in the reference case are greater than in the SOFC one, and what would be the environmental impacts of using an SOFC technology to supply a building.

For comparing reference and SOFC scenarios, the difference between the cumulative cash flows of the two systems is calculated, to quantify what is the most expensive over 15 years. If the difference is positive, it means that the SOFC system is the preferable option, because it leads to a saving of money over 15 years, instead if it is negative, the best option is the reference system. The first year in which there is the first positive value of this difference is called Relative Payback Time (*RPBT*).

$$CCF_{diff} = \sum_{i=1}^{15} CCF_{i\_SOFC} - CCF_{i\_Conv} \quad (35)$$

4. Results

The results section shows different analyzed scenarios, aimed to understand both the current economic performance of the system, but also the effect of different technical and economic aspects on the cash-flow profile, in particular:

- Baseline scenario
- Effect of existing subsidies
- Effect of technical improvements
- Target cost scenario

Table 7
LCOE for each country at current costs.

Location	LCOE [€/kWh]
Colorado	0.2554
Maryland	0.2790
Minnesota	0.2598
Washington	0.2608
Germany	0.2789
Italy	0.2755
UK	0.2713

Furthermore, a final comparison among the different results is presented, together with a simplified evaluation of the market potential in the two analyzed sectors.

4.1. Baseline scenario

4.1.1. Costs and revenues assessment - Hospital

For all analysed countries, LCOE is calculated with Eq. (34). Results (Table 7) show that there are countries with a higher LCOE: the variation depends on the size of the installed SOFC system, the cost of gas to feed the modules and on the electricity produced.

The size of the system does not impact too much on the results: US buildings need up to 15 SOFC modules more than EU buildings to satisfy the base load power (because of the higher energy intensity), but the costs related to the purchase are balanced by the electricity produced during their lifetime. Indeed, Colorado, Minnesota and Washington show the lowest LCOE among all locations, despite the very higher values of CAPEX and the higher cost of replacement (the LCOE is indeed strongly influenced by the gas price which is very impacting on the results: an increase of 0.01 €/kWh leads to an increase of 0.02 – 0.03 €/kWh in the LCOE).

In this section the results for UK, which is one of the most interesting

Table 8
Average values of technical specifications of the whole SOFC system over 15 years.

Technical specifications	Unit	Value
η_{el}	%	51.5
η_{th}	%	30.5
Gas_{input}	Sm^3/y	252′544

Table 9
CAPEX at current costs for a 150 kW SOFC system installed in UK.

CAPEX	Unit	Value
Manufacturing cost of the module	€	735,000
Manufacturing cost BOP	€	750,000
Commission and Installation cost	€	15,000
Company profit	€	148,500
Total	€	1,648,500

countries to install a SOFC-CHP system, are analyzed. The interest in the UK area is due to the high price of electricity (Table 4) and to the presence of several policies to support energy efficiency and renewable development [43]. Indeed, at current costs, UK shows the best results among all analysed locations.

The electrical base load of the UK typical hospital is calculated (P_{base} = 157 kW). An SOFC system composed of 6 modules, each with a P_{mod} equal to 25 kW, is then considered. Therefore, the installed capacity will be 150 kW ($P_{el,rated}$, from Eq. (4)). SOFC modules can cover 54% of the electricity demand and 7% of the heat need: UK is indeed the country that has the greatest heat demand among those analysed. Table 8 shows the technical specifications of the whole system, which are average values calculated over 15 years.

The analysis is conducted in constant currency: it does not incorporate the inflation effects, to give a real picture of cost trends. Cash flows are therefore presented in reference year currency, considering an inflation rate i = 0%. CAPEX costs are shown in Table 9.

SOFC system covers only a fraction of the total energy demand, so the remaining part has to be met by the use of conventional energy production systems. Consequently, there are the costs of purchased electricity and gas that has to be considered in the analysis. They account for k_{el} = 153,545 €/y and k_{gas} = 280,905 €/y. Cost to feed SOFC modules accounts for $k_{gas\,SOFC}$ = 64,848 €/y. In the case in which all the energy demand is met by a conventional energy system (reference scenario), there is no CAPEX (boiler is assumed as already installed) and the only costs are those related to the purchased energy, constant every year because the hospital energy demand is assumed unchanged over the years: k_{el} = 314,493 €/y and k_{gas} = 302,911 €/y. With the current economic conditions (energy prices and manufacturing costs), without the presence of any subsidies or financing supports, SOFC-CHP to feed an hospital building is still too costly for all analysed locations. Fig. 10 shows the cumulative cash flows for the conventional and the SOFC system in a hospital in UK. It can be seen that the curves are diverging, due to the increase in the slope of the SOFC curve when the replacement takes place. At current costs, the traditional system is the most convenient in economic terms to feed the hospital, as it involves a saving of € 1,370,000: RPBT is not achieved.

4.1.2. Costs and revenues assessment - Hotel

The same analysis in current conditions has been developed also for the hotel sector. LCOE values (Table 10) are comparable with the ones of the hospital sector. US countries still present the lowest LCOE among the analyzed areas, while higher values are related to Finland, Germany and Spain.

Base case results are presented and discussed for a typical hotel in Germany with 50 kW of installed capacity ($P_{el,rated}$). The investment costs (CAPEX) are shown in Table 11 and the cash flow curves for the SOFC-CHP and the traditional scenario in Fig. 11. The investment cost for a 50 kW is equal to around 550 k€, and – for the same reasons mentioned above – the RPBT is not reached. This scenario is assuming zero incentives for cogeneration and zero financial support for CHP.

Table 10
LCOE for each country at current costs.

Location	LCOE [€/kWh]
Colorado	0.26
Maryland	0.28
Minnesota	0.27
Washington	0.27
Finland	0.33
Germany	0.31
Spain	0.30

Table 11
APEX at current costs for a 50 kW SOFC system installed in Germany.

CAPEX	Unit	Value
Manufacturing cost of the module	€	245,000
Manufacturing cost BOP	€	250,000
Commission and Installation cost	€	3,000
Company profit	€	49,500
Total	€	547,500

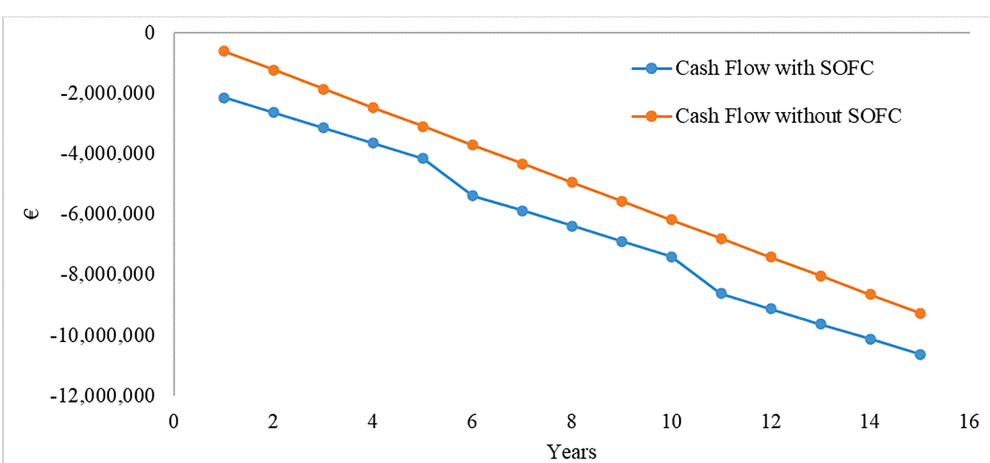

Fig. 10. Cumulative cash flow trend of a conventional and of a SOFC system, at current economic conditions, without subsidies (UK hospital).

