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A Viability Study for SOFC Combined Heat and Power Energy Systems for Buildings

MEMÒRIA

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Summary

The main objective of this work is to develop a software tool to perform an techno-economic feasibility analysis of cogeneration systems for electricity and heat production, based on fuel cell technology (FC-CHP). The software tool should provide useful information to the decision makers. Moreover, the developed software will be applied to specific case studies to obtain the main indicators of the economic viability of the system. A FC-CHP system is a technology with potential to change the current paradigm, which consists in obtaining electricity from the power grid and, separately, heat through gas boilers.

The method developed in this study allows to carry out a viability analysis over a specific time horizon, based on technical and economic parameters, to size the FC-CHP system and to adapt the calculations to the market conditions of each case study. It is important to consider the market conditions, because the previous works found in the literature remark that the viability of the FC-CHP technology depends on specific factors that vary by country and region.

Local economic factors include government policies to support new technologies of distributed generation, that is, generation of electricity at or near where it will be used. Another local factor is the difference in prices between natural gas and electricity ("spark spread"), and the expected evolution of these prices. From the environmental point of view, the composition of the country's power generation mix has influence on the emissions reduction using FC-CHP. The pattern of thermal and electrical energy demand of each specific case also influence, and the relative amount of each one (heat-to-power ratio).

The method developed requires a source of energy consumption data, which can be real or simulated. Special attention has been paid to see the impact of few consumption data in the results. A correction has to be made in the results for those situations when only the aggregate monthly or weekly consumption is available for analysis.

From heat and electricity consumption data, a Matlab/Simulink model is used to calculate the amount of fuel needed so that the SOFC-CHP system can meet the demand, the amount of thermal energy that should be provided by an additional system (a conventional condensing boiler), as well as the electrical energy to be imported or exported from the electricity grid. The annual results are extrapolated to a time horizon of 10 years, to validate the economic viability of the project.

Different operation modes (disconnected or connected to power grid) and operation strategies (heat-driven, power-driven, maximum-driven) of the SOFC-CHP system are analyzed in buildings of the Universitat Politècnica de Catalunya with varied heat-to-power ratios, to determine the strategy that best suits each case.

The results show that the high initial investment is one of the main obstacles to obtain a return on the investment in a reasonable time. However, the cogeneration system is economically viable in some of the studied cases, especially if the building has a heat to power ratio greater than one. The evolution of energy prices also greatly influences in the viability of the project. As for the operation strategies, those following maximum demand and those following electricity demand offer better results than the strategy that follows the thermal demand, because the former cases use the fuel cell throughout the year and can take more advantage of cogeneration.

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Glossary

AFC	Alkaline Fuel Cell
BOP	Balance of Plant
CAPEX	Capital Expenditure
CCHP	Combined Cooling Heat and Power
CHP	Combined Heat and Power
GHG	Greenhouse Gas
H:P	Heat to power demand ratio
kW_e	Kilowatt electrical power output
kW_{th}	Kilowatt Thermal power output
kWh	Kilowatt-hour
HT-PEMFC	High Temperature Polymer Electrolyte Membrane Fuel Cell
LCoE	Levelized Cost of Energy
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
NPV	Net Present Value
OPEX	Operating Expenditure
PBP	Payback Period
SOFC	Solid Oxide Fuel Cell
SR	Steam Reforming
TCO	Total Cost of Ownership

1. Preface

Generation of electrical and thermal energy traditionally relies upon fossil fuels. The use of fossil fuels has resulted in many negative consequences worldwide. Some of these include severe pollution, extensive mining of the world's resources, and struggles to increase political control of countries that have extensive resources. New power sources are needed that are energy efficient, have low pollutant emissions, and have an unlimited supply of energy.

The era of plentiful, cheap and consequence-free energy from fossil fuels is coming to its end. After the first oil crisis in 1973, and with more interest since de beginning of the 1990s with the climate change problem, many countries started to promote the use of combined heat and power systems (CHP) both for institutional and commercial organizations, because of the high efficiency and savings in energy bills. A CHP system consists of several individual components configured as an integrated engineering system to create electricity and useful heat. Always is present a heat recovery subsystem that captures the waste heat using a heat exchanger and allows the use of that energy for heating purposes.

An important constraint when using CHP is that thermal energy cannot be distributed over long distances, and consequently CHP systems must be located close to the demand points. Cogeneration technologies can be applied to residential, commercial and institutional applications, and can be classified according to their prime mover and their energy source, as follows [1]:

- Reciprocating internal combustion engine (ICE) based cogeneration systems.
- Micro-turbine based cogeneration systems;
- Stirling engine (SE) based cogeneration systems; and
- Fuel cell (FC) based cogeneration systems.

Fuel cell systems have gained attention in recent times due to their high efficiencies over a broad range of load profiles, and lower emissions. They can also offer benefits to society as a whole, such as reduced dependency on imported fuel and national CO_2 emissions reductions. National governments may decide to invest with subsidies or regulations to enforce the adoption of this new technology, provided that fuel cells offer a cost-effective route towards these benefits.

At EU level, there is a strong commitment towards decarbonization of the energy sector. This commitment has been reinforced by the COP21 [2] climate agreement. The means for achieve this goal are, mainly, improving energy efficiency and increasing the share of renewable energy. This is where the FC-CHP emerging technology can take its chance.

Studies have shown broad qualitative trends relating the performance and size of a FC-CHP system and the energy demand of the house or non-residential building in which the system is installed. But the results of these studies cannot be extrapolated to another situations and countries, because of the different parameters that intervene in the calculations and that are particular to each country.

Energy consumption habits are different throughout the world, depending on climate zone, year of construction of the building, and its degree of thermal insulation. Demand profiles are not easily transferred from the building stock of one country to another. In addition, the particularities of each country (support policies, energy mix, fuel prices) make that a particular combination of mode of operation of the FC-CHP system (for example, follow the demand for heat) combined with a certain economic incentive (for example feed-in-tariff) does not produce the same return on investment in one country as in another, and the same can be said of the reduction of greenhouse gas (GHG) emissions.

The European market for stationary fuel cells can be divided into three different market segments: residential, commercial and industrial. In terms of commercial buildings, the European fuel cell industry has not yet fully developed products in a medium power range of 5 to 400 kWel [3], which is the range needed in the buildings of the Universitat Politècnica de Catalunya (UPC). But gas-fueled FC-CHPs can potentially supply heat and power to buildings with a connection to the gas grid, offering a beneficial value proposition that can trigger a change of their heating system, and at the same time reduce CO_2 emissions (compared with the current situation of boilers and power grid supply). Emissions of other pollutants like NO_x and SO_x can be virtually eliminated when a FC-CHP system replaces conventional heating technologies.

In regards to the Universitat Politècnica de Catalunya, the "UPC Energy 2020 plan" aims to convert it into a low energy intensity and low-carbon university, in the framework of a sustainable energy society [4]. Among the lines of work of this program is energy efficiency, and also low carbon emissions. The present work can offer relevant information for the replacement of combustion-based systems by the new technology of fuel cells, resulting in lower consumption of primary energy, lower emission of pollutants and greater energy efficiency. The current context is an increase in energy expenditure in 2018 of 14% over the previous year (5.5M€ versus 4.9M€ respectively), due to the growth in consumption and the sharp increase in energy prices in the Spanish market [4][5].

2. Introduction

A fuel cell is an electrochemical device which converts the chemical energy of a fuel and an oxidant into electrical energy in a direct process, with heat and water as by-products and zero or very low harmful emissions. The fuel is typically hydrogen, an alcohol, a hydrocarbon or a substance derived from it, which can be supplied continuously. A fuel cell can generate electricity with no or very little emissions, and operates quietly, without generating noise or vibrations due to the absence of moving parts. Fuel cells can be used in applications with a broad range of electrical power needed, ranging from milliwatts (mW, 10^{-3} watts) to megawatts (MW, 10^{6} watts), thanks to its modular design:

- Transport applications, replacing internal combustion engines (ICEs) or batteries.
- Portable applications for powering consumer devices such as laptops or cell phones.
- Stationary power applications for households or commercial buildings.

Micro-CHP and mini-CHP systems can be thought of as small-scale power stations generating energy in the home or commercial building. They are a special class of distributed generation which can simultaneously meet the demands for heat and electricity. This presents two significant advantages over the traditional reliance on central power stations:

- Electricity has 3.0-3.5 times the economic value of natural gas, so converting low cost gas into high value electricity allows users to reduce their energy bills.
- By capturing ‘waste’ heat, efficiency can rise from 30-50% in central power stations to 70-90%.

One of the general conclusions of the studies in the literature on distributed FC-CHP systems is that they should be installed where the cost of electricity is relatively high and cost of natural gas is relatively low (large "spark-spread"). Costs savings in electricity provide a justification for the investment required to install and operate a distributed power source such as a FC-CHP system, rather than use power from the grid. The costs savings from using FC-CHP must pay off all the capital costs of the technology. However, the viability of the system depends very much on the specific conditions of each particular case.

The benefits inherent in the use of CHP fuel cell technology and distributed generation can be seen in the following figure. The efficiencies are illustrative and will vary depending on the type of system used and the power grid of the country.

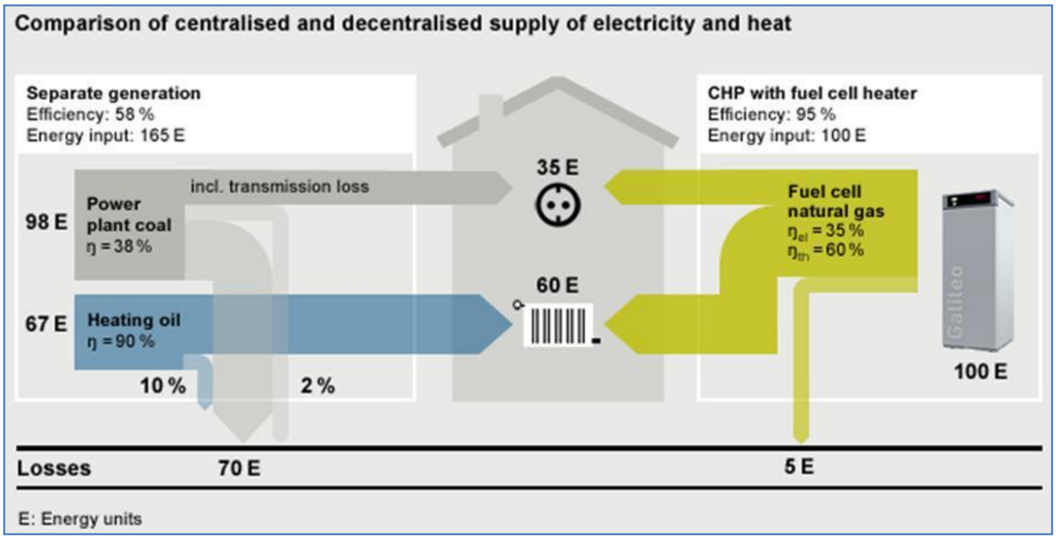


Figure 1.Example of comparison of overall primary energy consumption between centralized supply or on-the-spot FC-CHP, for a given power and heat requirements [6].

2.1. Project Objectives

The work presented here offers a methodology and software for an assessment of economic performance and greenhouse gas (GHG) emissions of a state-of-the-art SOFC-CHP system operating in real buildings with real demand data, in the context of the Spanish energy market.

The primary goal of the methodology is to determine the cases in which a FC-CHP system is competitive with grid-based electricity and conventional heating methods, using techno-economic parameters for the representation of the FC-CHP system and the buildings assessed. Different thermal and electrical energy demands, and different system control strategies of the system are considered.

The economic benchmarking criterion is the Total Cost of Ownership (TCO), that is, the total annual energy costs. Considered costs include initial investment, annualised capital cost, maintenance cost, natural gas and electricity costs necessary to cover the energy demand. Taking the view of the decision maker, the benchmarking thus answers question like: How much money can be saved annually when heating a building and supplying it with electricity using a new technology solution? How much time is needed to recover the investment in that new technology?

The assessment evaluates, over a one-year period, the operational costs and associated CO_2 emissions of a SOFC-CHP system operating under different control strategies, compared to a 'baseline case' of grid electricity and a natural gas boiler. After that, an assessment of a 10-year use-phase is carried out for every strategy.

One secondary goal of the project is to determine the impact of heat-to-power (H:P) demand ratio of the building in the economic feasibility of the system and in the emissions. This is done by applying the aforementioned methodology of techno-economic viability analysis in different buildings of the UPC, each one with a different heat-to-power ratio. With the information of the annual energy demand of the buildings, the current costs for the supply of electricity and natural gas will be calculated, and compared with the costs of satisfying the demand with a state-of-the-art SOFC-CHP system.

Another goal is to determine the effect of the amount of data available on the model results. The optimal situation is to have real data with the highest frequency possible (for example every 15 minutes). However, sometimes only aggregated data will be available: daily, weekly or monthly demand or consumption of energy. In those cases, it will be necessary to apply a correction to the results of the model, to adequately estimate the costs of the system.

2.2. Scope of the Project

A bibliographic research is carried out in order to have sufficient knowledge of the state-of-the-art of the technology, with a comprehensive study on the operation of fuel cells and the systems of cogeneration. Economic assessments on FC-CHP systems are reviewed in order to gather information for initial investment and maintenance costs of the technology.

The tasks to be performed in the project are listed below:

- Selection of the buildings to analyse, with different average heat-to-power ratio.
- Compilation of the consumption data of electrical and thermal energy of the selected buildings. Review and debugging of data.
- Sizing of the fuel cell to be installed in each case.
- Determination of the costs of electricity and gas supply in the current situation (baseline case).
- Determination of the investment, maintenance and operation costs of the SOFC-CHP system for each case.
- Determination of the costs of supplying natural gas (and electricity if needed) with the SOFC-CHP system for each case, according to the chosen control strategy.
- Projection of operating cash flow for 10-years use-phase and calculation of the payback period.

Chapter 3 is a review of the technology of fuel cells, with a summary of the state of the art for the generation of electricity and heat through solid oxide fuel cells (SOFC).

Chapter 4 explains the methodology used to perform the analysis, details the parameters of the techno-economic model, and explains the tool that has been created using Matlab/Simulink to calculate the annual costs of supplies to cover the energy demand of each of the buildings analyzed and the 10-year projection model to simulate the costs of the use-phase.

Chapter 5 details the case studies and the data of the buildings selected for the analysis, and analyzes the demand curves and their variation throughout the year, as well as the influence of the amount of data available in mentioned curves.

Chapters 6 and 7 explain the different fuel cell operating strategies that will be considered in the analysis, and the results are compared to determine the cash flow in each case study and the payback period expected. The effect of the sampling time of the data on the results returned by the model is also discussed.

Finally, the results of the analysis are summarized in the conclusions chapter, and from the results obtained, proposals are made to improve the viability of FC-CHP technology.

3. State of the art for CHP generation with SOFC

3.1. Introduction to FC-CHP systems

The definition of "Combined Heat and Power energy technology" (CHP) is the sequential or simultaneous generation of multiple forms of useful energy, usually electrical and thermal, in a single and integrated system. The total efficiency of a CHP system can be defined as the ratio of the sum of the net power and useful thermal energy divided by the total energy of the consumed fuel. CHP systems can achieve efficiencies of 85-90% combining the electrical and thermal efficiency, which is much higher than the efficiency of the electrical and thermal system taken separately. Thus, the amount of wasted energy can be reduced almost by half, while significantly reducing emissions produced per kWh [1].

A Fuel Cell CHP system (FC-CHP) consists of three primary subsystems: the fuel cell stack, the fuel processor and the power conditioning system. The fuel processor converts the fuel, for instance natural gas or methanol, into a hydrogen-rich feed stream that is supplied to the fuel cell stack, which in turn generates electrical and thermal energy. The power conditioning system is used to convert the power generated by the stack as DC voltage into a form of electrical power useful for the end user.

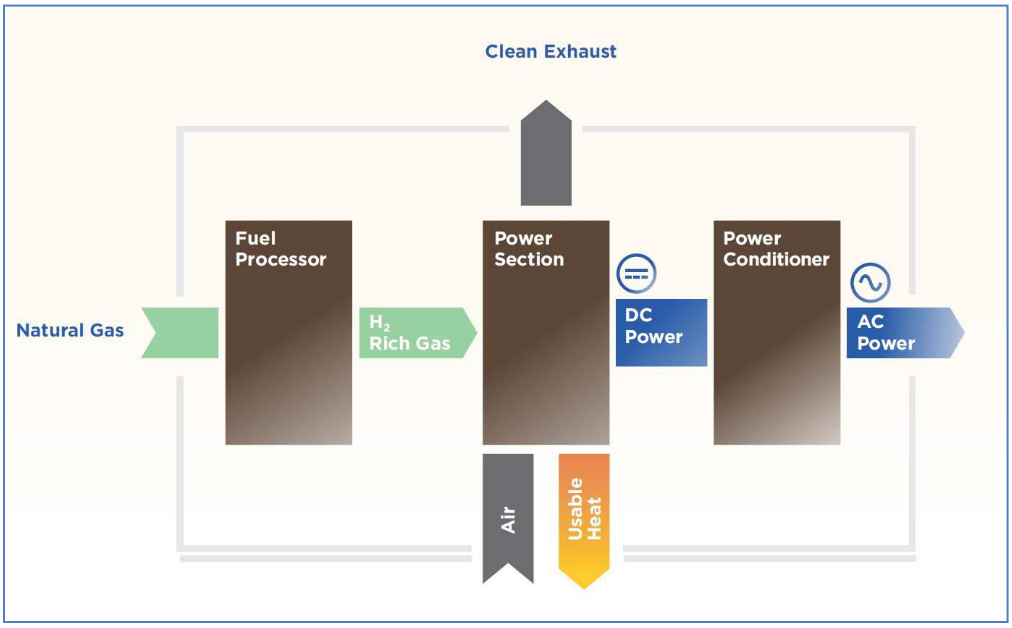


Figure 2. Sketch of the core components (the fuel cell module) of a typical FC-CHP unit. The input is natural gas and air; the output is heat, AC power and clean exhaust. [7]

Although fuel cells can be classified according to different criteria, the most commonly used classification is according to the electrolyte used:

- Alkaline fuel cells (AFC).
- Polymer Electrolyte Membrane fuel cells (PEMFC), which can be divided in low-temperature (LT-PEMFC) and high-temperature ones (HT-PEMFC).
- Phosphoric Acid fuel cells (FAFC).
- Molten Carbonate fuel cells (MCFC).
- Solid Oxide fuel cells (SOFC).

The following table shows a summary of the characteristics of the different fuel cell types.

Table 1. Summary of major differences of the fuel cell types. [8]

	PEFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Hydrated Polymeric Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide in asbestos matrix	Immobilized Liquid Phosphoric Acid in SiC	Immobilized Liquid Molten Carbonate in $LiAlO_2$	Perovskites (Ceramics)
Electrodes	Carbon	Transition metals	Carbon	Nickel and Nickel Oxide	Perovskite and perovskite / metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carbon or metal	Metal	Graphite	Stainless steel or Nickel	Nickel, ceramic, or steel
Operating Temperature	40 – 80 °C	65°C – 220 °C	205 °C	650 °C	600-1000 °C
Charge Carrier	H^+	OH^-	H^+	$CO3^=$	$O^=$
External Reformer for hydrocarbon fuels	Yes	Yes	Yes	No, for some fuels	No, for some fuels and cell designs
External shift conversion of CO to hydrogen	Yes, plus purification to remove trace CO	Yes, plus purification to remove CO and CO_2	Yes	No	No
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless-based	Ceramic
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Liquid Cooling Medium	Process Gas + Electrolyte Circulation	Process Gas + Liquid cooling medium or steam generation	Internal Reforming + Process Gas	Internal Reforming + Process Gas

LT-PEMFCs show promising potential in the CHP market because of their low temperature operation and high efficiency. LT-PEMFCs operate at temperature of up to 80°C and produce low-quality heat that is recovered in the form of hot water, that can be used for low temperature applications such as space/water heating in hospitals, universities or commercial buildings. On the other hand, HT-PEMFC have the advantage of operating at higher temperatures above 100°C, thus with no liquid water present in the system, making water management within the stack much easier.