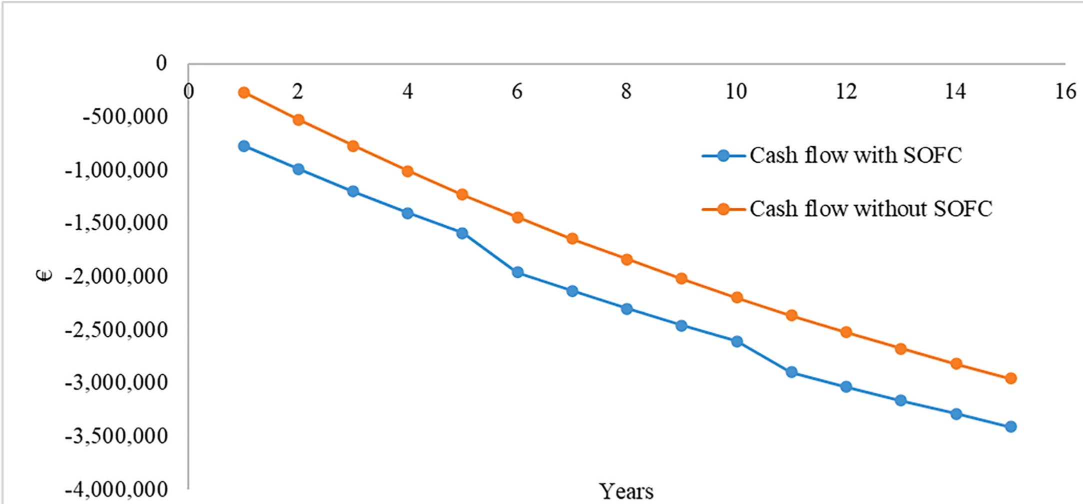

Fig. 11. Cumulative cash flow trend of a conventional and of a SOFC system, at current economic conditions, without subsidies for a hotel in Germany.

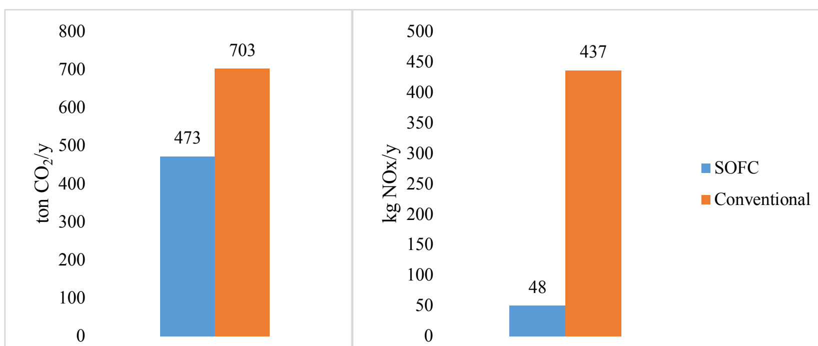

Fig. 12. Comparison between emissions per year from a conventional system and a SOFC system for energy production in a hospital building.

4.1.3. Environmental impact

A comparison is also made between the SOFC and the conventional system in terms of emissions produced for generating the same amount of energy (for the same 150 kW SOFC system in an hospital in UK). Emitted CO_2 from the SOFC system is significantly lower (about 33% less), due to the higher system efficiency (Fig. 12) and the emitted NOx is negligible (about 90% less). It is also important to mention that emissions levels from the SOFC system are detection limit of the instruments used for the analysis: real emissions could be even lower.

The emissions related to the total building (hospital) energy demand are also calculated, comparing the case in which the SOFC is installed with the case in which the energy is totally purchased from the grid. Obviously, pollutants reduction will be lower (in percentage) than in the previous calculation, because now the produced energy form SOFC is only a fraction of the total energy demand, so the impact on the total emissions is less relevant. Reduction in CO_2 and NOx thereby falls to 7% and 14% respectively, that are however 230 ton of CO_2 and 388 kg of NOx avoided per year.

4.2. Subsidies

Both in US and in EU different climate and energy targets have been set in the last years. The objective is to move to a sustainable low-carbon economy, by reducing greenhouse gases emissions and increasing the share of final energy consumption produced by renewable sources, and to improve energy efficiency. Different types of policies were therefore developed to achieve the goals and, in this analysis, three of them are considered:

- Capital investment subsidy: a part of the capital expenditure (system equipment and installation costs) is financed, expressed in € per kW of installed capacity or in percentage of the project cost. It is a refund for a year only.
- Feed in tariffs (FIT): it is a mechanism through which a rate is recognized for all the energy produced and fed into the grid, with renewable or high efficiency energy systems. Rate is expressed in € per kWh of produced electricity, and it is assigned for the years in which the mechanism is applied, depending on the country.
- Energy efficiency certificates: they are tradable securities that certify the energy savings achieved in the final uses of energy, realizing interventions to increase energy efficiency.

Many countries have their own financial package to support energy investments, but there are still not many policies to support fuel cells: more often subsidies exist for generic CHP systems. The model analyses specific subsidies to support SOFC systems, to show the impact on the cost effectiveness, and how they change the results of the cash flow evaluation.

At current economic situation, feed in tariffs seem to be the best option among existent subsidies, but in most cases, they are not enough high to make the SOFC investment profitable. Only UK had a sufficient value to support the installation and obtain a saving over 15 years, but the decree is no longer valid for new installations (it was valid until April 2019).

4.2.1. US cases: Colorado and Minnesota

In US, Congress reinstated Investment Tax Credit (ITC) for fuel cells

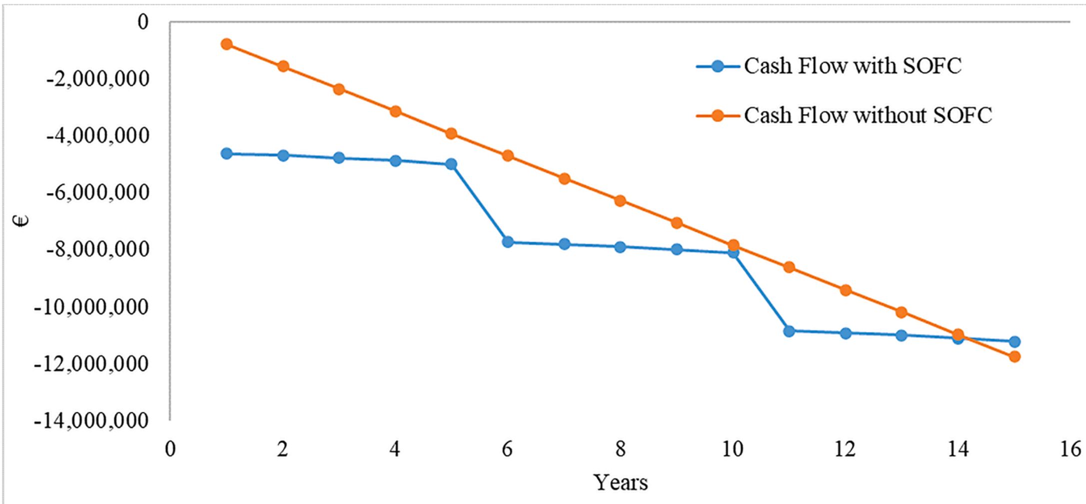

Fig. 13. Cumulative cash flow trend of a conventional and of a SOFC system, with feed-in tariff of 0.10 €/kWh.

for businesses and residential installations [44]. It consists of an economic support for fuel cell systems installed in the US, rated at 500 W or greater, with $\eta_{el} \geq 30\%$. ITC is calculated by taking the lesser of $3,000/kW installed capacity or 30% of project cost [44], because in this analysis SOFC system installation is assumed in 2019. Subsidies effect on the cashflow for an hospital in Colorado is presented. ITC minimum value is obtained by multiplying the installed power (in this case 550 kW, 22 SOFC modules) by 2′679 €/kW (according to rate of exchange 1.12 EUR/USD [45]). ITC amounts to € 1,473,214 and it is given on the first year, to reduce the CAPEX. Existing US subsidies are anyway not enough to have a profitable investment, if we adopt the current cost of SOFC technology in Europe. With subsidies, LCOE has a reduction from 0.26 to 0.23 €/kWh, but the revenues related to the energy savings are never enough to cover the high capital expenditure in 15 years, since manufacturing costs grow with the installed capacity (they are provided in €/kW). Therefore, an energy intensive building leads to a high CAPEX, unaffordable at current costs. US hospitals have in average the highest EI_{el} among analysed countries (Table 1), so if the costs are not enough depreciated, it is not favourable to invest in a SOFC system. Nevertheless, it is important to mention that US subsidies started around 10 years ago and now the cost of stationary FC systems in US is reduced (thanks to the dedicated supporting schemes) and consequently the current ITC is proportional to the cost of the technology in the country. In Europe the FC market is in its early stage and needs a higher support to start the technology deployment on mass scale.

The cash flow would benefit more from a feed-in tariff mechanism: with a subsidy of € 0.10 per kWh of produced electricity, considering a hospital in Colorado, SOFC system would lead to a saving of € 541,892 over 15 years of analysis. RPBT is14.2 years, so SOFC investment is the most profitable after this recovery period. In Fig. 13 the trend of the cumulative cash flows of a conventional and of an SOFC system is shown, considering a 0.10 €/kWh FIT. Blue line changes slope, having a steeper decreasing in some points: this is due to the replacement cost, which affects cash flow only in a few years. Otherwise, when there is no replacement, blue curve decreases less steeply than the orange, because the revenues contribute to save money. Indeed, in the case without SOFC, there are no revenues deriving from the fuel cell production.

The analysis for an SOFC installation in an hotel in Minnesota is also reported. P_{inst} amounts to 100 kW, so the installed SOFC modules are only 4. CAPEX is 5.5 times lower than the hospital case, but again the minimum value for ITC is calculated by multiplying the installed power by 2679 €/kW. Its value is € 267,900, not high enough to sustain the initial investment and to achieve the RPBT in 15 years. In Fig. 14 CCF_{diff} is shown, in both cases, with or without subsidies: this type of economic support is not sufficient to invert the trend of the curve.

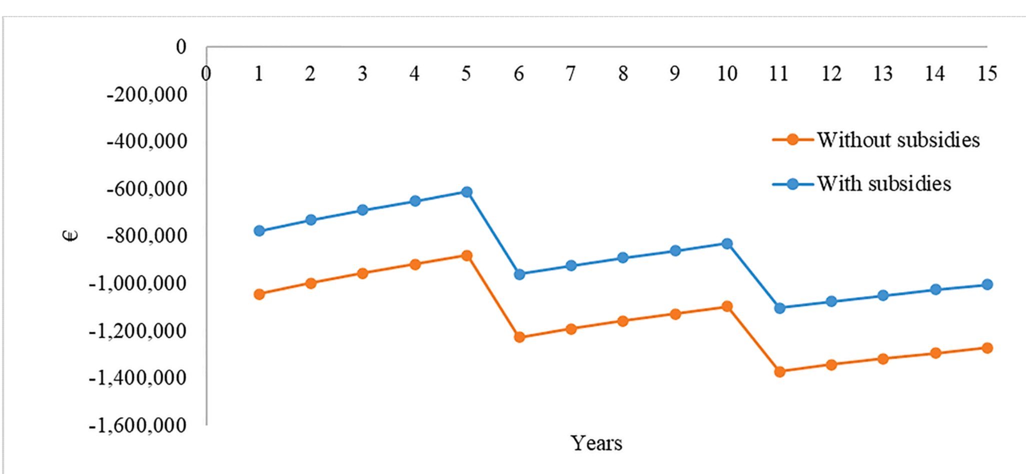

Fig. 14. Comparison of the difference between the cumulative cash flows of a conventional and a SOFC system, with or without existent subsidies (hotel in Minnesota).

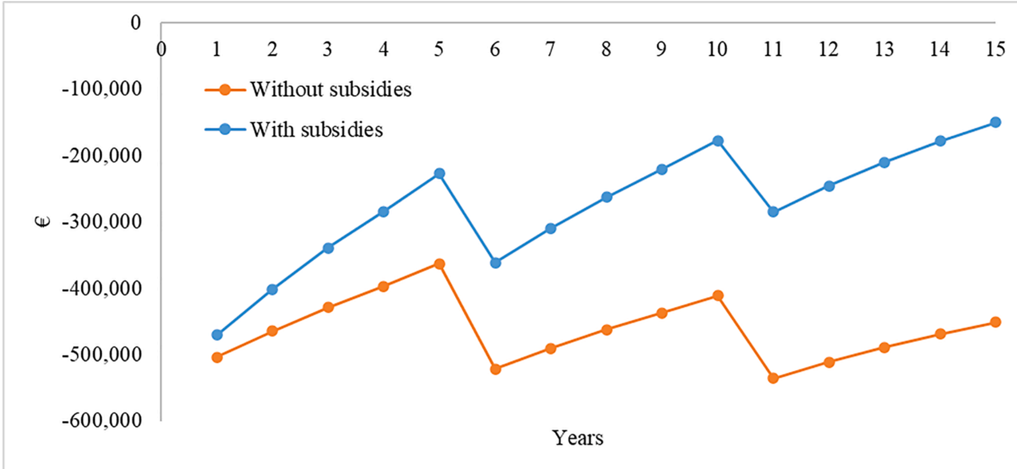

Fig. 15. Comparison of the difference between the cumulative cash flows of a conventional and a SOFC system, with or without existent subsidies (hotel in Germany).

4.2.2. EU cases: Italy and Germany

In Italy high efficiency cogeneration is supported with D.M. 05/09/2011 [46]. For cogeneration units approved as system with high efficiency (CAR- Cogenerazione ad Alto Rendimento), GSE (Gestore dei Servizi Energetici) provides energy efficiency certificates named "*Certificati Bianchi*" or TEE [47]. They are tradable securities that certify the energy savings achieved in the final uses of energy, realizing interventions to increase energy efficiency. For each TOE (Tonne of oil equivalent) of savings, that is 5,327 kWh of electricity or 11,628 kWh of heat, achieved thanks to the implementation of the energy efficiency intervention, a certificate is recognized, for all useful life established by the legislation for each type of project. Each TEE has a value of 260 €/toe (updated in September 2020 [48]), and it can be sold by the owner. Revenue from the sale of the certificate is an incentive to improve efficiency and, together with energy saving, helps to repay the investment to the subject.