SOFCs typically operate in the range 500-1000°C and ceramic material is used in the Membrane Electrode Assembly (MEA) instead of metal oxides. The operating temperature allow the use of nickel as a catalyst, instead of using expensive precious metals (as is the case with PEMFCs), and also produces high-quality heat that can be recovered in the form of steam (up to 10 bar).

The next paragraphs will go into the details of solid oxide fuel cells, which is the technology used for the present work, as it seems to be the one that best suits the demand for electrical and thermal energy for residential or commercial buildings. Apart from the fact that they have a higher quality and more usable exhaust heat, many commercial developers believe that the future market of FC-CHP will have an increasing share of SOFC systems due to lower capital costs, as they do not need to use expensive platinum catalysts such as PEMFC, and can be fueled directly with natural gas, with fuel reformation occurring directly on the anode. There are currently companies throughout the world working on the development and commercialization of SOFC fuel cells, ranging from small-scale applications for distributed and domestic generation, to industrial-scale power plants based on natural gas. The reader can find detailed information in [6].

A SOFC consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte which is a solid oxide. Its high operating temperature make SOFCs suitable for CHP applications, recovering and using the heat generated as a by-product of the generation of electricity.

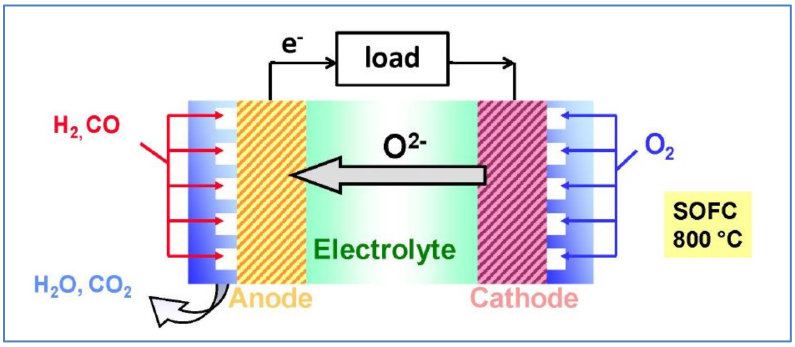


Figure 3.Solid Oxide Fuel Cell. [9]

Different system layout options exist to meet the technical requirements of specific applications as well as the cost targets for market entry. Main distinguishing features are the method of processing natural gas into a hydrogen-rich reformate (i.e. partial oxidation vs. steam reforming) and the cell stack technology used. As a result, electrical efficiencies, system complexity, and costs vary [9].The high operating temperature of SOFCs allows internal reforming of gaseous fuel and raises rapid kinetics to produce high quality heat for energy conversion. There are also some disadvantages of this technology, as for example the fact that because of the high operating temperature, long waiting times for heat up and cool down cycles are required in order to minimize the structural stresses caused by the expansion and contraction of materials in the cell, which expand and contract at different rates [10].

FC-CHP systems achieve higher overall efficiencies than other available CHP technologies at small scale power range. So, FC-CHP can be used in the commercial/industrial sector which requires a high power range (typically between 200 kW and 2.8 MW) as well as in the residential and small commercial sectors which demand lower power ranges, typically <10 kW. The following table shows a comparison of the different types of fuel cells, where the high efficiency of SOFC fuel cells can be appreciated, as well as the high working temperature, which favors the utilization of residual heat.

Table 2.Fuel Cell CHP systems classification based on power range.[1]

Power range	MW class	Sub-MW class		Micro CHP	
FC type	MCFC	PAFC	SOFC	PEMFC	SOFC
Electrical capacity	300 kW–2.8 MW	400 kW	up to 200 kW	<10 kW	
Operating temperature (°C)	600–700	160–220	700–1000	60–80[a] 100–200[b]	700–1000
Electrolyte	Li_2CO_3/K_2CO_3 materials stabilized in an alumina based matrix	100% phosphoric acid stabilized in an SiC based matrix	ZrO_2 supported ceramic electrolytes	Polymer membrane Nafion®[a] PBI[b]	ZrO_2 supported ceramic electrolytes
Typical application	Utilities, large universities, industrial-baseload	Commercial buildings-baseload	Commercial buildings-baseload	Residential and small commercial	
Fuel source	Natural gas, biogas, others	Natural gas	Natural gas	Natural gas	
Fuel compatibility	H_2, CH_4 (internal reformer)	H_2 (external reformer)	H_2, CH_4, CO (internal reformer)	H_2, methanol or ethanol (external reformer)	H_2, CH_4, CO (internal reformer)
Oxidant	O_2/CO_2/air	O_2/air	O_2/air	O_2/air	
Advantages	High efficiency, scalable, fuel flexible	High cogeneration efficiency	High efficiency	System availability > 97%	
Electrical efficiency	43–47%	40–42%	50–60%	25–35%	45–55%
CHP efficiency	85%	85–90%	90%	87–90%[a] 85–90%[b]	90%
CHP applications	Steam, hot water, chilling and bottoming cycles	Hot water, chilling	Depends on technology used	Suitable for facility heating	
Primary contamination sensitivities	Sulphur	CO < 1%, and sulphur	Sulphur	CO < 10 ppm[a], CO < 5%[b], sulphur and NH_3	Sulphur

[a] LT-PEMFC.
[b] HT-PEMFC.

3.2. Market situation for FC-CHP systems

The market of FC-CHP systems is growing rapidly, with the numbers practically doubling every year, but it is still behind other available domestic energy technologies [11]. Japan leads the way and has deployed 98% of the world's residential FC-CHP systems with over 223.000 systems sold as of October 2017 [12]. Although the most commonly used technologies in the residential sector are PEMFC and SOFC, only SOFC systems are able to achieve combined efficiencies of 90% and a high electrical efficiency, because of the high operating temperature. The Japanese Government roadmap plans to increase the number of residential fuel cells to 1.4 million in 2020 [13]. But FC-CHP systems still have high installation costs in distributed generation, and this is one of the few disadvantages for their deployment. Korea and Europe follow Japan but at a considerable distance, as can be seen in the following figure.

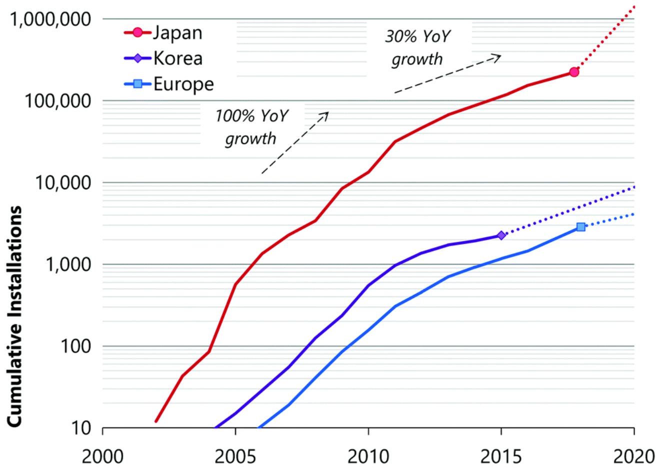


Figure 4. Cumulative number of fuel cell micro-CHP systems deployed in three major regions (solid lines) and near-term projections (dotted lines).[12]

Europe has a share of 11% of installed CHP capacity in the cogenerated electricity business. The Ene.field Programme (echoing the Japanese Ene.Farm Programme) was a European-wide micro-CHP field demonstration scheme that was launched in 2013 with the aim to install around 1.000 fuel cell micro-CHP systems across 10 Member States of the European Union by 2017, with an expected cost of ~US$69.5 million. The Ene.field project was the predecessor of the current PACE project, which aims to deploy more than 2.800 fuel cell micro-generation units in 10 European countries by 2021 [14].

Table 3. Manufacturers of Micro-CHP systems with the correspondent output power. [1]

Micro FC-CHP systems under field trials.

Manufacturer	FC type	Output power (W)	Remarks
Dantherm Power	LT-PEMFC	1700–2500	Under field trials in Denmark, 2013
BaxiInnotech	LT-PEMFC	300	Under field trials in Germany, UK and market launch planned for 2015
Elcore	HT-PEMFC	750	First field trial installation was done 2013
Viessmann	LT-PEMFC	250–700	Ready to launch in Germany by April 2014
Vaillant	LT-PEMFC	1000–4600	Developing for multi-family home
Sofc power	SOFC	500–1000	Prototype packaged micro CHP system
Hexis	SOFC	1000	Field trials in Germany, Switzerland under Callux project
Ceres power	SOFC	1000	Ready to launch by 2016
Vaillant	SOFC	1000	Under field trials in Germany, 2013
Topsoe	SOFC	1000	Prototype packaged micro CHP system of larger (20 kWe) product
Acumentrics	SOFC	250–1500	A wall-mounted residential CHP unit is in field trials
Hyosung, GS Fuelcell, fuel cell power	LT-PEMFC	1000	RPGs (Residential power generators) are in field trials
Plug power	HT-PEMFC	300–8000	Under field trials in Europe in the product name of GenSys

Already in 2012 the micro-CHP systems with fuel cells surpassed traditional CHP systems, with 64% of sales [15]. SOFC fuel cells in particular have been gaining market share in recent years, as can be seen in the following figures, and in fact SOFCs are likely to emerge as the fastest growing fuel cell segment over the next six years [16].

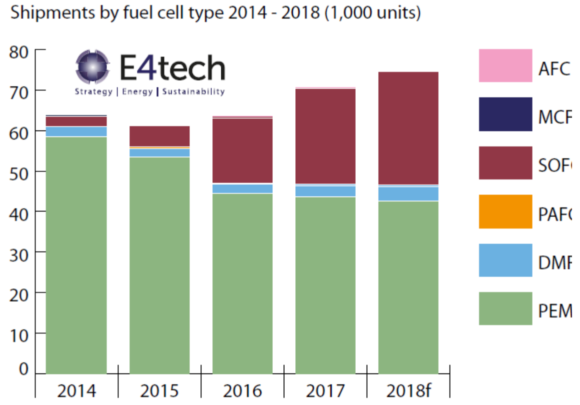


Figure 5. Shipments by fuel cell type 2014-2018.[17]

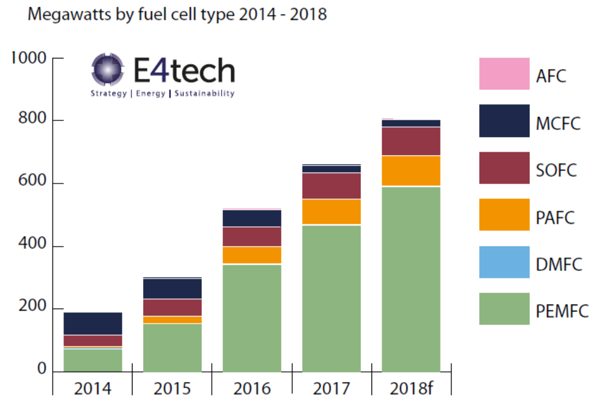


Figure 6. Megawatts by fuel cell type 2014-2018.[17]

3.3. Efficiency of SOFC-CHP systems

SOFC systems operating on natural gas have a wide range of electrical efficiencies, from 35% to 60%, depending upon the operating conditions. The efficiency of SOFC-CHP systems benefits from the high fuel cell operating temperature, and waste heat from the fuel cell can be used for thermal applications. The heat from the fuel and air exhaust is also used to pre-heat the incoming reactants.

SOFC- CHP units have an electrical efficiency advantage of 10 to 15 % (even 20 to 25 % in small scale below 50 kWel) compared to conventional CHP units [9]. Theoretical electrical efficiency could be as high as 70% of the fuel energy, but in real systems the efficiency is between 40-60% and almost independent of the scale of the system (combustion-based technologies can only reach 55% electrical efficiency in very large power plants of hundreds or thousands of MW) [6].

The calculation of profitability or payback period depends on the electrical efficiency, and the local natural gas and electricity prices have to be considered. Another main factor is the heat usage: if all the heat can be used locally, so that a constant overall efficiency is obtained, then the yearly cost savings are less dependent on the electrical efficiency and more dependent of the power to heat ratio. In contrast, if the SOFC system is only operated as power generator, then the electrical efficiency is the main factor for profitability, but payback periods are much longer. On the other hand, electrical efficiency is important to get a high utilization factor that means higher number of operation hours at high loads, which decreases the payback period.

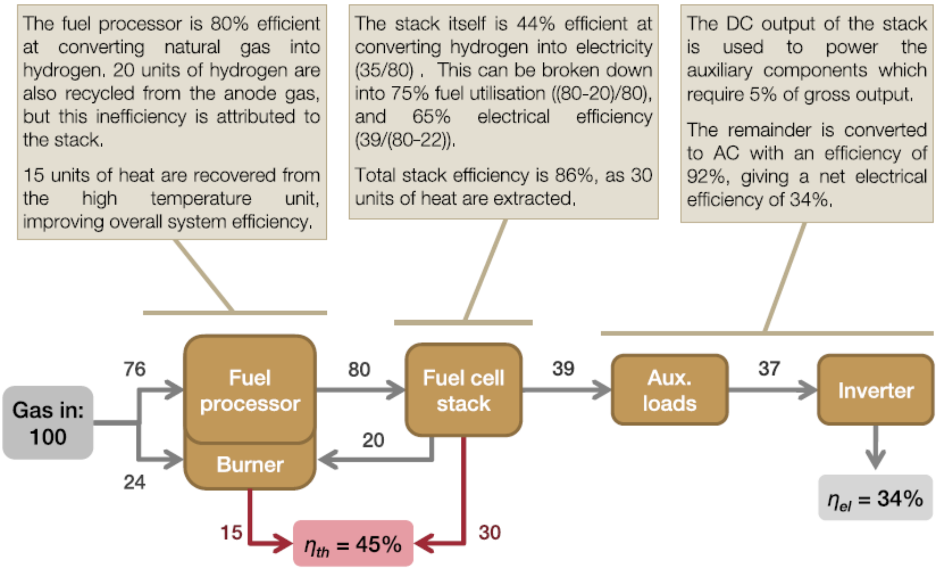


Figure 7. Typical breakdown of the overall efficiency of a FC-CHP system, showing how a 34% efficient fuel cell stack can give a system with 79% net system efficiency.[18]

3.4. Components of a SOFC-CHP System

SOFC-CHP systems are capable of generating power using hydrogen or carbon monoxide as the fuel. The lower temperature systems require an external fuel processing system to convert natural gas to reformate (hydrogen, carbon monoxide, carbon dioxide, and steam). However, the external fuel processor does not require a shift reactor to convert carbon monoxide and steam to hydrogen because the SOFC can use the carbon monoxide as fuel.

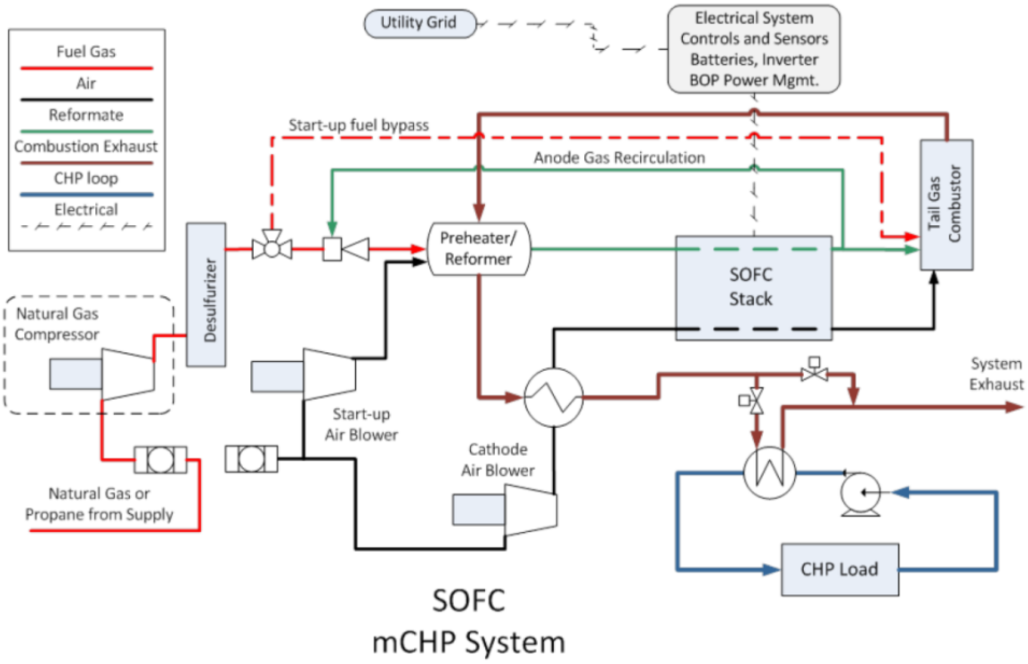


Figure 8. Schematic diagram representative of a SOFC CHP system.[19]

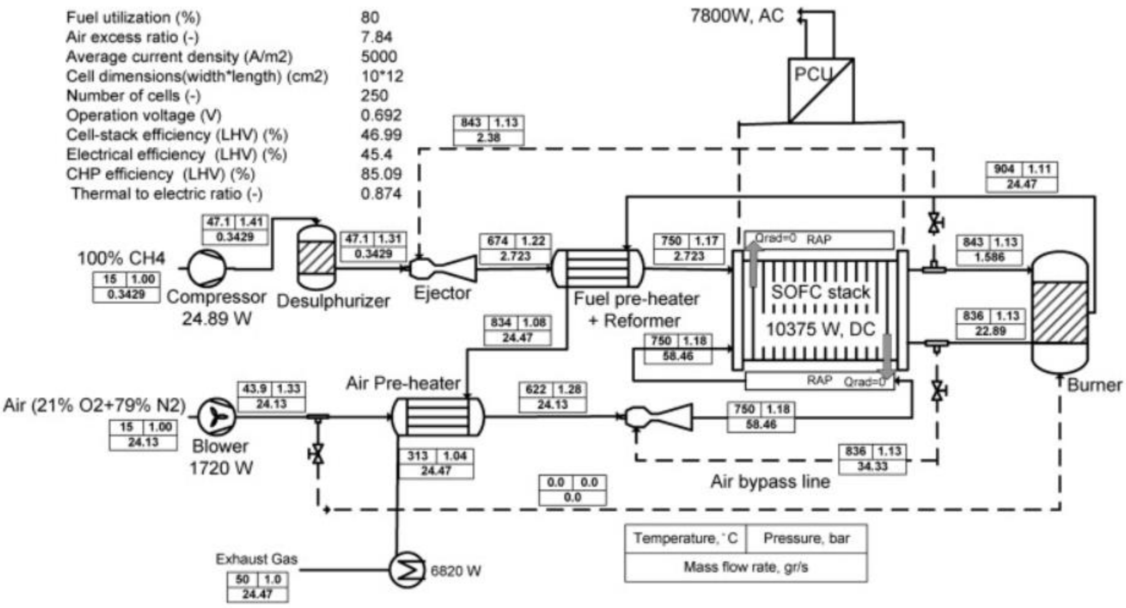


Figure 9. Process flow-sheet diagram of an optimized methane-fuelled SOFC system, with data for typical operation points.[20]

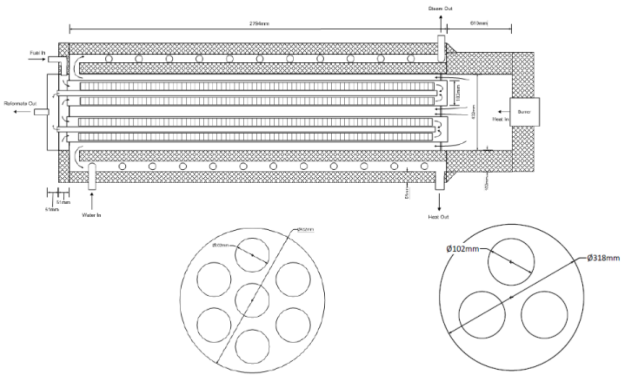


Figure 10. Seven-tube 250 kW reformer configuration and three-tube 100 kW reformer configuration. [19]

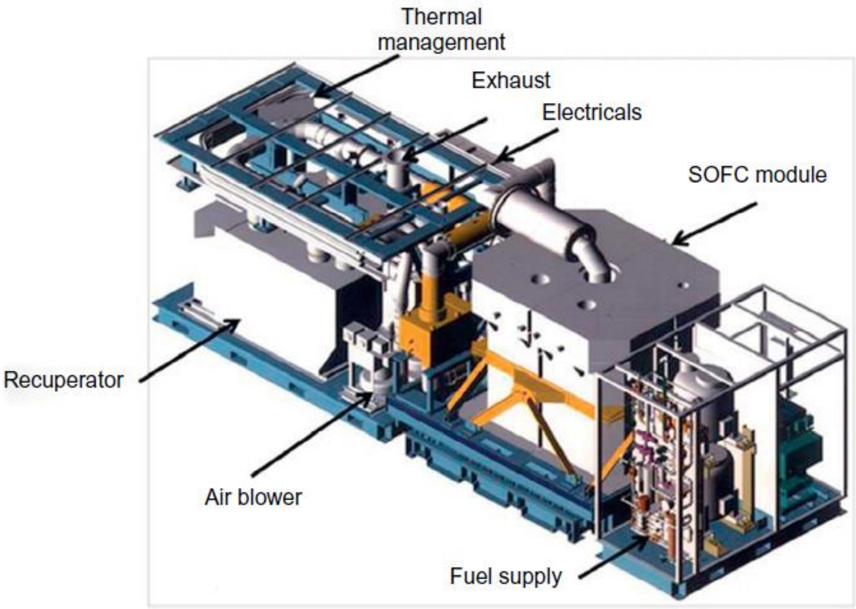


Figure 11. An example of a 100 kW SOFC-CHP system.[21]

Although SOFC systems do not use a platinum catalyst as PEM fuel cells, they are costly to produce due to expensive high temperature materials for interconnects, heat exchangers, manifolding, and power conditioning system.