Procedure is indicated by GSE [47]: first the cogeneration unit must necessarily achieve a primary energy saving (PES) greater than 10% of the installed capacity for system below 1 MW, and verify the condition of high efficiency ($\eta_{sys} \geq 80\%$). Article 4 of Ministerial Decree 5 September 2011 requires that the cogeneration units be entitled, for each calendar year in which they meet the CAR requirements, to issue the certificates, in a number commensurate with the primary energy savings achieved in the year in question. If positive, it is calculated as follows:

$$\boldsymbol{RISP} = \frac{\boldsymbol{E_{CHP}}}{\boldsymbol{\eta_{Erif}}} + \frac{\boldsymbol{H_{CHP}}}{\boldsymbol{\eta_{Trif}}} - \boldsymbol{F_{CHP}} \tag{37}$$

E_{CHP}: Electricity produced by cogeneration unit.

H_{CHP}: Heat produced by cogeneration unit.

F_{CHP}: Power supply consumed to feed the cogeneration unit.

η_{Erif}: conventional average efficiency of the Italian electricity production park assumed of 46%.

η_{Trif}: conventional average efficiency of the Italian thermal production park assumed of 90%.

Based on the primary energy savings calculated according to the formula described above (RISP), the cogeneration unit is entitled for a specific year to a number of certificates equal to:

$$\boldsymbol{CB} = \boldsymbol{RISP}^{*}0.086^{*}\boldsymbol{K} \tag{38}$$

K is a harmonization coefficient, which varies according to the power of the cogeneration unit. For power below 1 MW is K = 1.4.

The study is here applied to a generic Italian hospital, according to definition done in the previous chapter. It consists of 7 connected modules, which provide $P_{el,rated} = 175$ kW. Every year the system produces in average $E_{el} = 1{,}405{,}485$ kWh (50% of the total electricity demand) and $E_{th} = 926{,}844$ kWh (18% of the total heat demand). PES for SOFC system is 27%, and with a global efficiency $\eta_{sys} = 85\%$, so it is admitted to the procedure to achieve TEE. SOFC-CHP system obtains in average 163 TEE per year: their value on the cash flow is a subsidy of 42,400 €/y. It is a too small percentage (2%) of the annual cash flow to have a great impact on the costs: to achieve the relative payback time over 15 years they need to be 25.6% of the annual cash flow.

Germany is the country, with US and Japan (here the first ever commercialization of a residential fuel cell cogeneration system (CGS), ENE-FARM, was carried out [11,49]), in which there is the highst fuel cell installed power. Indeed, it is the European country where fuel cell policy has been most supportive. In particular the 'Technologieeinführungsprogramm' (TEP) is designed to help and support the installation of fuel cell micro-CHP [50], and there are also programmes with the aim of increasing net electricity production from cogeneration. With cogeneration act [51], feed-in tariffs for electricity production by CHP systems have been established. Their value depends on the power capacity: for systems from 100 kW to 250 kW, € 0.05 are given per kWh of produced electricity. Highest value is 0.08 €/kWh and it is given for small CHP systems up to 50 kW.

An hotel in Germany is here used to verify the applications of the subsidy scheme. A typical Germany hotel is equipped with a 50 kW SOFC-CHP installation. The impact of the subsidies on LCOE is not relevant, but there is a trend change in the cash flow evolution. Results show that the CCF_{diff} is decreasing in the case without subsidies, and it is increasing with the application of feed-in tariffs (see Fig. 15). This change involves the achievement of the relative payback time, which is however reached beyond the analysed period. Necessary subsidies to reach the RPBT in 15 years are calculated: they amount to 0.11 €/kWh, as in the US case. They are 3 cents higher than the current maximum values.

4.3. Technical improvements

Solid oxide fuel cells are already high efficiency systems to produce electricity, and they can reach the highest combined efficiency among all CHP systems. However, many research and development programmes are in progress, to improve technical features and operation, for example with the use of more performing materials to build the stack and other equipment. The generic SOFC model chosen for the analysis is not the best alternative on the market, both in terms of costs and performance, but an average solution representative of the different products available.

This section aims to analyse what are the most effective parameters that can change the assessment on the profitability of the installation of a SOFC-CHP system to feed an hospital (the analysis is here presented only for the hospital case study). Starting from the base case analysed in Scenario 5.1 (UK is the selected country, with 150 kW of installed SOFC system, at current economic conditions), it is studied the evolution of the main techno-economic results, assuming a variation in a meaningful range of four technical features, chosen as the most impacting ones on the economic performance of the system:

- $\eta_{el} = 55 - 65[\%]$
- $\varepsilon_{deg} = 0.2 - 0.5[\%/kh]$
- $Lifetime = 43,000 - 69,000[h]5 - 8years)$
- $Availability = 98 - 99[\%]$

Variation range is reasonable, because the indicated values are associated to SOFC modules already available on the market [52]. For convenience of representation, only the evolution of the main results is shown. They are:

- LCOE [€/kWh]
- Gas_{input} cost over 15 years [€]
- E_{el} produced over 15 years [kWh]
- CCF_{diff} [€]

Each outcome is more sensible to specific parameters, so results are presented varying them one at a time. It is important to mention that in current conditions some improvements may not seem effective because of the high CAPEX which hides the benefits. For this reason, yearly savings in absolute terms for the UK hospital have been also calculated and here reported. The figures related to the technical improvements' evaluation are available in Appendix B (Figure B1, B2 and B3 which are referred to electrical efficiency, degradation rate and lifetime respectively).

4.3.1. Electrical efficiency

Variation of electric efficiency of 10% is examined: increasing η_{el}, there is a linear decreasing of LCOE and gas costs and an increasing of CCF_{diff}. Instead, produced electricity is unchanged: if the module works with a higher efficiency, obviously it needs less methane to produce the same energy (Eq.13). Consequently, less input gas means fewer annual costs, that are significantly lower than the base case, about −15% over 15 years. With a more efficient module, potential saving of € 150,000 per year can be achieved, with a reduction of 72 tonnes of CO_2 emitted per year, 1,080 tonnes over the entire period of analysis. LCOE is reduced of 3% and CCF_{diff} increases of 1%: in the current economic conditions, relative payback time is anyway not achieved.

4.3.2. Degradation rate

The degradation rate ε_{deg} involves the reduction of electricity produced with the working hours: with the use of innovative and more performing materials to build the module, its value may be reduced, improving the overall producibility of the system. It is assumed a variation range of the P_{el} per 1000 h between 0.5 and 0.2%. This enhancement has not a relevant effect on the results: there is a negligible variation of gas costs, lower than 0.1%, and an increase of the produced electricity of 4.1%. LCOE is reduced by 1%, so it is 0.26 €/kWh with the lowest degradation rate. CCF_{diff} shows an increase of about 5.6%, but it is still negative. The saving in this case is equal to € 76,700 per year.

4.3.3. Technical lifetime

The chosen baseline SOFC model has a technical lifetime of 43,000 h (see Table 3). Considering 98% of availability, system works 8584 h per year, so the replacement of the module is necessary after around 5 years of operation. In the base case it occurs 2 times, in the 6th and in the 11th years, each time with a k_{rep} equal to 735,000€. If the technical lifetime increases, SOFC system can work for more years, and consequently fewer replacements are needed in 15 years. It is considered a variation range from 43,000 to 69,000 h: the upper end is expressly chosen to study a case in which the replacement takes place only once in the lifetime, in the 9th year. Indeed, in the scenario in which the module can work for 8 years, LCOE decreases to 0.24 €/kWh (13% reduction). The percentage variation of the CCF_{diff} compared to the base case in which the module can work for 43,000 h is evaluated: results show that for each additional year of operation, there is a progressively greater increase of the CCF_{diff}, which is 50% higher with an 8 years' module. In this new scenario, RPBT is still far, but trend is positive and tends to the break-even point, where the CCF_{diff} is zero.

Table 12
Reduction of necessary subsidies to achieve RPBT, at current costs, using the best performing module.

Country	Base case module Necessary subsidies [€/kWh]	Best performing module Necessary subsidies [€/kWh]	Reduction [%]
Germany	0.10	0.05	− 50
Italy	0.09	0.05	− 44.4
UK	0.08	0.05	− 37.5
USA	0.10	0.07	− 30

4.3.4. Availability

The impact of the availability on the results is also evaluated. With 99% of availability, the module works for 8672 h per year, increasing its electricity and heat production, but needing more methane in input than in the base case. So, there is no evident difference on the cash flow, because the higher revenues related to the energy production are counterbalanced by the higher costs to purchase the gas. Also LCOE is not affected by relevant changes. All variations are less than 1%, so an increase in the availability to 99% is not really effective (current availability of 98% is already optimal for the application).

4.3.5. Best performing module

The analysis on the best performing module has been applied to the UK hospital (150 kW) analyzed before: it has the same technical specifications as the SOFC module, except for electric efficiency, degradation rate and technical lifetime. The improvement in these parameters is shown:

- $\eta_{el} = 65[\%]$
- $\varepsilon_{deg} = 0.2[\%/kh]$
- $Lifetime = 69,000[h]$

There is a relevant difference in the results compared to the base case. Indeed, at current prices and considering a feed-in tariff of 0.05 €/kWh (like the one already present in Germany, [51]), RPBT is achieved in three countries:

- Germany: 14 years
- Italy: 14 years
- UK: 12 years

With the module used in the base case it was never achievable with a subsidy of only 0.05 €/kWh, but it was needed a higher support (0.10 €/kWh for Germany, 0.09 €/kWh for Italy and 0.08 €/kWh for UK). In addition, 0.08 €/kWh would be enough to reach the RPBT in the 7th year for UK and in the 8th both for Germany and Italy. Also for US it is possible to achieve the RPBT with a more performing module over 15 years, but it takes a minimum subsidy of 0.07 €/kWh. With the base module it was reached with a 0.10 €/kWh feed-in tariff: if the same tariff is applied with the new module, relative payback time is in the 8th year. All results are shown in Table 12.

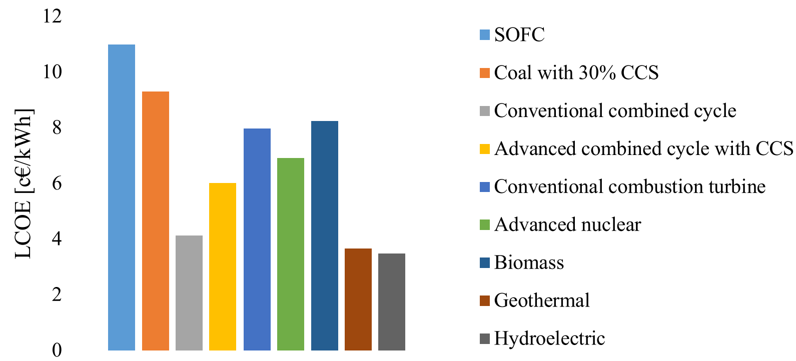

Fig. 16. LCOE comparison between different technologies at target costs (3000 €/kW).

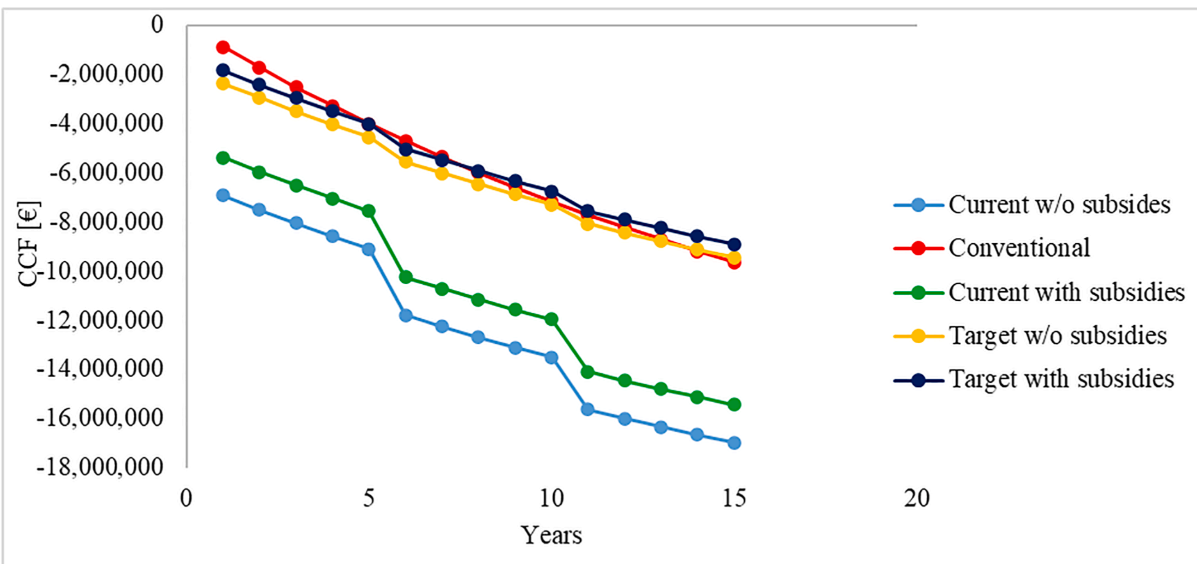

Fig. 17. Cumulative cash flow comparison between SOFC and conventional system in different costs scenarios.

4.4. *Target costs scenario*

If the development in the SOFC market will confirm the projections, there will be a growing in the sales volume per manufacturer, and a consequent decrease in manufacturing and operational costs.

Considering the target prices provided by the companies' market forecasts, a cost reduction of about 70% is achievable (see target costs in Table 3). With an investment cost of 3,000 €/kW, LCOE has a significant drop to 0.11 €/kWh (average value among all analysed countries). Comparison with other technologies is shown in Fig. 16: at target costs, SOFC-CHP system may be a good option for the electricity production, especially in countries with a high spark spread.

The analysis is conducted in current currency, to include expected effects of inflation on investment and expenses, and it approximates more closely future cash flows. However, the cheapest option does not change if constant or current analysis is used. Discount rate $d = 7\%$ [42] and inflation rate $i = 2\%$ are assumed: chosen i is an average value between various countries, updated in May 2019 [53].