Manufacturers of SOFCs need to take into account and control the following parameters:[22]

- Electrical and CHP efficiency.
- Factory cost.
- Transient response characteristics.
- Start-up time.
- Operating lifetime.
- Degradation with cycling.
- System availability.

- Capital cost reduction through manufacturing capability.

Several subsystems must be considered:

- A fuel such as natural gas has to be converted to a H_2-rich feed with minimal sulphur.
- Ambient air has to be cleaned up to remove any particulate and chemical impurities.
- DC power generated by the fuel cell has to be converted to AC using a power conditioning system (PCS).

All of these components should be included in a compact unit like those seen in the following figures. It should be borne in mind that available spaces may be limited in the domestic market (micro-CHP) or even in the non-residential public buildings (mini-CHP).

Figure 12.SOFC unit for residential micro-CHP from Japanese firm Aisin Seiki. [23]

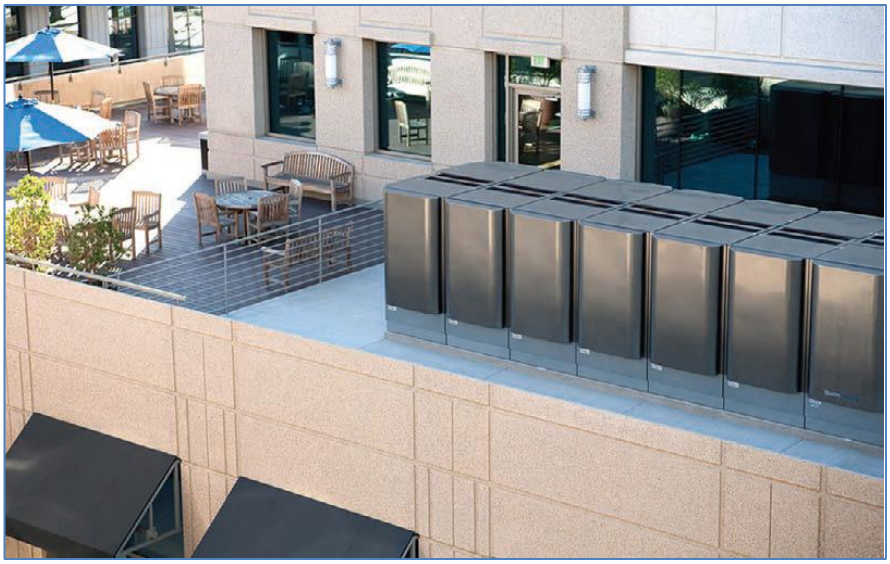


Figure 13. Modular SOFC system for CHP in a building from USA firm Bloom Energy. Several modules are combined to meet the required power. [15]

In SOFC systems, oxygen ions are produced at a cathode and travel through a ceramic electrolyte to the anode. The cell construction for SOFC may be planar or tubular. The electrolyte layer is very thin to minimize resistive losses across the electrolyte. SOFC uses non-noble metal catalysts and therefore offers a cost saving in this regard [22]. The main components are discussed in the following paragraphs.

- **Fuel cell stack:** Where hydrogen and oxygen are combined to convert the chemical energy of hydrogen into electricity, producing heat and water as a by-product. The Membrane Electrode Assembly (MEA) is the "heart" of every fuel cell stack and this component determines the stack operating conditions and influences its performance. SOFC stacks typically operate at 550-1000ºCwith very high CO tolerances [1]. For SOFC systems, tubular cell and stack construction is expected to yield better gas sealing and thermal cycling capability, but it may be more expensive than planar construction, especially for stacks in the 1–10 kW power range [22].

- **Fuel processor:** Converts a hydrocarbon fuel such as natural gas into hydrogen and CO_2. The fuel processor is one of the most significant components, estimated to contribute around 80% of the balance of plant (BOP) costs in an FC-CHP system. A fuel purification sub-system, e.g. fuel desulfurization module, also adds to the additional cost for SOFC [1]. Natural gas is assumed to be the fuel of choice for baseline residential or stationary FC-CHP applications. Hydrogen is extracted from natural gas via steam reforming at 700°– 800°C. Steam reforming (SR) uses steam and it requires a substantial amount of heat as an input due to its extremely endothermic reaction. A typical natural gas reformer can achieve efficiency in the range of 75-90% (calculated for Lower Heating Value LHV) while a range of 83-85% is expected. SR has a rich H_2 concentration of 70-80%. The steam reforming reaction is as follows:

  $$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (\Delta H = +206\ kJ/mol,\ endothermic\ reaction)$$

  For high temperature fuel cells such as SOFC systems, waste heat is available at the reforming temperatures, so there is no electrical efficiency penalty because it is not necessary to obtain supplementary heat by burning fuel, which penalizes electrical efficiency. It is also advantageous to perform at least a part of the reaction in an "internal" reformer within the stack, which helps provide stack cooling and cell temperature uniformity [22].

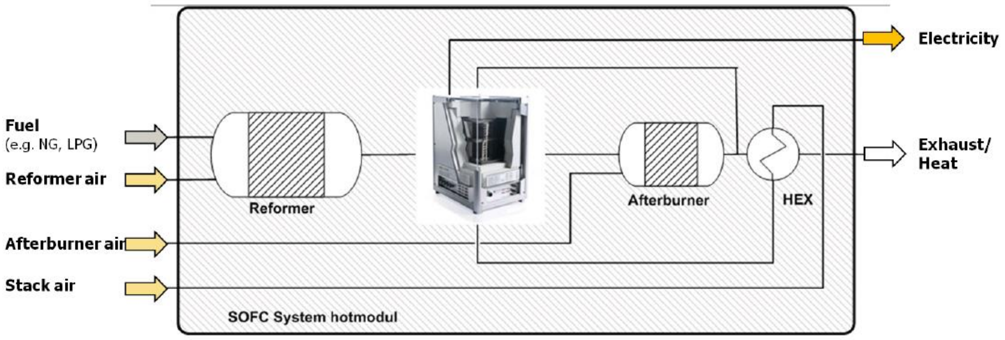


Figure 14. Schematic of SOFC-CHP system with the different components. [9]

- **Heat recovery system:** Heat recovery from a SOFC-CHP is essential in order to improve efficiency, performance and durability of the system. It is done by supplying air in excess to the cathode. The excess cathode air and unconsumed fuel in the stack are combusted in a burner and the produced heat is used for preheating the reactants supplied to the reformer or the fuel cell stack. Large quantities of air are required for reactant air preheating and for cooling. The air is usually supplied to the fuel cell stack by an air blower. Efficient, cost-effective blowers are desirable to keep costs at bay, and also low-cost heat exchangers for heating/cooling various gas streams [1].
- **Power Conditioning System:** DC power produced by the fuel cell has to be converted to AC power in a power conditioning system (PCS). Inverters and converters are used to condition the DC electrical output of the fuel cell stacks to be useful for the end-user power requirements. The efficiency of this equipment is inversely proportional to the cost. The inverter efficiency is typically around 85-95% for a 10 kWel FC-CHP system. The AC electrical power can be used for building applications and the excess of produced energy can be fed back into the grid if the system is running in a grid-parallel mode or it can be stored in batteries for future use [1]. The input operating voltage range also affects the cost of PCS. If the design can be standardized, order volume can be high, leading to cost reduction. The control system for fuel cell, fuel processing, and PCS can be integrated, reducing the total system cost [22].
- **Balance of plant:** includes pumps, fans, valves sensors, piping and control system, used to ensure the whole system functions in a safe, efficient manner for long term stable operation. The cost of BOP components is significantly higher per kW of system power for low power systems, especially at the 1-2 kW range. As the system size and the annual manufacturing rate increases, the system cost decreases.

The overall cost of the common parts of a SOFC-CHP system includes all the aforementioned components: the fuel processor, the fuel cell stack, the power conditioning and the heat recovery system, as well as other components such as pumps, blowers, control valves, sensors and pipes and. In particular, SOFC-CHP systems require heat exchangers operating at relatively high temperatures, which are often costly [1][19].

Additional items that can be part of the system for residential or commercial SOFC-CHP applications are the following [24]:

- **Boiler:** to provide peak thermal loads when needed.
- **Thermal energy storage:** a hot water tank to store the thermal output of the fuel cell.
- **Smart meters:** to measure and record energy production and consumption.
- **Internet connection:** to facilitate remote connection and data acquisition.

The following figure shows an example of implementation of these components together in a 5 kW system model.

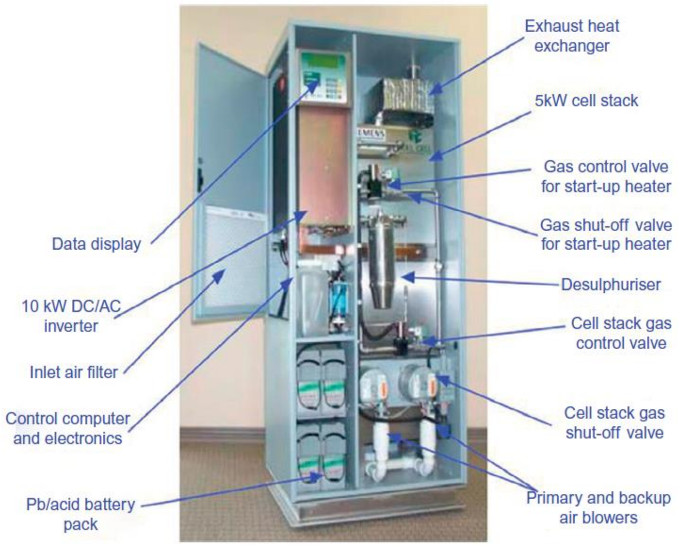


Figure 15. A 5 kW SOFC system model showing the stack and other supporting components [21].

From the point of view of user requirements, the following characteristics are required for an on-site fuel cell unit:

- High electrical efficiency.
- High thermal efficiency.
- Expected return of investment in 3 - 5 years.
- High reliability and durability.

In regards to lifetime of the system, degradation rates have been steadily decreasing in recent years, and an estimation of the lifetime of a stack is expected to reach 40.000h before 2020 and 60.000h by 2026 [25]. The following figure shows how the expected life time has increased in recent years.

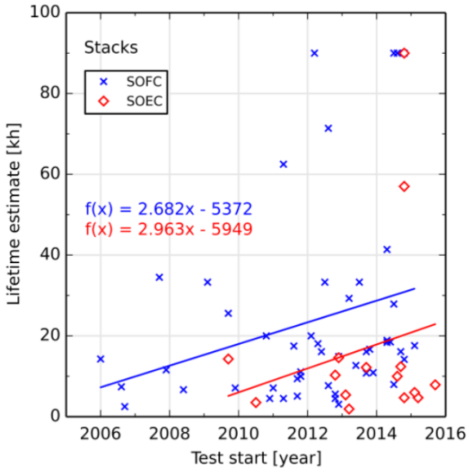


Figure 16. Lifetime improvement in fuel cell system lifetimes.[25]

4. Techno-economic model and developed tools

4.1. Techno-economic model

The modeling framework presented in this work is a techno-economic static model of a SOCF-CHP system operating for a period of 10 years. The objective is to calculate the costs for meeting a given electricity and heat demand with the system, and compare it with the cost of the reference case, which is electricity imported from the power grid and gas imported from the gas grid and converted into heat with a conventional boiler. This will not only determine the annual operating cash flow, but also calculate the time needed to recover the investment made. A sketch of the system can be seen in the following figure.

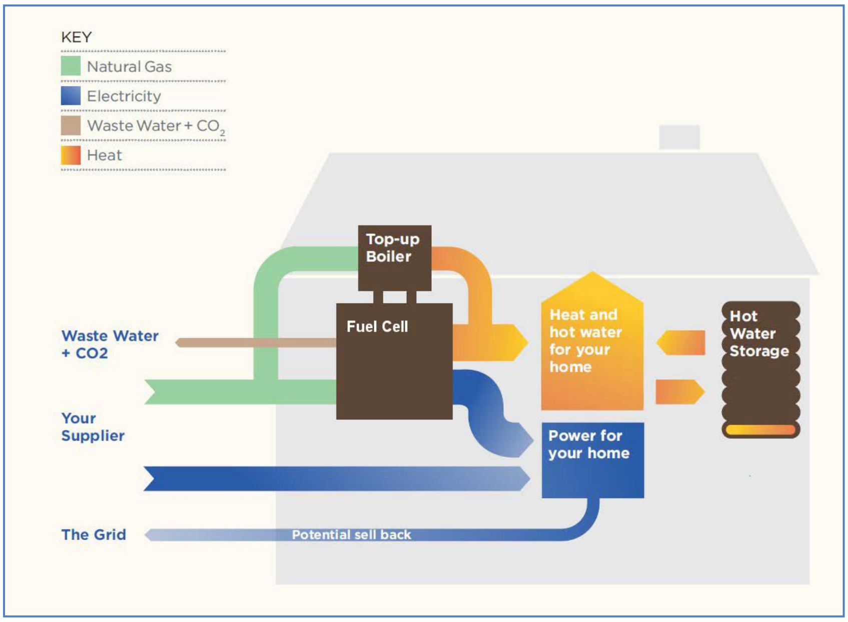


Figure 17. Simple sketch of a complete SOFC-CHP unit including gas condensing boiler for back-up (peak load) and hot water storage tank. [7]

The model contains technical parameters, economic parameters, an objective function and some decision variables. The technical parameters reflect the best state-of-the-art found in the literature for SOFC-CHP technology. The economic parameters reflect the current situation of the Spanish gas and electricity market, taking the current composition of the supply prices for the existing tariffs. The expected evolution of prices is also taken into account.

The demand for heat and electricity is based on real data taken from the SIRENA system [26], covering a period of one year and corresponding to measures of electrical and thermal demand with a sampling time of 15 minutes. This is one of the points that differentiate this work from others found in the literature: real data are available with sufficient resolution to perform a realistic simulation of the operation of the CHP system.

Although having the SIRENA system with real data is a great advantage, it is desired that the model be of general application for other cases in which such abundant information is not available. In order to validate the results offered by the model in case of having less information, the results will be compared with the ones obtained with the same data aggregated in different intervals: hourly, daily, weekly and monthly.

To determine how the sampling time of the available data affects the results of the model, a correction factor will be defined to relate the economic result obtained with 15-minutes-sampling data with the result obtained with data aggregated in other intervals. This correction factor will serve to correct the result of the model when there is little data available, for example when only the monthly consumption of the building is available, which is the usual case when the only information available is the consumption reported by the utility in monthly invoices.

The parameters of the model are the following:

- CHP system technical parameters:
  - Overall heat and power efficiency.
  - Capacity (kWe).
  - Supplementary integrated boiler efficiency.
- Economic input parameters:
  - System cost.
  - Installation cost.
  - Price of gas supply from the gas network (including fixed, variable and tax costs).
  - Historical evolution of gas prices.
  - Price of electricity supply from the power grid (including fixed, variable and tax costs).
  - Historical evolution of electricity prices.
  - Price of electricity sold to the grid.
  - Maintenance cost of the CHP system.
  - Government subsidies to support investment in CHP systems.
  - Loan to cover the investment for the CHP system, interest rate and rate of inflation.

The objectives of the model are:

  - Calculate cost of meeting energy demand with CHP system for different control strategies.

- Calculate payback period.

The decision variables are:

- Operation mode: maintain the connection to the power grid or dispense with it. In the first case, the grid can be used as backup if the fuel cell does not provide all the necessary electrical power. In the second case, there is no backup but the fixed costs of connection to the grid are avoided.
- Operation strategy: follow heat demand, follow maximum demand, or follow electrical demand.

The following figure shows how the technical and economic parameters, objectives and decision variables of the model are related.

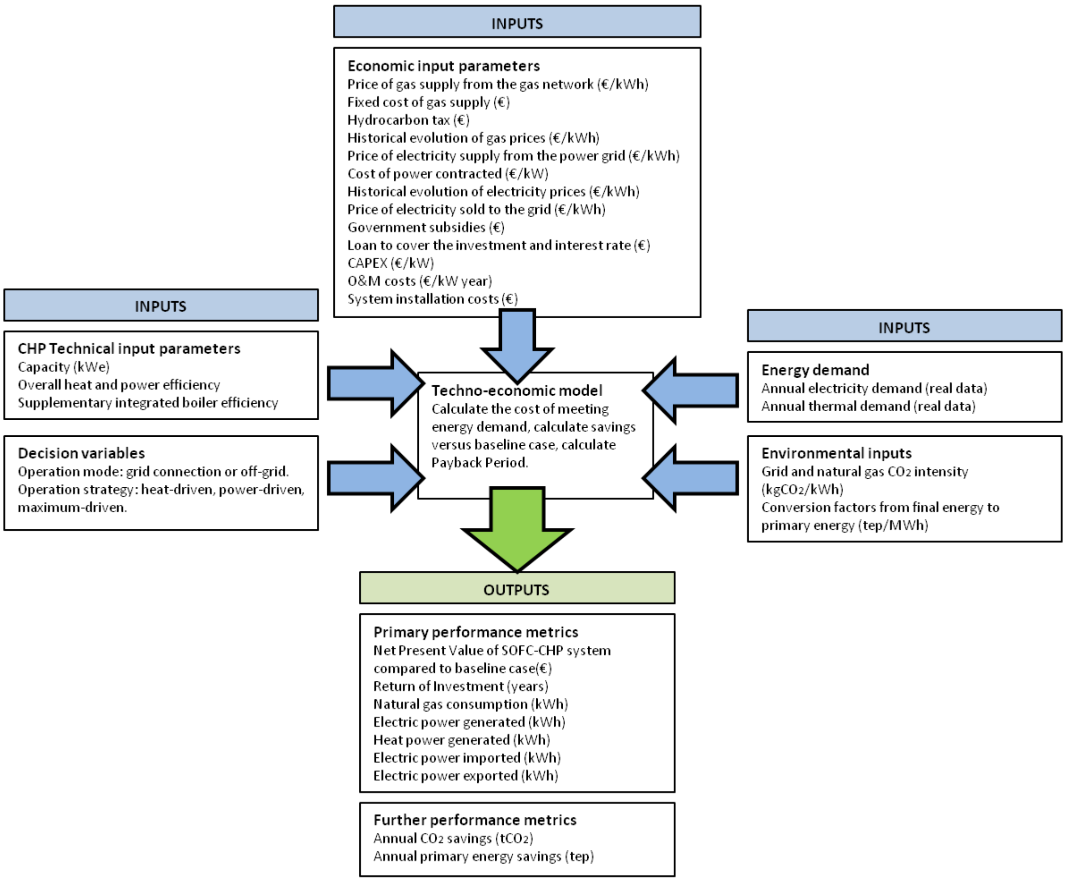


Figure 18. Overview of the inputs and outputs of the techno-economical model.

4.1.1. Assumptions

- The system is sized to cover the maximum electrical demand of the building.
- It is assumed that the SOFC-CHP unit can operate anywhere between 0%

and 100% of its rating and that it can ramp up and down at any rate to follow changes in demands.

- In case that the demand of heat is larger than the fuel cell heat at maximum power, the rest of heat will be given by an auxiliary boiler.
- The system has batteries because energy storage is required to allow start-up and load changes when necessary, because in some operation modes considered the grid will not be available. The cost of the batteries are included in the total cost of the system [19].
- A resistor bank is required in case of load decrease to dump some excess power as the reformer decreases reformate output, or to provide additional heat if needed, which is considered in one of the operation strategies. The cost of the resistor bank is included in the total cost of the system [19].
- All the thermal energy in the baseline case is obtained by means of gas boilers.
- All boilers used are assumed to be 90% efficient as a basis for comparison.
- The total efficiency of the SOFC-CHP system is 90%, with an electrical efficiency of 50% and a thermal efficiency is 40%, according to the state-of-the-art technology as stated in [19].
- The cost of installing the system will be 15% of the total amount of it. This is an average value of the references found in the literature, ranging from 8% to 25%[3][19].
- Recent work carried out in Europe in the demonstrations of the Ene.field project has returned system availability data of 99% (in a period of 6 months)[7]. For this reason, the effects of possible breakdowns in the system will not be included in the model, and they are considered negligible thanks to adequate preventive maintenance.
- Natural gas and electricity rates correspond to commercial rates for businesses and companies. In the case of the electricity tariff, only the prices corresponding to the flat period are used for simplification purposes (the most important part of the consumption will be within that time frame, as can be seen in the following figures).

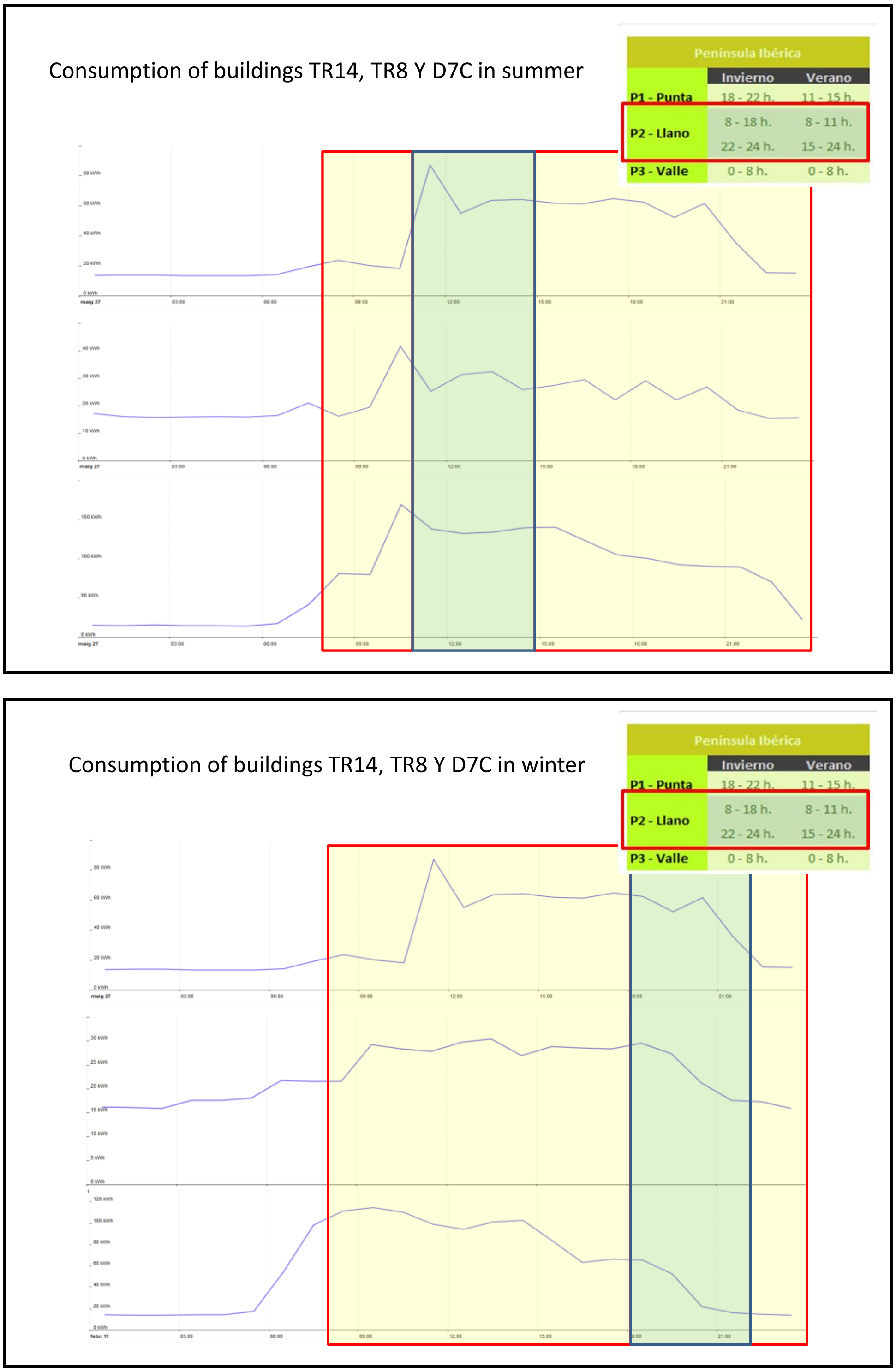


Figure 19. Example of consumption and periods of the electricity tariff. The yellow part is the consumption in the "flat" period. The green part is the consumption in "peak" period. [27]

For the techno-economic analysis, the **net present value** (NPV) methodology is used, i.e. a static approach that allows the calculation of an investment's market value within a specific timeframe. The NPV represents the overall value of a project, determined by negative investment costs plus the present value of the expected future net cash flows (i.e. revenues minus costs) [28]. The NPV is calculated using the following equation, where *t* denotes time, *i* the discount rate (adjusted for inflation rate), and CF_t the net cash flow generated in year *t*.

$$NPV(i,N) = \sum_{t=0}^{N} \frac{CF_t}{(1+i)^t} \qquad Eq.(1)$$

The cost of the energy produced by the system is evaluated using the metric known as **Levelized Cost of Electricity** (LCoE) [29]. The LCoE takes into account all the actualized investment (CAPEX) and operating (OPEX) costs of the system, and puts them in relation with the amount of energy produced by the system. The resulting amount can be compared with the one obtained in the baseline case, which results from the ratio between the amount of electricity consumed and the cost of it, that is, the annual amount of the electricity and natural gas supply bills. The LCoE thus evaluates the total costs per MWh of the system, and takes into account investment, operations and management costs, fuel expenditures, decommissioning, expected lifetime and discount rate. In this project, the decommissioning costs are considered negligible in front of the other costs, and so the formula adopted will be the following [30]:

$$LCoE = \frac{\sum_t((CAPEX+OPEX+Fuel)_t)\cdot(1+r)^{-t}}{\sum_t(Energy\cdot(1+r)^{-t})} \qquad Eq.\ (2)$$

The **payback period** (PBP) is widely used when long-term cash flows (over a period of several years) are difficult to forecast. It may be used for preliminary evaluation or as a project-screening device for high-risk projects in times of financial uncertainty. Payback period is usually measured as the time from the start of production to recovery of the capital investment. The payback period is the time taken for the cumulative net cash flow from the start-up of the plant to equal the depreciable fixed capital investment [31]. Payback period tells us how long it takes to get back our CAPEX from revenues/profits/savings.

4.1.2. Manufacturing costs of the system

The cost of the SOFC-CHP considered in the model is extracted from [19]. It is a report which contains a detailed cost analysis of a SOFC-CHP system, based on information collected from the main companies in the market. It provides an estimate of the manufacturing cost for systems with a power output between 100 and 250kW, and can be considered an excellent approach to the state-of-the-art of this technology. A complete system has the following components (the reader is referred to the document for more details):

- Main fuel cell system:
    - A fuel cell stack that converts hydrogen to heat, electricity and water.

  - A fuel processing system that converts natural gas (or other hydrocarbons) to hydrogen and CO_2.
  - A grid-tie inverter to convert low-voltage DC to AC with export ability.
  - Heat exchangers to transfer waste heat from the exhaust and coolant loops to an external system.
  - Balance of plant (BOP): pumps, valves, sensors, pipework, electronic control systems, etc.

- Additional thermal management:
  - An auxiliary boiler to supply peak heat demands (usually integrated into the fuel cell system).
  - A high-efficiency heat store, so that a low-capacity fuel cell can supply the majority of the building's heat demand.
  - A resistor bank to dispose of waste heat or use it if appropriate.

- Control, interaction and feedback:
  - Touch-screen LCD interface.
  - Remote control system.
  - Smart-meter for measuring consumption and production.
  - Internet-based remote monitoring and control.

The manufacturing costs analysis made in the mentioned document gives the following conclusions:

- Balance of plant (BOP) dominates system costs.
- Within BOP, hardware directly related to connecting to the grid represents major portion of cost for SOFC-CHP systems.
- Recently developed hybrid inverters eliminate need for separate DC/DC Converter, though power electronics still represent the highest cost system component.
- Heat exchangers, particularly high temperature, also represent a major portion of the BOP.

The following figure shows the production costs of a 250kW system, which is in the size range of the systems used in this work. The price already includes the manufacturer's margin, and has been converted to Euros for calculations.

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$87,497	$70,430	$66,665	$66,327
Fuel, Water, and Air Supply Components	$18,298	$15,700	$14,309	$13,556
Fuel Processor Components	$14,347	$9,797	$8,604	$8,253
Heat Recovery Components	$33,857	$31,718	$29,718	$28,470
Power Electronic, Control, and Instrumentation Components	$117,962	$95,050	$75,453	$62,217
Assembly Components and Additional Work Estimate	$19,110	$17,410	$15,710	$14,180
Total system cost, pre-markup	$291,072	$240,105	$210,458	$193,004
System cost per net KW, pre-markup	$1,164	$960	$842	$772
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$436,608	$360,157	$315,686	$289,505
System cost per net KW, with markup	$1,746	$1,441	$1,263	$1,158

Figure 20. A 250 kW SOFC-CHP system cost summary [19].

The following figure shows the relative weight of each subsystem in the total.

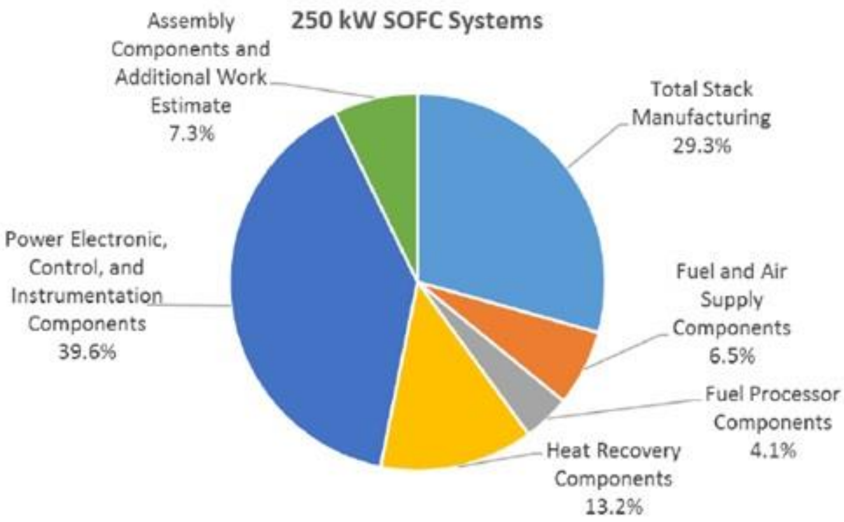


Figure 21. Detail of costs for a 250 kW SOFC system for CHP [19].

4.1.3. Operation modes and operation strategies

In general, there are two main operating strategies for CHP systems which need to be considered when selecting the technology and dimensioning the system: (1) electricity-driven plant operation, that is, the system must follow the electricity demand, and (2) heat-driven plant operation, which means that the system must follow the heat demand. A third option would be to follow the most requiring demand. Apart from these strategies, there are other variables that can be considered for the techno-economic analysis in addition to the control of the fuel cell, such as the connection or not to the power grid, and also the use of surpluses of electrical energy produced.

In this assessment, a total of five strategies will be analyzed, and all of them will be compared with the baseline case, which is the usual situation of electrical energy imported from the power grid and thermal energy generated with a boiler connected to the natural gas grid. The strategies considered are listed in the table below. It is indicated for each case how the energy demand is followed, what is done with the surplus electricity, and whether or not the building is connected to the electricity grid.

Table 4. Strategies assessed: follow heat demand, follow maximum demand (with or without power grid connection), and follow electricity demand (with or without power grid connection).

	Case study 1 (baseline case)	**Case study 2**	**Case study 3A**	**Case study 3B**	**Case study 4A**	**Case study 4B**
Operation mode	-	Grid connection	Grid connection	Off-grid	Grid connection	Off-grid
Operation strategy	-	Follow heat demand	Follow maximum demand	Follow maximum demand	Follow electricity demand	Follow electricity demand
Use of surplus electricity	-	Sell to grid	Sell to grid	Generate heat	No surplus electricity	No surplus electricity

- **Case study 1: Baseline case.**
  - It represents the current situation, in which buildings use natural gas-fired water heaters and boilers to meet the thermal demand, and are connected to the power grid to meet the electricity demand.
- **Case study 2: Follow heat demand, building connected to the power grid.**
  - The SOFC-CHP system must follow the heat demand. This means that the fuel cell will not work throughout the year, but only in the months in which heating is necessary.
  - The building remains connected to the electricity grid, so that in case the FC's electrical production does not cover the electricity demand, the network acts as a backup.

  - There is the possibility of exporting electricity to the grid when production exceeds demand.

- **Case study 3A: Follow maximum demand, building connected to power grid.**
  - In this case, the fuel cell must follow the maximum demand, be it thermal or electrical.
  - The building remains connected to the electricity grid, so that in case the FC's electrical production does not cover the electricity demand, the network acts as a backup.
  - There is the possibility of exporting electricity to the grid when production exceeds demand.

- **Case study 3B: Follow maximum demand, building disconnected from the power grid.**
  - In this case there is no backup for the demand for electricity, so the fuel cell must have enough power to cover the building's electrical demand throughout the year.
  - Excess electricity cannot be exported to the network, losing that source of income.
  - In this case, additional savings are achieved by not being connected to the power grid, because the fixed costs of grid connection are avoided.
  - The surplus of electricity is used to generate heat by means of resistors with an efficiency of 100%, thus reducing the need for natural gas.

- **Case study 4A: Follow electricity demand, building connected to the power grid.**
  - In this case there is no surplus of electricity produced, because the fuel cell follows the electrical demand.
  - The building remains connected to the electricity grid, so that in case the FC's electrical production does not cover the electricity demand, the network acts as a backup.

- **Case study 4B: Follow electricity demand, building disconnected from power grid.**
  - In this case there is no surplus of electricity produced, because the fuel cell follows the electrical demand.
  - In this case, additional savings are achieved by not being connected to the

power grid, because the fixed costs of grid connection are avoided.

The model developed is used to make a ten-year projection of the results obtained in the simulation performed with Matlab/Simulink for a full year. In this projection, the evolution of the prices of supplies is taken into account, in line with the trend of historical data obtained from EUROSTAT[32].

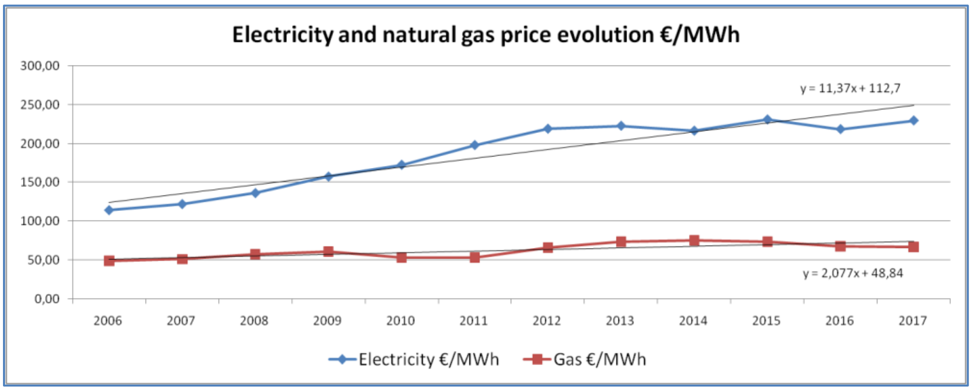


Figure 22. Evolution of prices of gas and electricity2006-2017.[32]

4.1.4. Inputs and outputs of the model

The required inputs for the model are:

- Specific capital cost of the system.
- Installation costs.
- Operation and maintenance costs of the system.
- Electricity and heat demand, with data with different sampling times.
- Electrical and thermal efficiencies of the system.
- Efficiency of the current boiler/heater.
- Fuel cell control strategy (operation mode and operation strategy).
- Prices of natural gas and electricity (imported from and exported to the grid).
- Composition of the natural gas and electricity prices (fix and variable terms, taxes).
- Trend in gas and electricity prices
- Loan amount for system acquisition.
- Loan interest rate.
- Expected inflation rate.
- Government subsidies.
- Emission factor of power grid.
- Emission factor of natural gas in a boiler.
- Emission factor of SOFC-CHP system.

The model determines the following outputs:

- Costs of the system for a whole year of operation.
- Cash flow of the system, comparing the system costs with the usual supply costs (baseline case).
- 10-year projection of system costs and cash flow in the use-phase, and Net Present Value (NPV) of the cash flow.
- Payback period of the system.
- Levelized Cost of Energy (LCOE) for the system and for the current situation (baseline case).