Comparison between current and target results are shown in detail for two hospitals (results are very similar in the case of hotels), one for US (Minnesota), and one for EU (Germany). Typical base load consumption is indeed different between European and US buildings, so this choice was made in order to analyse the effect of the cost reduction in two different SOFC sizes. Minnesota hospital is one of the most energy-intensive, instead Germany hospital requires the minimum amount of energy among all locations.

4.4.1. *US – Minnesota*

Minnesota hospital needs an installation of 23 modules to satisfy the base load ($P_{el,rated} = 575$ kW), that is well above the installed power for a European health centre (UK has $P_{el,rated} = 150$ kW. Due to the large number of installed modules, there is a great CAPEX, that amounts to € 6,319,250 at current costs, and an expenditure of input gas of € 230,000 per year. Since the SOFC system covers only 55% of electricity demand and 58% of heat, the revenues are not as high as to sustain the huge costs, and consequently each year there is a greater expense. Over 15 years, making a comparison with a conventional system, there is a CCF_{diff} = -7,339,063 €: at current costs, SOFC system is the most expensive, and the investment cannot achieve the RPBT. Indeed, in Fig. 17 it is shown the trend of the cumulative cash flows of two current costs, with and without subsidies (blue and green curves): after each replacement, the curves diverge more and more, and so it is not possible to reach the RPBT (it corresponds to the year in which the curves meet). Even applying the existent subsidies for US, the RPBT is never achieved at current costs. Assuming a target price of 3000 €/kW, results are completely different: relative payback time is in the 14th year (yellow curve), and over 15 years there is a total saving of € 208,000 by installing a SOFC system. The costs reduction therefore leads to a difference (in absolute terms) of € 7,500,000 when compared to the current costs scenario. If existent subsidies were also applied, the RPBT would be

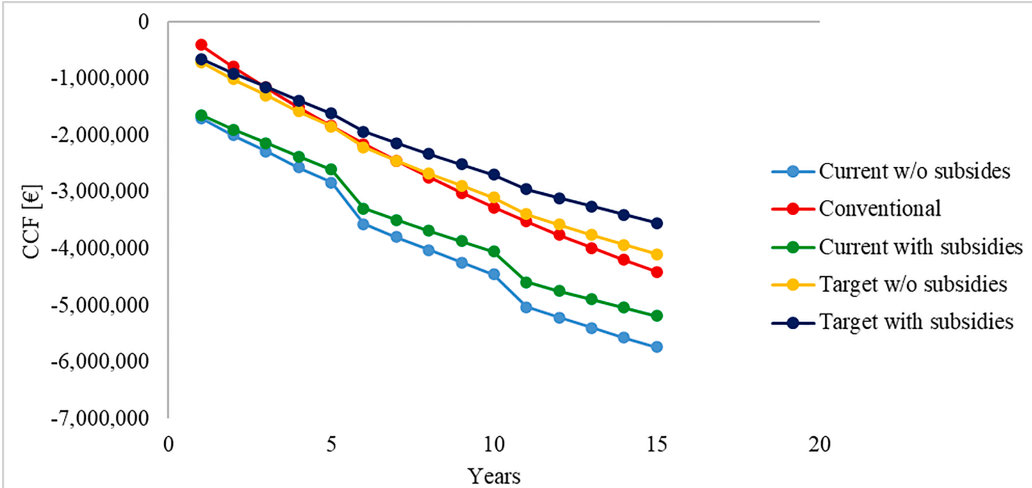

Fig. 18. Cumulative cash flow comparison between SOFC and conventional system, at target costs.

achieved in the 5th year (light blue curve): it is shown the point where the curves meet for the first time, and their diverging trend, that leads the light blue curve higher and higher than the red one.

4.4.2. EU – Germany

At current costs, investment is not convenient, and also with the aid of current feed-in tariffs the RPBT is never achieved (see Fig. 18). Instead, in the target scenario, SOFC system becomes the best alternative: RPBT is reached in 5 years only (yellow curve), and if the existent subsidies are applied, it is in the 3rd year, with a saving of €864,024 over 15 years. Indeed, considering an investment of 3,000 €/kW, CAPEX falls to €383,750, and replacement cost to €150,000. k_{rep} now does not have much influence on the cash flow, because it constitutes only 35% of the average CF, and therefore it does not affect too much the slope of the curve. Comparing blue curves in Figs. 17 and 18 it is evident that in the points in which the replacement takes place, there is a gradual reduction of the slope: k_{rep} , indeed, is progressively decreasing, from the current price for Minnesota (highest) to the target price for Germany (lowest). In the first graph, where replacement cost is maximum, blue curve shows the steepest gradient.

4.5. Comparative results

There are countries more indicated than others for the SOFC-CHP investment in the short-to-medium term. This is due to the base load profile (which may be particularly or less suitable to be satisfied by the SOFC), to the energy prices and to the presence of subsidies and policies to support the investment. A comparison is made between all the studied locations, and the different results obtained are analysed to show in which countries the investment in SOFC-CHP technology could be more effective.

4.5.1. Levelized Cost of Electricity (LCOE)

If in a country LCOE is lower than the electricity price, it means that investing in the technology in that country is more profitable than purchasing energy from the grid. At target costs, for hospitals, LCOE from SOFC is lower than the electricity price in Germany, Italy and UK (without subsidies): they are indeed the most attractive markets where to install the SOFC system, also due to the high electricity price. If existent subsidies are applied (it is supposed the German feed-in tariff, 0.05 €/kWh, where there are no existent subsidies), LCOE has a greater reduction: also Colorado becomes an interesting market, because LCOE is lower or very close to the electricity price. Value for each country, with or without subsidies, is compared with the electricity price of the location in Fig. 19.

For hotels, without subsidies, at target costs the LCOE is higher than the electricity price in every country (Fig. 20). It means that, at target price, higher than existent subsidies are anyway necessary to make the investment profitable: only Germany could achieve RPBT before 15 years.

4.5.2. Relative payback time (RPBT)

CAPEX and the consequent k_{rep} are the most impacting costs on the cumulative cash flow. With a reduction of 70%, that leads to a cost of 3000 €/kW, it is therefore possible to achieve the relative payback time for six hospitals out of seven, without the provision of subsidies, over 15 years (Table 13). UK, Germany and Italy achieve RPBT in a shorter time than the other countries, and even without any subsidies it is possible to

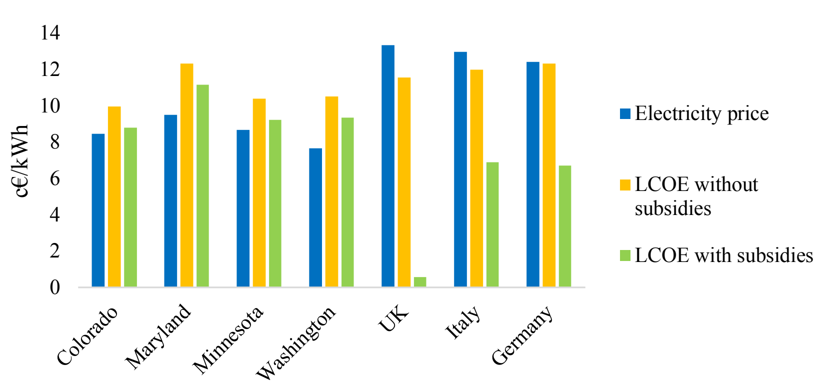

Fig. 19. LCOE comparison between various locations, at target costs, with or without subsidies applied (hospitals).