The following table shows the summary of the model parameters, the values adopted and the references that have been used to determine the values.

Table 5. Parameters of the techno-economic model.

Input data	Value	Comments/References
Size of the system (kW)	Decision variable	
Capital cost (€/kWe)	1033 €/kW	[19]
Installation costs (€)	15% of CAPEX	Different amount in several sources.[19][33][3]
O&M costs (€/year)	1% of CAPEX	Different amount in several sources.[30][34][19][35]
System expected lifetime (h)	90.000h	With proper maintenance and a change of stack.[12]
Stack expected lifetime (h)	45.000h	Different value in several sources.[36][37]
Electricity/Heat demand (kWh)	SIRENA	Real data with 15 min resolution.[26]
FC electrical efficiency (%)	50%	[19][3]
FC total efficiency (%)	90%	[19][3]
Boiler efficiency (%)	90%	Energy Certificates of buildings.[3][38]
Operation mode	Decision variable	Grid connection / off-grid
Operation strategy	Decision variable	Follow heat demand / follow maximum demand / follow electric demand.
Price of NG imported (€/kWh)	0,04572 €/kWh	www.naturgy.es
Price of power imported (€/kWh)	0,105 €/kWh	www.somenergia.coop
Price of power exported (€/kWh)	0,056 €/kWh	www.somenergia.coop

Taxes in NG supply	Rate 3.4 for business customers	www.naturgy.es
Taxes in power supply	Rate 3.0 for business customers	www.somenergia.coop
Price trend for power	11% annual increase	According to EUROSTAT.[32]
Price trend for NG	2% annual increase	According to EUROSTAT.[32]
Amount of loan	Decision variable	
Interest rate	Variable	According to Bank of Spain Statistics, depends on the amount of loan.[39]
Inflation rate	1,5%	According to Bank of Spain IPC projection. [40]
Government subsidies	Variable	
Emission factor of power grid ($kgCO_2/kWh$)	0.25 kgCO2/kWh	According to Red Eléctrica de España.[41]
Emission factor of natural gas in a boiler ($kgCO_2/kWh$)	0.203 kgCO2/kWh	According to Ministerio para la Transición Ecológica [42]
Emission factor of SOFC-CHP ($kgCO_2/kWh$)	0,29 (kgCO2/kWh)	Different value in several sources. Takes into account compensation for co-produced heat. [12][35][6]

4.2. Implementation in Matlab/Simulink

The techno-economic model described in the previous section has been implemented in Matlab/Simulink to calculate the cost of covering the energy demand for one whole year for each of the case studies, and for the different data sets, from the most detailed (energy demand known every 15 minutes) to the least detailed (only monthly demand known).

The data available for calculating the annual cost of the system are arranged in a file that has been structured in 7 columns. The file size is 35,040 rows in the most detailed case (observations every 15 minutes, 24 hours a day, 365 days), and only 12 rows in the case where the data is more aggregated (monthly consumption). The details of the structure of the Excel files and the explanation of the information contained in each column is detailed in the following table.

Table 6. Explanation of the information contained in each column of the data file.

Column	Data	Comments
1	Counter	Correlative number

2	Thermal demand	Thermal demand of the building in the specified interval, extracted from SIRENA.
3	Electrical demand	Electrical demand of the building in the specified interval, extracted from SIRENA.
4	NG for SOFC	Natural Gas to be feed to the CHP System to cover demand (according to the strategy chosen in each case).
5	NG for additional boiler	Natural Gas to be feed to the additional boiler if the SOFC-CHP system is unable to meet demand.
6	Electricity from SOFC	Electricity produced by the CHP system (according to the strategy chosen in each case).
7	Electricity from grid	Electricity imported from grid because the CHP system is not covering demand (according to the strategy chosen in each case).
8	Electricity sold to grid	Surplus electricity sold to the grid (according to the strategy chosen in each case).

Table 7. Nomenclature used in the calculations of natural gas and electricity needed for the SOFC-CHP system.

Data	**Comments**
NG_{fc}	Natural gas supplied to the FC
NG_{boiler}	Natural gas supplied to the additional boiler
D_{th}	Thermal energy demand
D_{el}	Electrical energy demand
η_{th}	Thermal efficiency of the fuel cell
η_{el}	Electrical efficiency of the fuel cell
η_{b}	Thermal efficiency of the boiler
$H_{fc,max}$	Maximum thermal energy supplied by the FC
E_{fc}	Electricity obtained from the FC
E_{imp}	Electricity imported from the power grid
E_{exp}	Electricity exported to the grid
ε_{grid}	Emission factor of the power grid

ε_{boiler}	Emission factor of the boiler
ε_{fc}	Emission factor of the SOFC-CHP system

The calculation of the natural gas and electricity that the SOFC-CHP system needs for each operation strategy is detailed in the following paragraphs.

- **Case study 2: Follow heat demand, building connected to the power grid.**
  - The amount of natural gas that must be supplied to the fuel cell (NG_{fc}) is calculated considering the thermal efficiency of the CHP system, so that the energy of the incoming gas must be equal to the thermal demand (D_{th}) divided by the thermal efficiency (η_{th}) of the fuel cell.

$$NG_{fc} = D_{th}/\eta_{th} \qquad \text{Eq. (3)}$$

  - If the CHP is unable to meet the heat demand, the additional boiler act as a backup. The amount of gas that must be supplied to the additional boiler (NG_{boiler}) is calculated considering the heat demand and the maximum heat ($H_{fc,max}$) that can generate de CHP system.

$$if\ D_{th} > H_{fc,max} \quad \rightarrow \quad NG_{boiler} = (D_{th} - H_{fc,max})/\eta_{th} \qquad \text{Eq. (4)}$$

  - The electricity obtained from the fuel cell (E_{fc}) is calculated from the amount of gas determined above and the electrical efficiency of the fuel cell (η_{el}). The energy contained in the incoming gas is multiplied by the electrical efficiency of the fuel cell.

$$E_{fc} = NG_{fc} \times \eta_{el} \qquad \text{Eq. (5)}$$

  - When the CHP system is unable to provide enough electricity, the electricity grid acts as a backup. The electricity imported from the grid (E_{imp}) is calculated by subtracting the electrical demand (D_{el}) minus the electricity provided by the fuel cell (E_{fc}).

$$if\ D_{el} > E_{fc} \quad \rightarrow \quad E_{imp} = D_{el} - E_{fc} \qquad \text{Eq. (6)}$$

  - When the CHP system provides more electric energy than needed, the surplus (E_{exp}) is exported to the grid. The surplus is calculated by subtracting the electricity provided by the fuel cell (E_{fc}) minus the electrical demand (D_{el}).

$$if\ E_{fc} > D_{el} \quad \rightarrow \quad E_{exp} = E_{fc} - D_{el} \qquad Eq.\ (7)$$

- **Case study 3A: Follow maximum demand, building connected to power grid.**
  - If the heat demand (D_{th}) is higher, the amount of gas that must be supplied to the fuel cell (NG_{fc}) is calculated taking into account the thermal efficiency of the system (η_{th}) and is limited by the maximum heat capacity ($H_{fc,max}$).

$$if\ D_{th} > D_{el}\ \ and\ \ D_{th} \leq H_{fc,max} \rightarrow\ NG_{fc} = D_{th}/\eta_{th} \qquad Eq.\ (8)$$

$$if\ D_{th} > D_{el}\ \ and\ \ D_{th} > H_{fc,max} \rightarrow\ NG_{fc} = H_{fc,max}/\eta_{th} \qquad Eq.\ (9)$$

  - When the CHP is unable to meet the heat demand, the additional boiler act as a backup. The amount of gas that must be supplied to the additional boiler is calculated as in equation *(4)*.
  - If the electric demand (D_{el}) is higher, the amount of gas that must be supplied to the fuel cell (NG_{fc}) is calculated taking into account the electric efficiency of the system (η_{el}) and is limited by the maximum power capacity ($E_{fc,max}$).

$$if\ D_{th} \leq\ D_{el}\ \ and\ \ D_{el} \leq E_{fc,max}\ \rightarrow\ NG_{fc} = D_{el}/\eta_{el} \qquad Eq.\ (10)$$

$$if\ D_{th} \leq\ D_{el}\ \ and\ \ D_{el} > E_{fc,max}\ \rightarrow\ NG_{fc} = E_{fc,max}/\eta_{el} \qquad Eq.\ (11)$$

  - The electricity obtained from the fuel cell (E_{fc}) is calculated from the amount of gas determined in the previous point and the electrical efficiency of the fuel cell (η_{el}) as in equation *(5)*.
  - The electricity imported from the grid (E_{imp}) is calculated by subtracting the electrical demand (D_{el}) minus the electricity provided by the fuel cell (E_{fc}), as in equation *(6)*.
  - The electricity exported to the grid (E_{exp}) is calculated by subtracting the electricity provided by the fuel cell (E_{fc}) minus the electrical demand (D_{el}), as in equation *(7)*.
- **Case study 3B: Follow maximum demand, building disconnected from the power grid.**
  - Apply the same equations as in case study 3A.

  - When the CHP system provides more electric energy than needed, the surplus (E_{exp}) is used to produce heat, thus decreasing natural gas demand.

  - The electricity imported from the network is zero, because the building is off the power grid. The electricity exported to the network is also zero for the same reason.

- **Case study 4A: Follow electricity demand, building connected to the power grid**
  - The amount of natural gas that must be supplied to the fuel cell (NG_{fc}) is calculated taking as in equations (10) and (11).

  - When the CHP is unable to meet the heat demand, the additional boiler act as a backup. The amount of gas that must be supplied to the additional boiler is calculated as in equation *(4)*.

  - The electricity obtained from the fuel cell (E_{fc}) is calculated from the amount of gas determined in the previous point and the electrical efficiency of the fuel cell (η_{el}) as in equation *(5)*.

  - The electricity imported from the grid is zero, because all the electricity needed to cover the demand is obtained from the fuel cell. Obviously, the electricity exported to the network is also zero.

- Case study 4B: Follow electricity demand, building disconnected from power grid.

  - Apply the same equations as in case study 4A.

  - The case is economically relevant for the savings that occur when the building is disconnected from the power grid.

The start-up of the SOFC-CHP system would require a certain amount of energy due to the time required, however this was not modeled as they were assumed to remain operational continuously over the entire year or during the cold months in the case of following the thermal demand, and the fuel cell will be operating at its minimum rate even at night, when there is no thermal demand for heating.

The model has been structured in Matlab/Simulink in different sub-modules. In this way, it can be seen how each sub-module contributes to the calculation of the resulting annual cash flow. A description of the sub-modules implemented is detailed below:

- Current costs of the supply of electricity and natural gas: First, the cost of the baseline case is calculated, using information extracted from a rate considered representative of those offered by the retailers of the Spanish market, and taking into account all the price components in each case, including fixed terms, variable terms, fees and taxes. The efficiency of the boiler has been taken into account to calculate the real quantity of natural gas from the consumption data provided by SIRENA.

- Capital and O&M costs of the CHP system: The data has been taken from the most recent bibliography that has been accessed. Please refer to the table with the techno-economic parameters to see the references.

- Cost of the gas supply of the CHP system: The price calculation is carried out in the same way as in the reference case, since the supply of natural gas is assumed in the same economic conditions. The amount of natural gas needed will depend on the strategy adopted in each case. The thermal efficiency of the fuel cell is taken into account.

- Cost of the gas supply of an additional boiler: The amount of natural gas to be supplied to the auxiliary boiler is added to the natural gas supplied to the CHP system. It is assumed that the efficiency of that boiler is equal to that used in the reference case, because it is the same technology.

- Cost of the supply of electricity from the grid: Costs of electricity imported from the grid, in case the demand for electricity is not met by the fuel cell. This module is the same as the one used to calculate the electricity supply costs in the reference case, because the supply conditions are assumed to be the same.

- Revenue from surplus electricity sales: It is calculated with the sales price of electricity, which is determined by the market regulator in the regulated market, or by the corresponding retailer in the free market. This value fluctuates every hour for traders in the regulated market. For calculations in the techno-economic model proposed, a fixed value will be considered, as if the electricity was sold to a retailer of the free market. In the regulated market, the value of the energy sold oscillates around an average value according to the time of day, but it is expected that on average it will be close to the value offered by the retailers in the free market by obvious reasons of competition.

In regards to GHG emissions and other pollutants, by avoiding a combustion process to convert fuel to electricity, the SOFC does not produce nitrous oxides (NO_x) or fine particulate matter. Furthermore, because sulphur compounds are poisonous for the fuel cell, they need to be extracted from the fuel beforehand to ensure reliable operation, therefore sulphurous oxide (SO_x) emissions are also insignificant [6]. The calculations for the emissions will be reduced to those of CO_2, since the emissions of the rest of pollutants can be considered negligible, as can be seen in the following table.

Table 8. SOFC Emission factors in grams per kWhe using natural gas as input fuel. [35]

Pollutant	g/kWhe
CO_2	340
NOx	Negligible
SOx	Negligible
PM_{10}	Negligible
VOC	Negligible
CO	Negligible

Source: NETL (2009) and EPA (2015)

- Baseline case:
  - The CO_2emissions are calculated as the sum of emissions of the boiler and the power grid. The parameters for the calculations are the electric demand (D_{el}), the power grid's emission factor(ε_{grid}), the thermal demand (D_{th}), the boiler's efficiency (η_{boiler}) and the boiler's emission factor (ε_{boiler}):

$$(D_{el} \cdot \varepsilon_{grid}) + \left(\frac{D_{th}}{\eta_{boiler}} \cdot \varepsilon_{boiler}\right) \qquad \textit{Eq. (12)}$$

- Case studies:
  - The CO_2 emissions are calculated as the sum of emissions of the SOFC-CHP system, the auxiliary boiler's emissions, and the power grid's emissions. Emissions are discounted by electricity injected into the grid, since it is assumed that it displaces electricity that would otherwise be generated by other means with subsequent emissions. The parameters for the calculations are the electricity imported from grid (E_{imp}), the electrical emission factor of the power grid (ε_{grid}), the natural gas supplied to the fuel cell (NG_{fc}), the emission factor of the SOFC-CHP system (ε_{fc}), the natural gas supplied to the boiler (NG_{boiler}), and the boiler emission factor (ε_{boiler}):

$$(NG_{fc} \cdot \varepsilon_{fc}) + (NG_{boiler} \cdot \varepsilon_{boiler}) + (E_{imp} \cdot \varepsilon_{grid}) - \left(E_{exp} \cdot \varepsilon_{grid}\right) \qquad \textit{Eq. (13)}$$

The figure in next page shows a complete image of the Matlab / Simulink model.

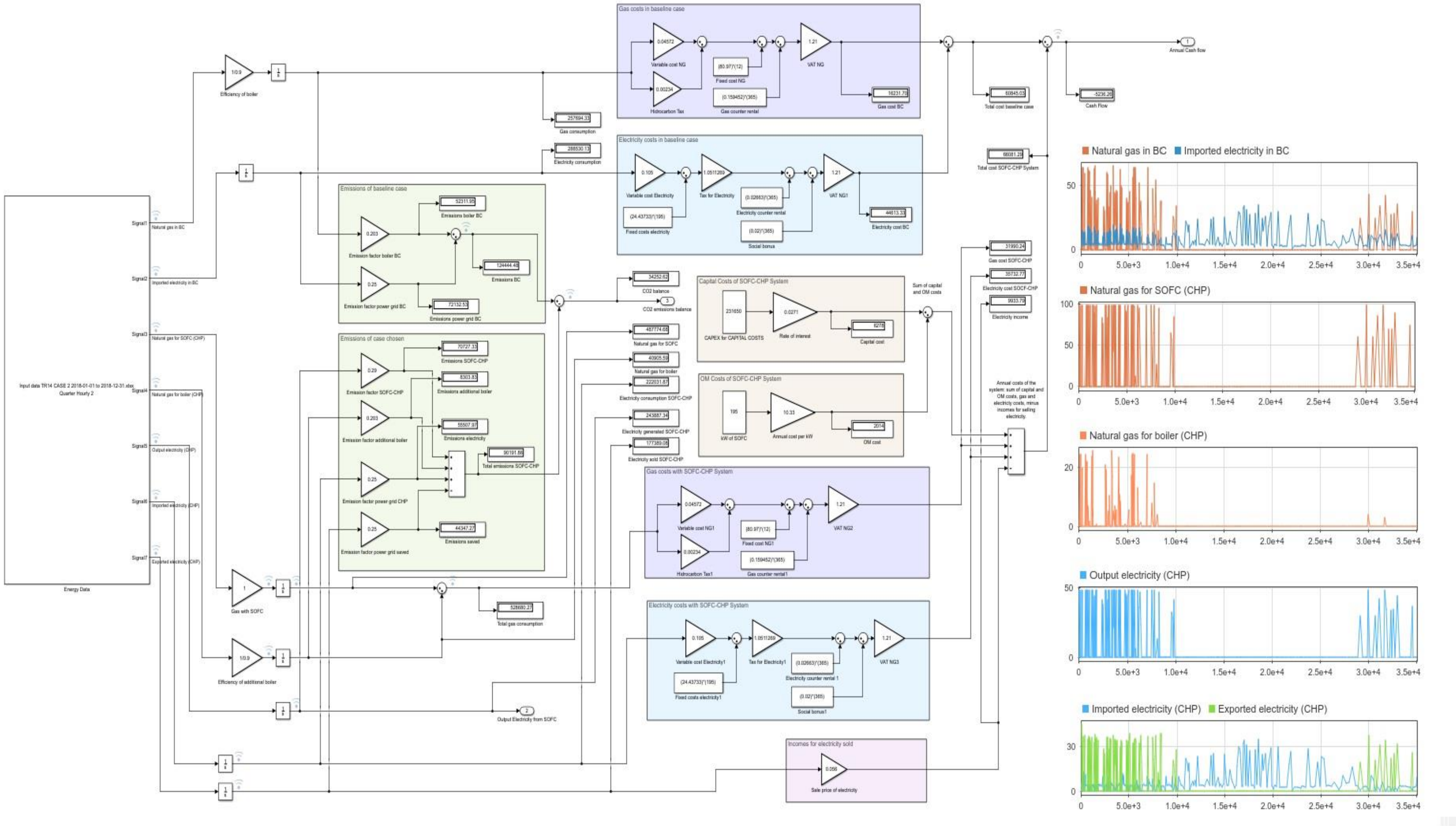


Figure 23. Matlab/Simulink model developed to calculate the cash-flow and CO_2 emissions for different fuel cell operation strategies. Source: own elaboration.

The details for the calculation of natural gas and electricity costs can be seen in the following figure. It contains fixed costs, variable costs and taxes.

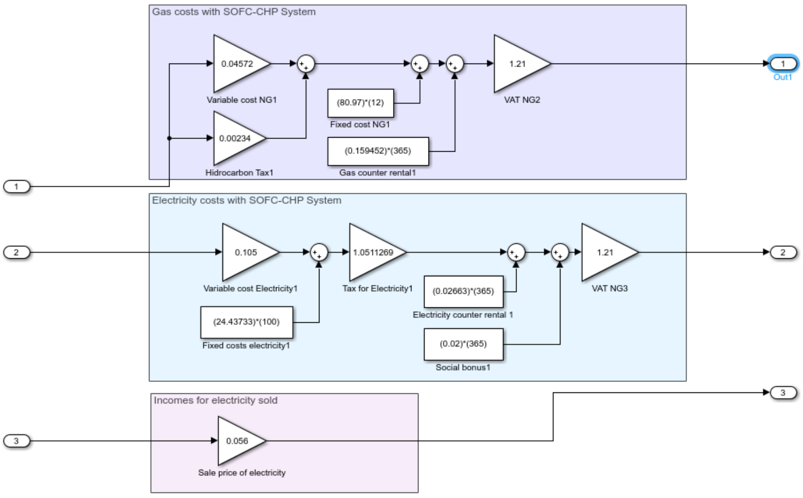


Figure 24.Detail of the subsystem for determination of gas and power supply costs.

The details for the calculation of CO_2 emissions can be seen in the following figure, with the corresponding emission factor for every technology, both for the baseline case and the other case studies.

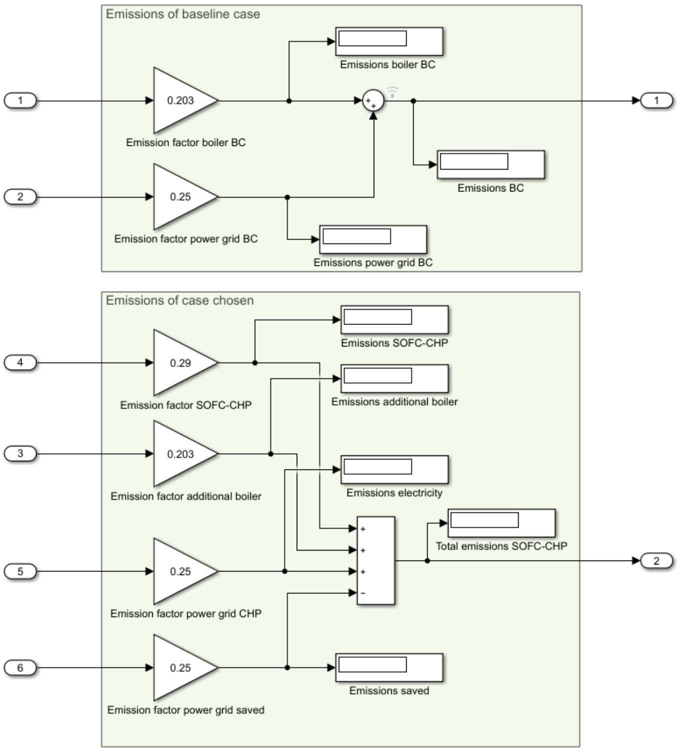


Figure 25.Details of the subsystem for determination of CO_2 emissions. Adapted from [43].

The following figures show examples of the results of the model execution.

- Inputs: heat and electricity demand curves.
- Outputs: natural gas consumption in the fuel cell and in the auxiliary boiler, electricity generated, imported and exported to the power grid.

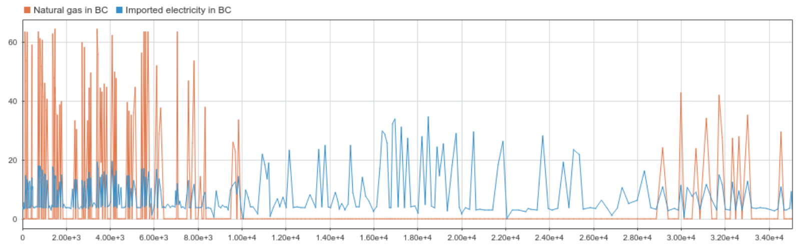


Figure 26. Inputs for the model: demand of heat and electricity of one building for a whole year.

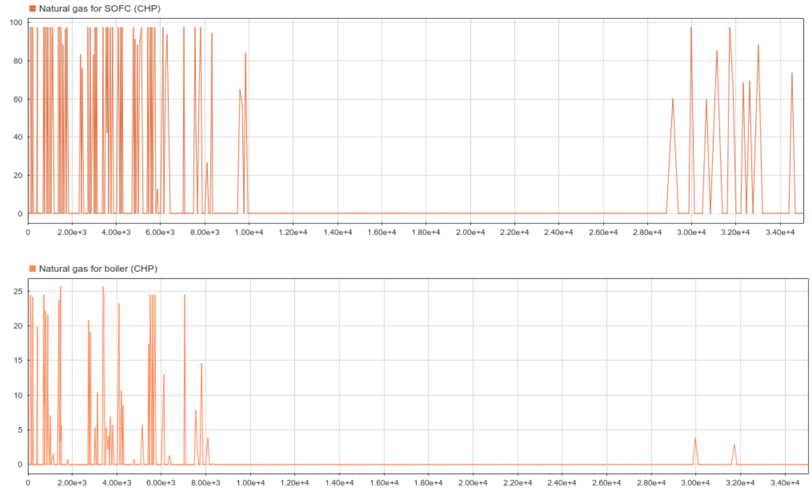


Figure 27. Outputs of the model: natural gas for the CHP system and for the auxiliary boiler.

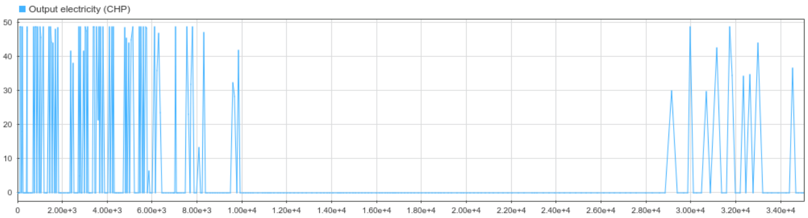


Figure 28. Another output of the model: output electricity of the CHP system.

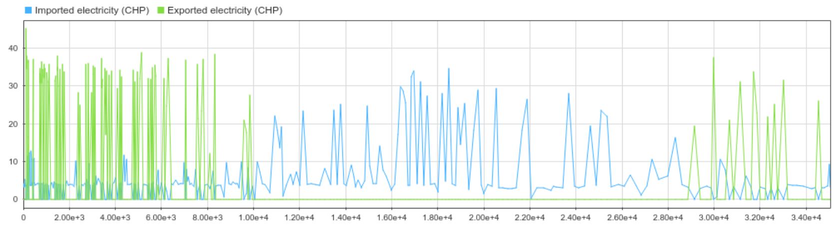


Figure 29. Outputs of the model: imported and exported electricity.

Cash flow calculation is carried out according to the following formula (14):

$$f(x) = \sum_{i=0}^{n} \left(GSC_{bc} + ESC_{bc} - \left(CAPEX_{CHP} + OM_{CHP} + GSC_{CHP} + GSC_{CHP,boiler} + ESC_{CHP} - IES_{CHP} \right) \right)$$

n	*Number of annual observations (maximum 35.040, minimum 12)*
GSC_{bc}	*Gas Supply Costs for the baseline case*
ESC_{bc}	*Electricity Supply Costs for the baseline case*
$CAPEX_{CHP}$	*Capital Costs for the CHP System*
OM_{CHP}	*Cost of O&M for the CHP System*
GSC_{CHP}	*Gas Supply Costs for the CHP System*
$GSC_{CHP,boiler}$	*Gas Supply Costs for the auxiliary boiler*
ESC_{CHP}	*Electricity Supply Costs for the CHP System*
IES_{CHP}	*Income from Electricity Sales for the CHP System*

The output of the model is the determination of the amount of gas to be imported from the grid, the amount of electricity generated, the amount of electricity to be imported from the grid and the amount of electricity that could be exported. The results are conditioned to the operation strategy that corresponds in each case. By combining this information with the economic parameters (supply rates, initial investment, interest rate, sale price of the surplus of electricity), the cash flow is calculated for a whole year of operation of the CHP system.

Besides the costs of supplies, there are more criteria that impact the investment plan and the prospects for return of investment: subsidies, CO_2 taxation, or acceptance of power feed-in in the grid (in Spain the situation has changed for good recently, see the corresponding royal decree at [44]).

After each run of the Matlab/Simulink model, the results are used to perform a 10-year projection corresponding to the use-phase. It is possible to observe the variations of the economic cash-flow and NPV when changing several economical variables:

- Electrical power of the fuel cell to be installed.
- Existence of government grants to cover the initial investment.
- Use of own capital or third party loan subject to interest rate.
- Changes in the trend of evolution of electricity and natural gas supply prices.

This allows a sensitivity analysis to be made for cash-flow and payback period based on the aforementioned variables. This analysis is done in section 7.

CASE 2 OPERATION MODE: GRID CONNECTION OPERATION STRATEGY: FOLLOW HEAT DEMAND

YEAR OF OPERATION	0	1	2	3	4	5	6	7	8	9	10
FUEL COSTS BASELINE CASE (GAS FROM GRID)											
GAS CONSUMPTION (kWh) (SIRENA)		257.694	257.694	257.694	257.694	257.694	257.694	257.694	257.694	257.694	257.694
TOTAL GAS UTILITY COSTS (€)		16.231 €	16.556 €	16.887 €	17.224 €	17.569 €	17.920 €	18.279 €	18.644 €	19.017 €	19.398 €
ELECTRICITY COSTS BASELINE CASE (ELECTRICITY FROM GRID)											
ELECTRICITY CONSUMPTION (kWh) (SIRENA)		288.530	288.530	288.530	288.530	288.530	288.530	288.530	288.530	288.530	288.530
TOTAL ELECTRICITY UTILITY COSTS (€)		44.613 €	49.520 €	54.968 €	61.014 €	67.726 €	75.175 €	83.445 €	92.624 €	102.812 €	114.122 €
TOTAL COSTS BASELINE CASE (€)		**60.844 €**	**66.076 €**	**71.854 €**	**78.239 €**	**85.295 €**	**93.096 €**	**101.724 €**	**111.268 €**	**121.830 €**	**133.519 €**
FC-CHP SYSTEM INVESTMENT & OPERATION COSTS											
CAPEX (€)	231.650 €										
CAPITAL COSTS (€)		6.278 €	6.278 €	6.278 €	6.278 €	6.278 €	6.278 €	6.278 €	6.278 €	6.278 €	6.278 €
O&M (€)		2.014 €	2.014 €	2.014 €	2.014 €	2.014 €	2.014 €	2.014 €	2.014 €	2.014 €	2.014 €
REPLACEMENT COSTS (€)		- €	- €	- €	- €	- €	69.495 €	- €	- €	- €	- €
TOTAL COSTS (€)	231.650 €	8.292 €	8.292 €	8.292 €	8.292 €	8.292 €	77.787 €	8.292 €	8.292 €	8.292 €	8.292 €
FUEL COSTS FC-CHP (GAS FROM GRID)											
GAS CONSUMPTION SOFC (kWh)		487.774	487.774	487.774	487.774	487.774	487.774	487.774	487.774	487.774	487.774
GAS CONSUMPTION BOILER (kWh)		40.905	40.905	40.905	40.905	40.905	40.905	40.905	40.905	40.905	40.905
TOTAL GAS UTILITY COSTS (€)		31.990 €	32.630 €	33.282 €	33.948 €	34.627 €	35.320 €	36.026 €	36.746 €	37.481 €	38.231 €
ELECTRICITY COSTS FC-CHP (ELECTRICITY FROM GRID)											
ELECTRICITY CONSUMPTION (kWh)		222.031	222.031	222.031	222.031	222.031	100	222.031	222.031	222.031	222.031
TOTAL ELECTRICITY UTILITY COSTS (€)		35.762 €	39.696 €	44.062 €	48.909 €	54.289 €	60.261 €	66.890 €	74.248 €	82.415 €	91.481 €
INCOMES FC-CHP (ELECTRICITY TO GRID)											
ELECTRICITY GENERATED BY SOFC (kWh)		243.887	243.887	243.887	243.887	243.887	100	243.887	243.887	243.887	243.887
ELECTRICITY SOLD TO THE GRID (kWh)		177.389	177.389	177.389	177.389	177.389	100	177.389	177.389	177.389	177.389
ELECTRICITY INCOMES (€)		9.933 €	11.026 €	12.238 €	13.585 €	15.079 €	16.738 €	18.579 €	20.622 €	22.891 €	25.409 €
TOTAL COSTS WITH FC-CHP SYSTEM (€)		**66.111 €**	**69.592 €**	**73.398 €**	**77.565 €**	**82.129 €**	**156.630 €**	**92.629 €**	**98.664 €**	**105.297 €**	**112.595 €**
CASH FLOW											
CASH FLOW (SAVINGS+INCOMES-SYSTEM COSTS)	- 231.650 €	- 5.267 €	- 3.516 €	- 1.544 €	674 €	3.165 €	- 63.534 €	9.095 €	12.604 €	16.532 €	20.925 €
CASH FLOW (NPV)	- 231.650 €	- 5.205 €	- 3.434 €	- 1.490 €	643 €	2.983 €	- 59.174 €	8.371 €	11.464 €	14.860 €	18.586 €
ACCUMULATED CASH FLOW	- 231.650 €	- 236.917 €	- 240.433 €	- 241.977 €	- 241.303 €	- 238.138 €	- 301.672 €	- 292.578 €	- 279.973 €	- 263.441 €	- 242.516 €
ACCUMULATED CASH FLOW (NPV)	- 231.650 €	- 234.126 €	- 234.802 €	- 233.526 €	- 230.132 €	- 224.437 €	- 280.967 €	- 269.286 €	- 254.650 €	- 236.790 €	- 215.414 €

PARAMETERS	
Gas cost (€/kWh)	0,04572
Fixed costs gas (€/día)	2,699
Energy of gas (HHV) (kWh/m3)	11,537
Hydrocarbons tax (€/kWh)	0,00234
Expected annual price increase (%)	2%
Electricity cost (€/kWh)	0,105
Electricity sale price (€/kWh)	0,056
Price per Power contracted (€/kW)	24,43733
Power contracted (kW)	195
Electricity Tax (%)	5,11%
Counter daily fee (€/day)	0,02663
Social Bonus (€/day)	0,02
Expected annual price increase (%)	11%
Effective Interest rate (%)	1,2%
Inflation expected (%)	1,5%
VAT (%)	21%
SOFC-CHP System CAPEX (€/kW)	1033
SOFC-CHP System power (kW)	195
SOFC-CHP System O&M (€/(kw x year))	10,33
SOFC-CHP System installation costs (%)	15%
SOFC-CHP System loan interest rate (%)	2,71%
SOCF-CHP System Electrical Efficiency (%)	50%
SOCF-CHP System Thermal Efficiency (%)	40%
SOFC-CHP System annual degradation (%)	0%
Boiler Efficiency	0,9
Capital from loan	YES
Government Grant (or own capital)	0%

Figure 30.Exemple of 10-year projection of the results obtained from the Matlab/Simulink model.

In the following section, the actual heat and electricity demand data of the three buildings that have been considered in the analysis are presented. Each of them has a different heat-to-power ratio, and therefore the results of the operating strategies of the SOFC-CHP system vary quantitatively and qualitatively from one building to another.

5. Case Study real data

5.1. Selection of the buildings

An important factor to determine the economical feasibility of a CHP system is the "utilization factor": the calculated hours of operation of a CHP system expressed as a percentage of the total number of hours in a year. The maximization of the utilization factor of a CHP system is important since it will greatly affect the efficiency and cost effectiveness (payback time). To be economical, a good base load for electrical demand and heat demand must exist. Such base loads arise where building occupation or process activities are extended or continuous in operation. This typically includes for hospitals, manufacturing processes, swimming pools, airports, hotels, apartment blocks, etc.

The case of this work do not correspond with the aforementioned cases. Therefore, the profitability calculation of a SOFC-CHP system requires a detailed analysis for every particular building, with its particular heat and electricity load.

Another important factor that determines the CHP economics is the gas and electricity price, or more exactly the price difference between gas price and (substituted) electricity price. Spain would be a favored country for CHP systems because that difference is superior to other European countries [9][32].

Thermal and electrical energy consumption data in this work come from the SIRENA information system, a monitoring tool for energy and water consumption in buildings of the UPC. SIRENA has a web interface that offers data for different buildings, both electrical energy consumption (kWh) and thermal energy consumption (kWh) at resolution of 15 minutes. It also calculates the maximum peak power of the day, by taking the maximum value of energy consumed every quarter of an hour and multiplying the value by four. It offers data on energy consumption in 74 buildings of the UPC.

The data of the buildings have been analyzed, and three of them have been chosen with different consumption loads:

- A building with heat-to-power ratio near 1 (similar annual demand of heat and power), building TR14.
- A building with heat-to-power ratio near 2 (double annual demand of heat versus power), building TR8.
- A building with heat-to-power ration near 0,5 (double annual demand of power versus heat), building D7C.

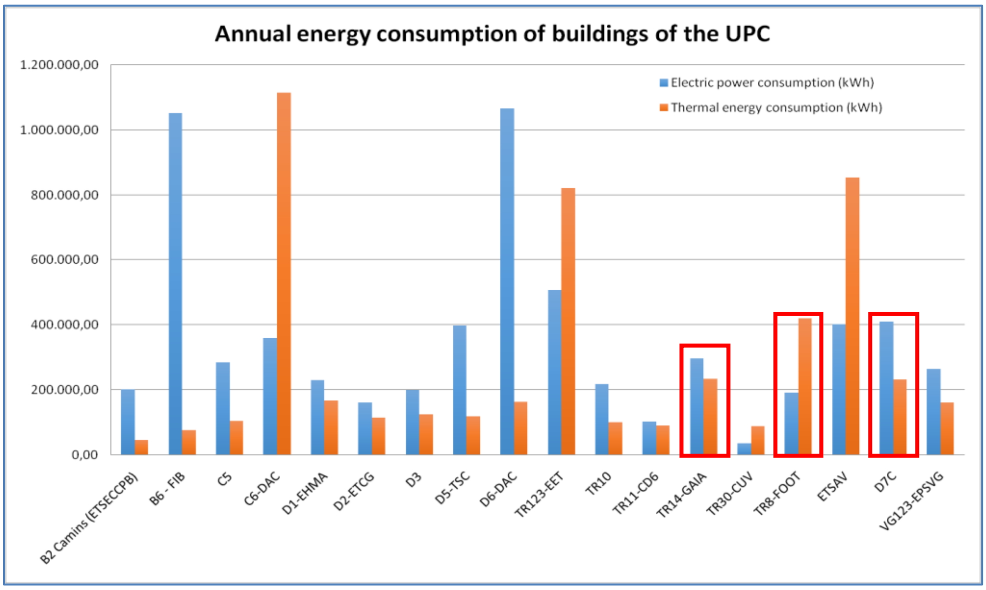


Figure 31. Electrical annual energy consumption and thermal energy consumption of several buildings of the UPC. Source: SIRENA and own elaboration.

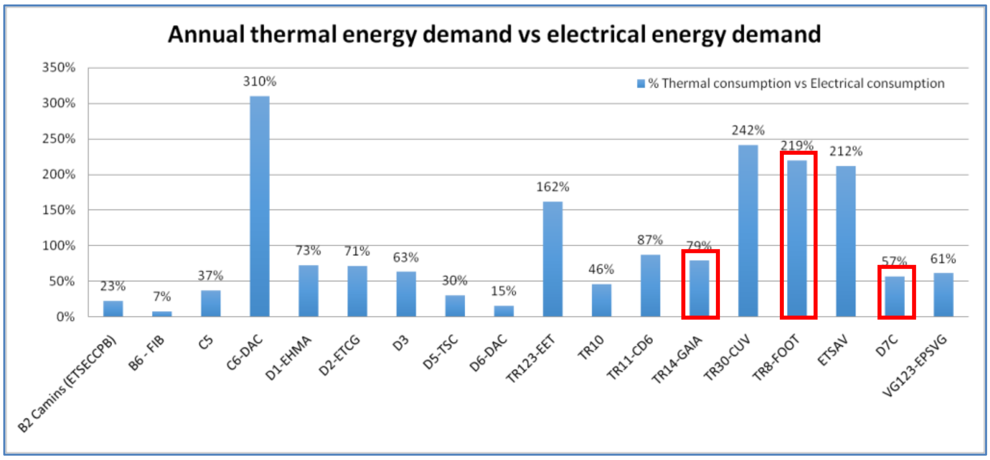


Figure 32. Percentage of thermal energy consumption versus electric power consumption of several buildings of the UPC. Source: SIRENA and own elaboration.