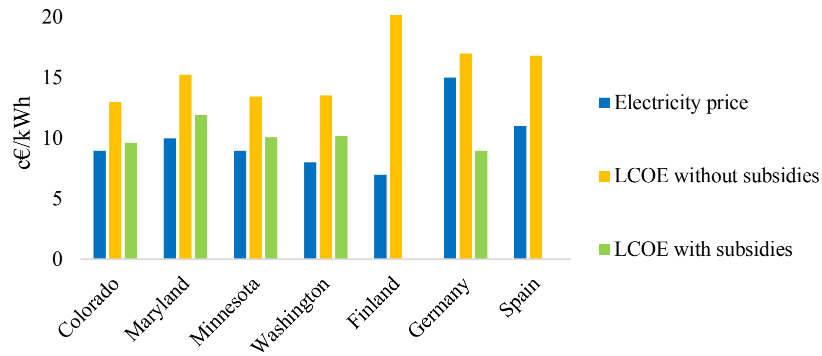

Fig. 20. LCOE comparison between various locations, at target costs, with or without subsidies applied (hotels).

Table 13
RPBT achieved at target costs, without subsidies applied.

Country	RPBT [y]
Colorado	13
Germany	5
Italy	5
Maryland	15
Minnesota	15
UK	4

Table 14
Necessary subsidies to achieve RPBT in 5 years at target costs.

Country	Percentage on CAPEX [%]	Feed-in tariffs [€/kWh]	Energy efficiency certificates [€/toe]
Colorado	31	0.03	30
Maryland	37	0.04	30
Minnesota	31	0.03	30
Washington	44	0.04	90

have higher profitability than a conventional system in 5 years at most. Instead, the only hotel that achieves RPBT is the German one (9 years).

It is calculated the effect of different typologies of subsidies on all locations, to study what their value should be to reach the RPBT in 5 years, at target costs, for all types of policies analysed in Chapter 6 (Germany, Italy and UK are not reported, because they achieve it even without subsidies). Results are shown in Table 14: feed-in tariffs appear to be the most suitable option for supporting the installation of SOFC systems in the commercial sector.

4.5.3. Spark spread

If spark spread is higher, the revenues related to the energy production are higher, and the gas input costs are lower, so the RPBT is achieved in less time, for the same CAPEX and replacement cost. RPBT dependence from the spark spread, for countries in which it is achieved (at target costs), is shown in Fig. 21: where *SS* is higher, RPBT is lower (for Germany, Italy and UK). Despite Italy and UK have the same SS, the relative payback time is different, because UK load profile is more suitable and allows higher savings of money in the analysed period.

4.6. Market potential

Considering the average EI_{el} and EI_{gas} and the number of hospital in Europe and US, the potential SOFC capacity that could be installed in each analysed country has been calculated, together with the related impact on their hospital sector. The potential is evaluated by multiplying the SOFC installed capacity necessary for a typical hospital by the number of hospitals of each nation. Results, with corresponding LCOE at target costs without subsidies, are shown in Table 15: for US, the average values between the four studied countries were chosen.

Total potential installed power is almost 5000 MW: health centres are indeed among the most energy-intensive buildings, and their base load consumption is much higher than other typical commercial facilities. Therefore, the installation of a SOFC-CHP system to supply them could have an effective impact on the entire national buildings sector.

Data for hotels are reported in Table 16: US market is not analysed due to the absence of information in literature about the number of hotels, but it can play an important role thanks to its dimension

Table 15
Market potential of installed capacity for the hospital sector.

Country	Number of hospitals	Potential capacity [MW]	LCOE [€/MWh]
Germany	3,138 [24]	392	124
Italy	1,135 [24]	199	120
UK	522 [54]	78	116
US	6,210 [25]	3,664	105

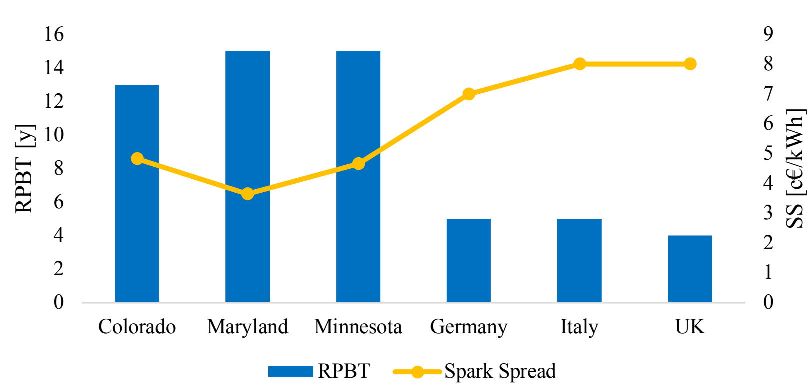

Fig. 21. Dependence between relative payback time and spark spread at target costs, without subsidies applied.

Table 16
Market potential of installed capacity for the hotel sector.

Country	Number of hotels	Potential capacity [MW]	LCOE [€/MWh]
Finland	794 [32]	397	202
Germany	32′182 [32]	5,630	120
Spain	19′683 [32]	2,950	116

compared to other locations.

5. Conclusions

This work is focused on the techno-economic analysis of SOFC-CHP systems used to feed the base load consumption of non-residential buildings, with focus on the hotel and hospital sector. The evaluation is based on technical specifications of commercially available SOFC systems (data from manufacturers) and real energy consumption profiles from existing hospitals and hotels. The primary novelty of this work is indeed related to the use of reliable input data: hourly load consumption for the buildings and technical input data from the operation of SOFC systems in real environments.

The study has been carried out by means of an Excel tool, able to perform the analysis in different configurations: the user can indeed choose the country for the installations, the current or target performance and costs for the SOFC system (two scenarios have been analyzed) and the availability of incentives to support the investment (supporting schemes).

The SOFC system sizing is performed in order to match its electricity and thermal production with the base load of the real existing building hour by hour; then, the savings related to the installation of the SOFC, both in environmental and economic terms, are evaluated. The analysis is not focused on a single case study and provides results for buildings with higher or lower base load consumptions, considering also the different energy prices related to the geographical location.

Results demonstrate that the exploitation of this technology on a commercial scale could lead to great advantages, but with some remarks. Indeed, there is not yet a fully developed market, and the current SOFC costs make this technology not already competitive with other solutions in the energy production (until dedicated incentives will be issued). The key results are summarized below.

At current costs (around 11,000 €/kW) and level of technology, SOFC-CHP is economically more convenient, compared to a conventional system, only with the provision of subsidies in the form of feed-in tariff, greater than or equal to 0.09 € per kWh of electricity produced, and in countries with a spark spread near to 0.07 €, as Germany, Italy and UK.

Germany, Italy and UK seem to be the most suitable markets for this technology, also due to the high share of CHP in their national energy production, and to the presence of several policies to sustain the installation of high efficiency and low pollutant CHP energy systems (already existing supporting schemes for cogeneration units). However, only UK had a sufficient feed-in tariff (0.11 €/kWh) to achieve the relative payback time, at current costs, in the 10th year. Installation costs for US are instead too high to reach RPBT with existent subsidies (given as incentives on the investment: € 2679 per kW of installed power), due to the very high CAPEX, which accounts for more than € 6 million in the hospital case.