The information of energy demand is available in different time intervals, from data every 15 minutes to monthly-aggregated data. After a detailed review of the data to eliminate anomalous observations and correct "holes" (points where the measurement was missing), detailed consumption curves of the selected buildings for a full year could be obtained.

For each three buildings, the consumption data of SIRENA has been supplied to the Matlab/Simulink model, and a comparison has been made between the costs of the current situation (baseline case) and the costs of the SOFC-CHP system.

The techno-economical parameters used for the model are summarized in the following table.

Table 9. Key parameters used in the model for calculations in use-phase of the SOFC-CHP system.

Parameter	Description
Building types	Administrative buildings, classrooms and research laboratories.
Locations	Terrassa and Castelldefels, Catalonia.
Load Shapes	Electricity load and space heating demand derived from real data from SIRENA. Annual demand data with a resolution of 15 minutes.
Fuel cell system size	Building dependent: • 70 kW for building TR8 (Facultat d'Òptica i Ortometria), equal to current electrical power contracted according to data published by the UPC [4]. • 275 kW for building D7C, 170 kW for building TR14, according to the average of maximum power measured in SIRENA in the month of maximum demand (July) with a safety factor of 15%.
Waste heat usage	Waste heat can be used for: • Space heating (focus in this report). • Space cooling (trigeneration with adsorption chillers, possible improvement).
Supplementary energy sources	Purchased electricity from the grid if total electrical demand exceeds fuel cell capacity. Natural gas conventional heating if the total space heating demand exceeds FC output at any given time.
Electricity cost	Rate 3.0 for companies from retailer Som Energia. Taxes and fees according to current legislation.
Installation costs	15% of the system acquisition cost (€).
O&M costs	1% of the acquisition cost (€/kW).
Natural gas costs	Rate 3.4 for companies from retailer Naturgy. Taxes and fees according to current legislation.
Lifetime of system	10 years, with one stack replacement.

In the following sections will be detailed the information collected from the SIRENA system for the selected buildings. The annual graphs of electric and thermal energy consumption will be displayed. It will show how the shape of these curves changes according to the density of the data, which leads to different results in the evaluation of the economic viability of the CHP system with SOFC.

5.2. Building TR14: Similar demand for heat and power

The first selected building is TR14 Gaia Building, from Terrassa Campus, with a demand for thermal energy that represents almost 80% of the demand for electric power.

The following figures show the electrical demand for a whole year, with data every 15 minutes aggregated per day, week and month. The demand for energy increases in the hottest months of the year, presumably because of the air conditioning equipment.

When using data per week and month, the shape of the curve is maintained but some detail is lost. For example, when using weekly data the detail of the daily oscillations is lost. In the same way, when using monthly data the detail of the weekly oscillations is lost.

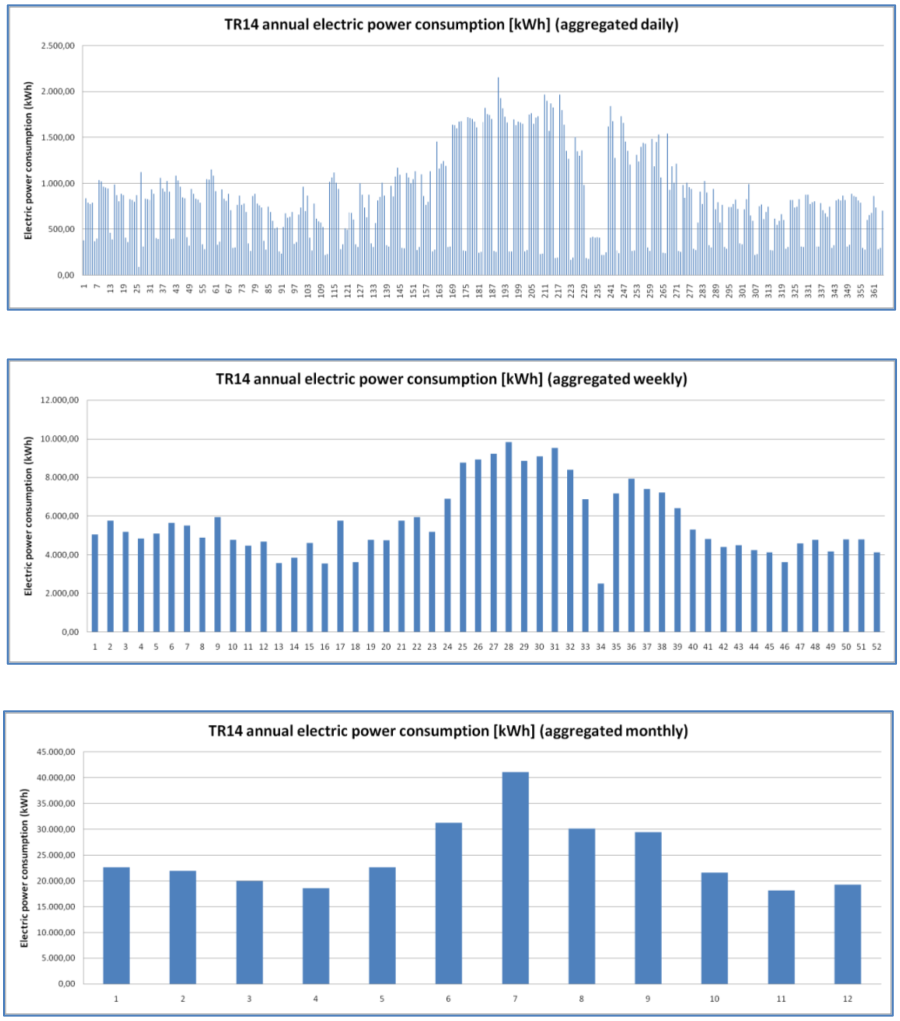


Figure 33. Electrical energy consumption for a whole year for TR14 Building: daily, weekly and monthly basis. Source: SIRENA and own elaboration.

The following figures show the thermal demand for a whole year, with data every 15 minutes aggregated per day, week and month. The pattern appears corresponding to a strong demand in the coldest months and a zero demand in the warmer months. It is also appreciated that the consumption decreases to zero daily during some hours even in the cold months, due to the fact that the demand for heating is null at night, as it is a non-residential building.

As has already been seen with electrical consumption, when using aggregate data the shape of the curve is maintained but some detail is lost.

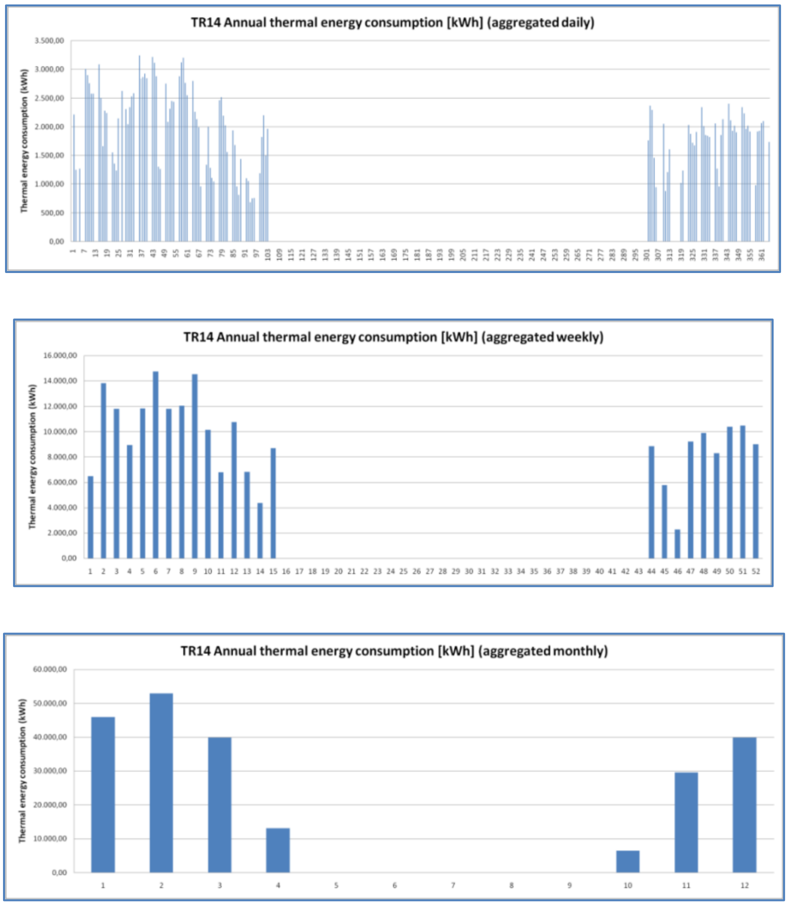


Figure 34. Thermal energy consumption for TR14 Building: daily, weekly and monthly basis.Source: SIRENA and own elaboration.

The joint demand that the fuel cell has to cover can be seen in the following figure where the two overlapping demands is seen on a daily basis.

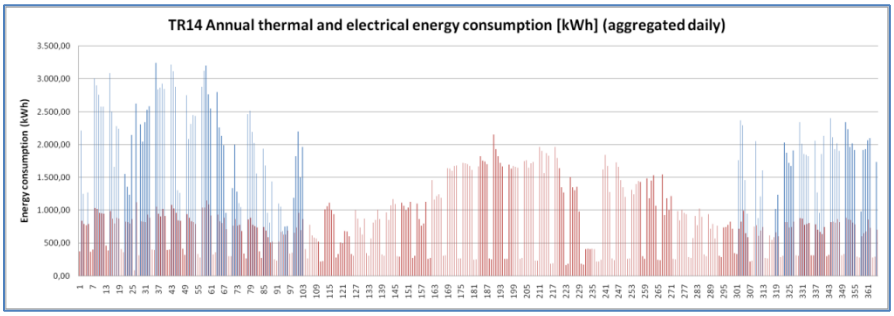


Figure 35. Electricity and gas consumption combined for TR14 Building, daily basis. Source: SIRENA and own elaboration.

In the following figures can be seen the superposition of the curves (with measurements taken every 15 minutes) of the electrical and thermal energy demand for a summer day, a winter day, and a day of the months with intermediate temperatures. The higher demand is one or the other depending on the time of day except on summer days, when there is no demand for thermal energy for heating and therefore there is only demand for electrical energy. It can also be seen that the electricity demand is never zero.

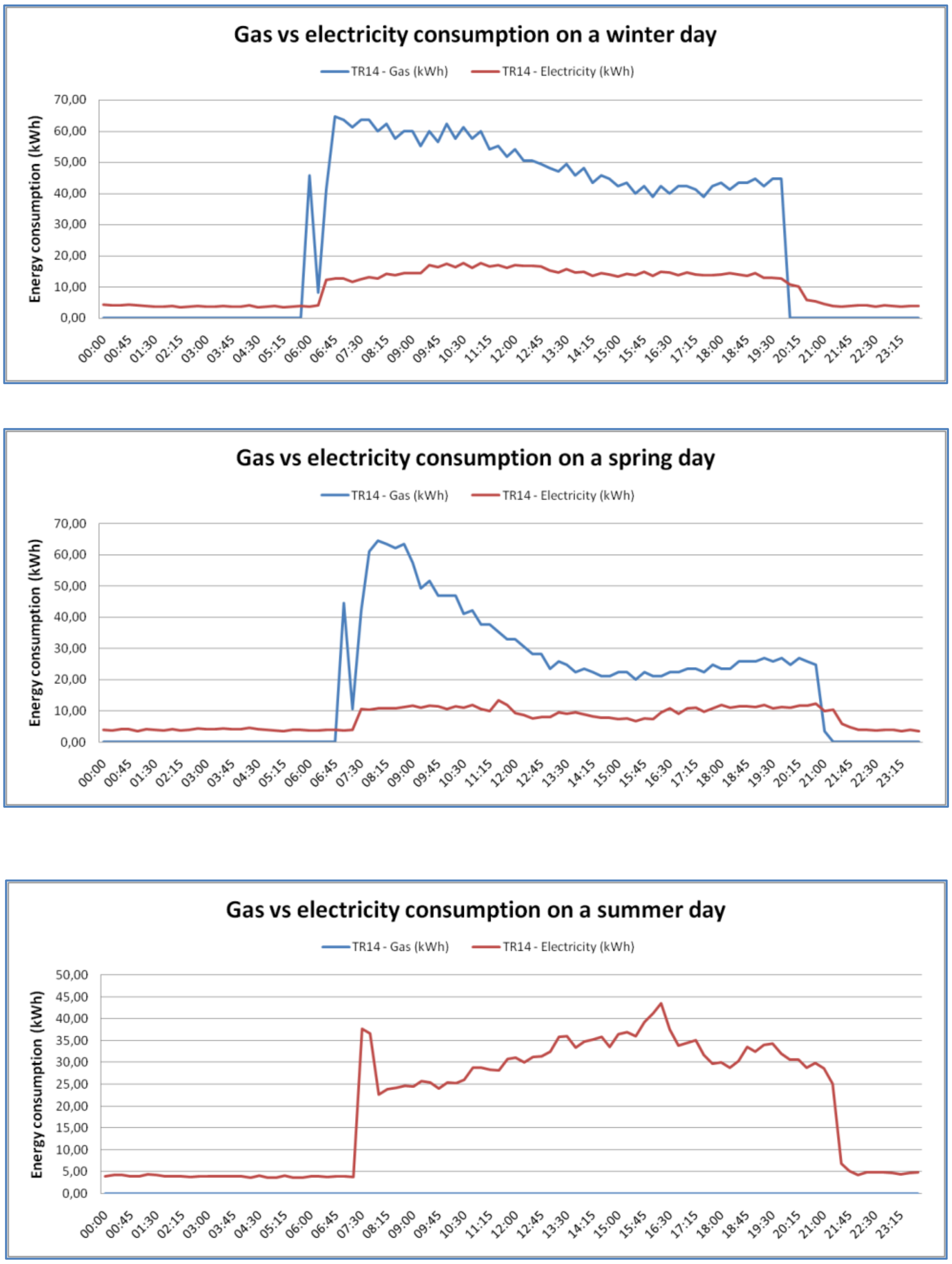


Figure 36. Electricity and gas consumption on a winter day, spring day and summer day. Source: SIRENA and own elaboration.

5.3. Building TR8: Heat demand doubles power demand

The selected building is TR8,Facultat d'Òptica i Ortometria, from Terrassa Campus, with a demand for thermal energy that represents 220% of the demand for electric power.

The following figures show the electrical demand for a whole year, with data every 15 minutes, added per day, week and month.

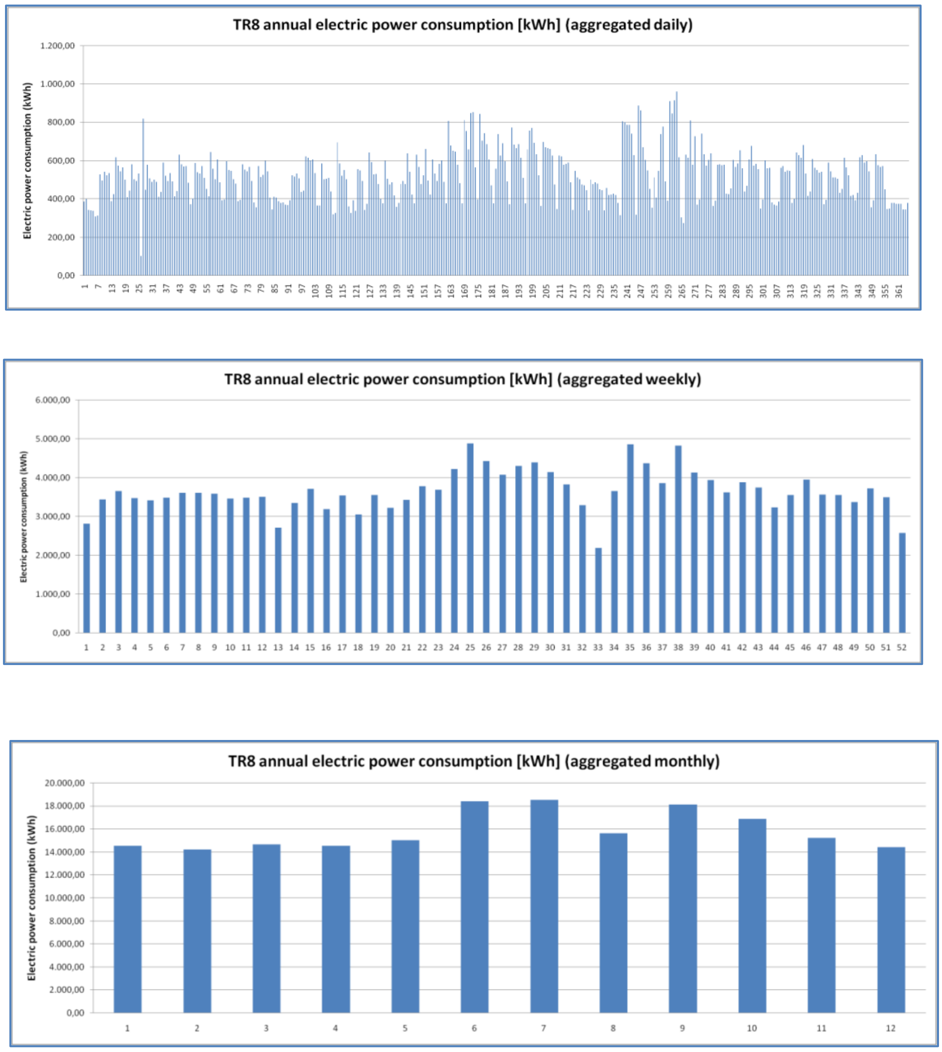


Figure 37. Electricity consumption for a whole year for TR8 Building: daily, weekly and monthly basis. Source: SIRENA and own elaboration.

The following figures show the thermal demand for a whole year. As in the two previous building, a pattern of strong demand in the coldest months and a zero demand in the warmer months is clear.

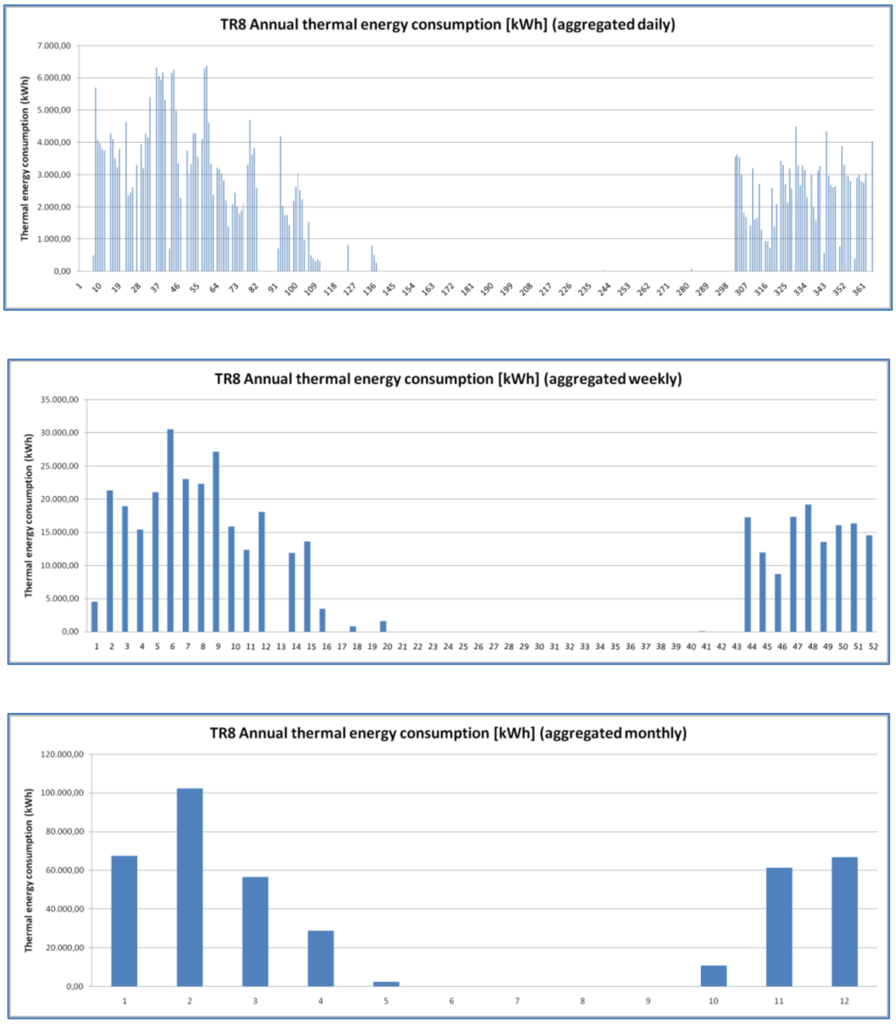


Figure 38. Gas consumption for a whole year for TR8 Building: daily, weekly and monthly basis. Source: SIRENA and own elaboration.