However, if the technology will achieve a target installation cost of 3,000 €/kW, and a consequent LCOE of 0.11 €/kWh, SOFC-CHP systems will become one of the main and most attractive solutions to produce energy, because of their higher combined efficiency (90%) and lower environmental impact, compared to current energy systems for stationary production. Indeed, even without any subsidies, relative payback time would be achieved, at target costs for hospitals, in all analysed countries except Washington, with RPBT of 5 years in Italy and Germany and 4 years in UK. Furthermore, with a 0.05 €/kWh feed-in tariff, like the one already existing in Germany, at target costs, RPBT would be reached before or during the 5th year, for all buildings.

Technical improvements in the electric efficiency and lifetime (module with 8 years of durability), would lead to relevant savings: with only one necessary replacement over 15 years it is possible to save up to € 1 million in EU countries, and about € 3 million in US. They would involve, at target costs, a reduction up to 7 years of the relative payback time (higher reduction in US countries, due to the higher installed power) and of CO_2 emissions (-15%, 73 tons avoided per year, compared to the current SOFC module analyzed).

Future works could be focused on expanding the countries of the analysis, in order to achieve a broader overview of interesting markets where the SOFC-CHP systems could be installed. Furthermore, ongoing works are based on the deep market knowledge, trying to understand better how the non-residential building is composed and how it depends on the building features. A multi-year sensitivity analysis, similar to the one developed by Jahangir et al. in [55] could also be implemented to increase the model potentiality.

CRediT authorship contribution statement

F. Accurso: Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **M. Gandiglio:** Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **M. Santarelli:** Conceptualization, Supervision, Validation, Visualization. **J Buunk:** Conceptualization, Validation, Visualization. **T. Hakala:** Validation, Visualization. **J. Kiviaho:** Funding acquisition, Validation, Visualization. **S. Modena:** Validation, Visualization. **M. Münch:** Validation, Visualization. **E. Varkaraki:** Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. Appendix A

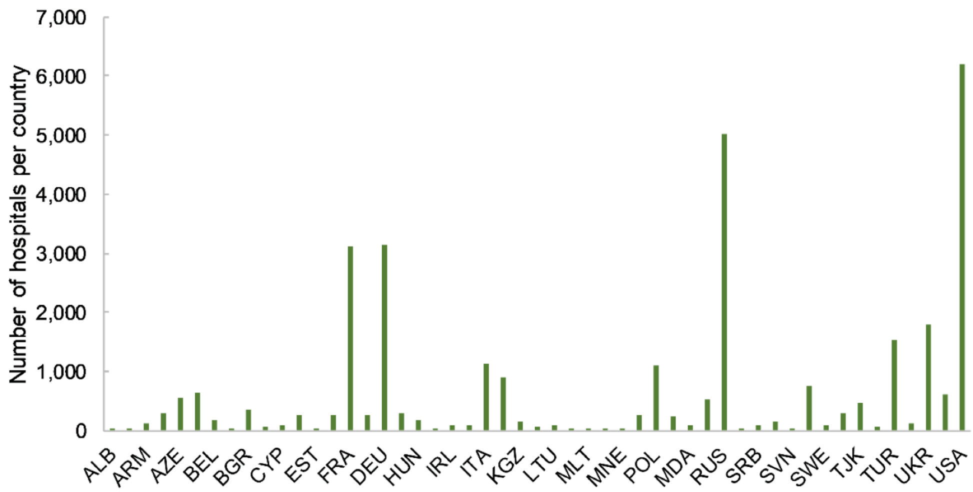

Fig. A1. Number of hospitals per country.

7. Appendix B

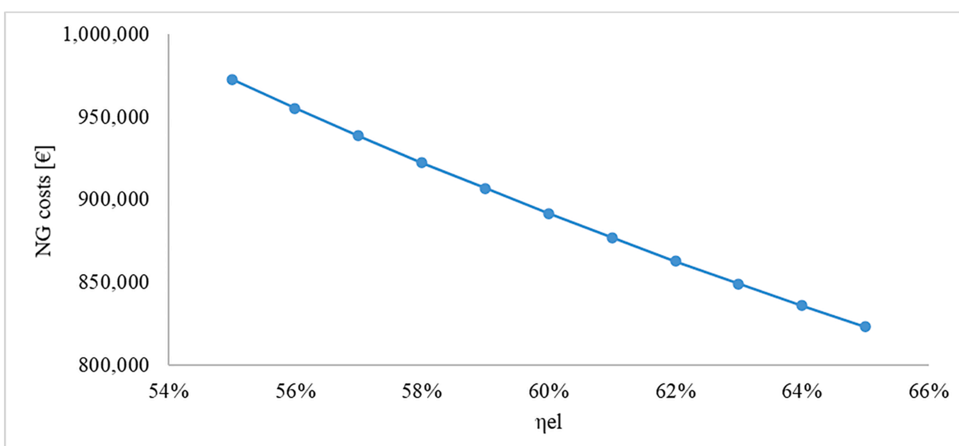

Fig. B1. Linear decrease of gas costs with increasing electric efficiency.

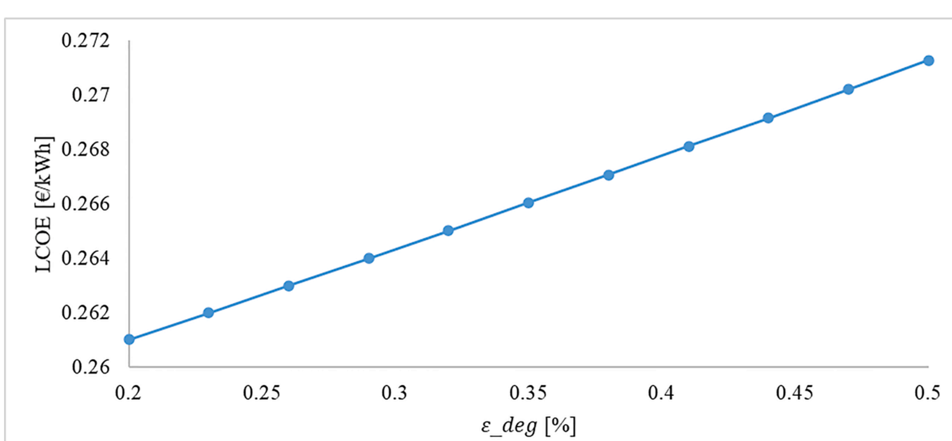

Fig. B2. LCOE variation with degradation rate.

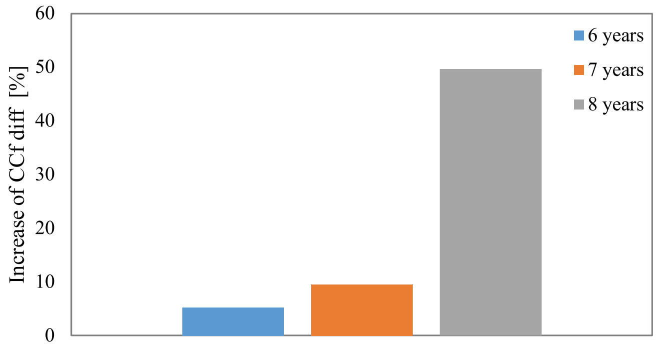

Fig. B3. Percentage increase of the CCF with the technical lifetime of the SOFC (compared to the baseline 5 years lifetime).

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