The joint demand that the fuel cell has to cover can be seen in the following figure where the two overlapping demands are seen on a weekly basis.

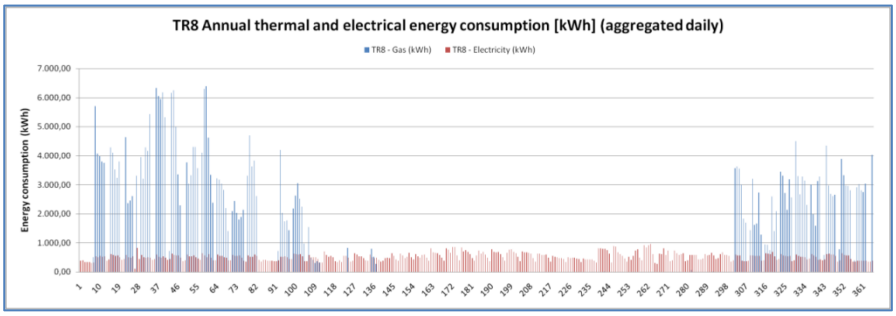


Figure 39. Electricity and gas consumption for a whole year for TR8 Building, separately and combined, weekly basis. Source: SIRENA and own elaboration.

In the following figures can be seen the superposition of the daily curves of the electrical and thermal energy demand for a summer day, a winter day and a day of the months with intermediate temperatures. The thermal demand is much higher than the electrical one in the months in which heating is required.

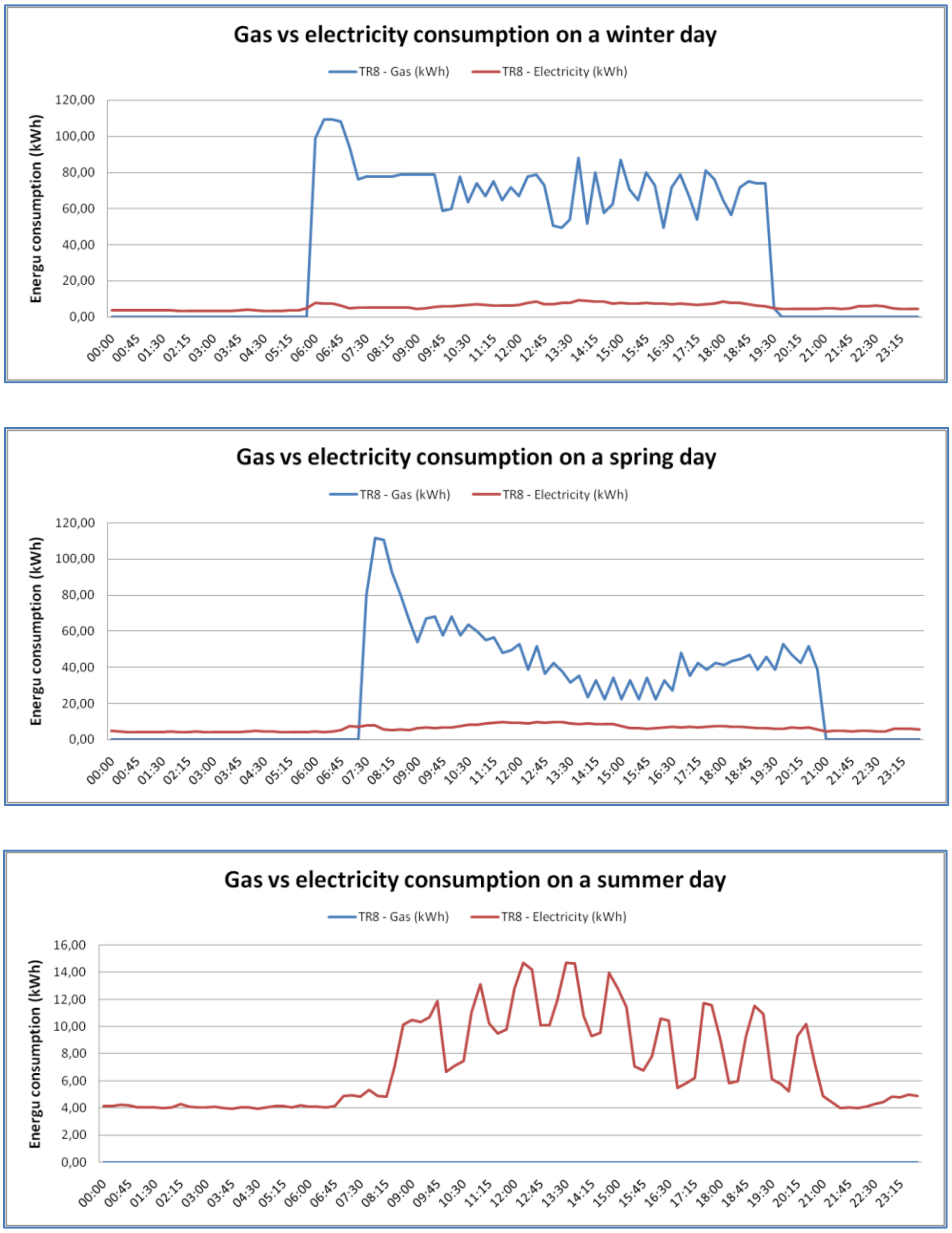


Figure 40. Electricity and gas consumption for TR8 building on a winter day, spring day and summer day. Source: SIRENA and own elaboration.

5.4. Building D7C: Power demand doubles heat demand

The selected building is D7C, Campus Building, from Castelldefels Campus, with a demand for thermal energy that represents only 57% of the demand for electric power.

The following figures show the electrical demand for a whole year, with data every 15 minutes aggregated per week and per month. In this case there is an increase in electricity consumption in the summer months, but not as pronounced as in the previous cases.

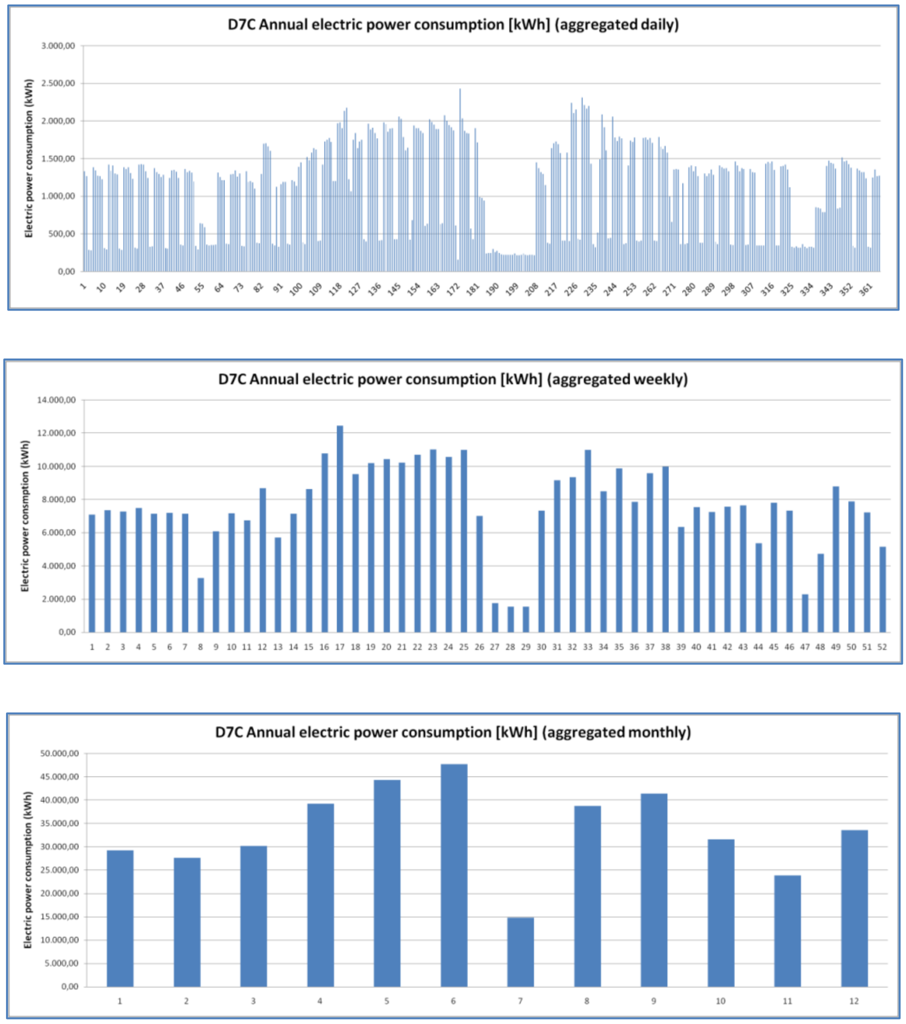
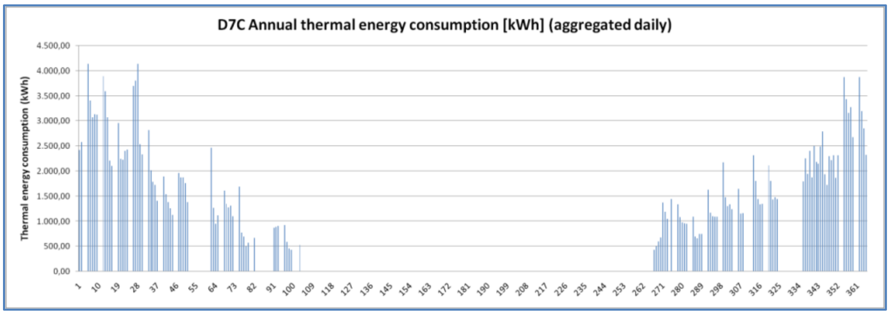
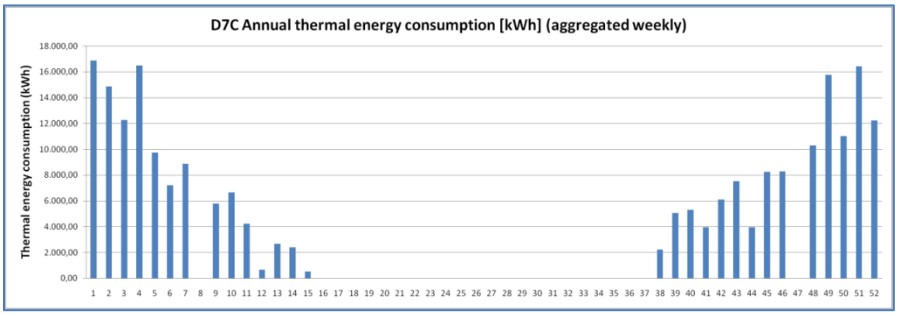


Figure 41. Electricity consumption for D7C Building: daily, weekly and monthly basis. Source: SIRENA and own elaboration.

The following figures show the thermal demand for a whole year. As in the previous building, a pattern of strong demand in the coldest months and a zero demand in the warmer months is clear.





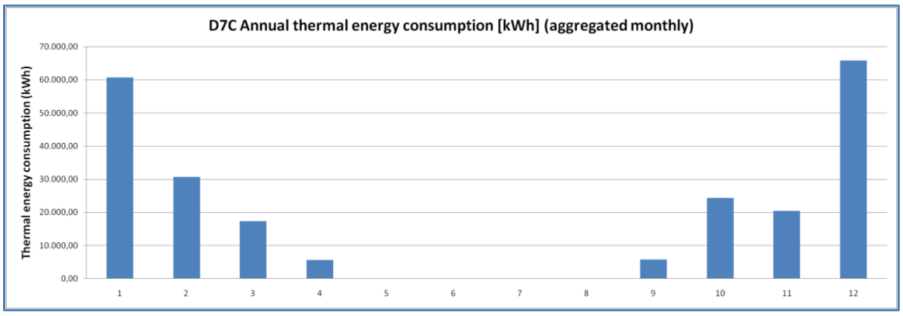


Figure 42. Gas consumption for a whole year for D7C Building: daily, weekly and monthly basis. Source: SIRENA and own elaboration.

The joint demand that the fuel cell has to cover can be seen in the following figure where the two overlapping demands are seen on a weekly basis.

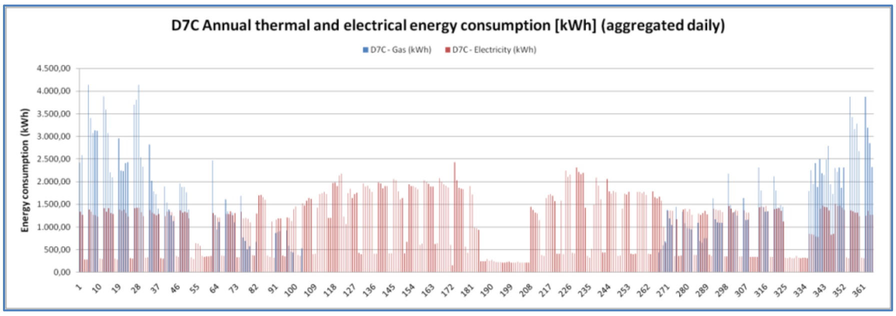


Figure 43. Electricity and gas consumption for a whole year for D7C Building combined, weekly basis. Source: SIRENA and own elaboration.

In the following figures can be seen the superposition of the curves (with measurements taken every 15 minutes) of the electrical and thermal energy demand for a summer day, a winter day and a day of the months with intermediate temperatures. The upper demand is thermal, for almost all the time that there is demand for heating. This means all school hours in the cold months, and approximately between 7 a.m. and 1 p.m. in the middle months. It can also be seen that the electricity demand is never zero.

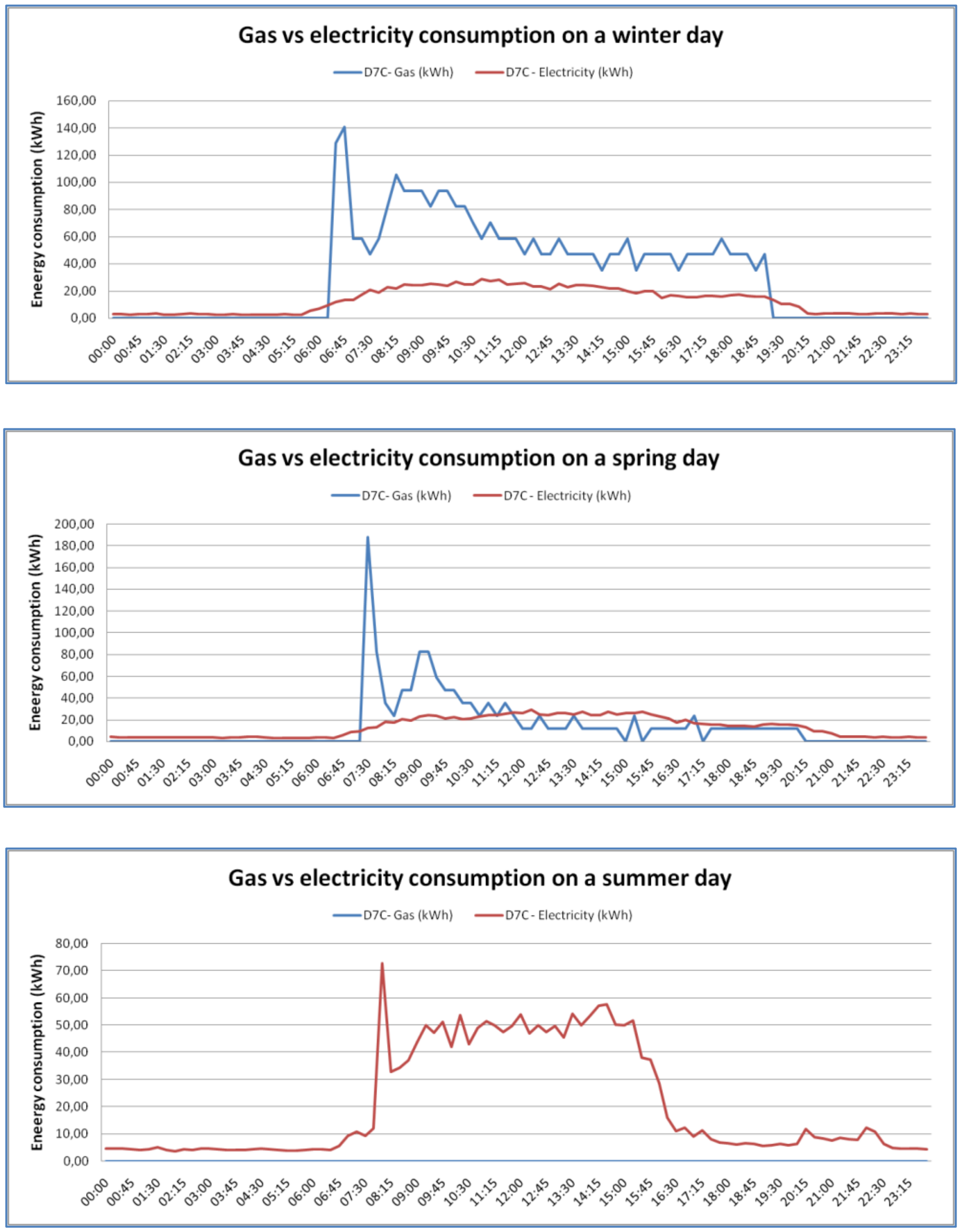


Figure 44. Electricity and gas consumption for D7C Building on a winter day, spring day and summer day. Source: SIRENA and own elaboration.

6. Scenarios and Operation Strategies

The following paragraphs describe the results of the model for each case study, that is, for each combination of building, operation mode and operation strategy. The economics of each option are the focus of the work, and the environmental outcomes in terms of carbon dioxide emissions and primary energy consumption are also considered in each case. All scenarios are compared with the baseline case, to determine the resulting cash flow savings and the reduction of emissions.

To calculate the annual cost, data from the SIRENA system is taken for a full year, with different sampling times, being the highest resolution of 15 minutes between observations. The higher the number of measurements, the better is captured the structure of electricity and heat demand. Altogether, data from the SIRENA system have been extracted with 5 different sampling time, namely:

- Measurements every 15 minutes.
- Measurements aggregated hourly.
- Measurements aggregated daily.
- Measurements aggregated weekly.
- Measurements aggregated monthly.

Every case study will be compared with the baseline case, in order to calculate the cash flow as the difference between the costs of the current situation and the case study in question. The following figure shows the general idea of the comparison.

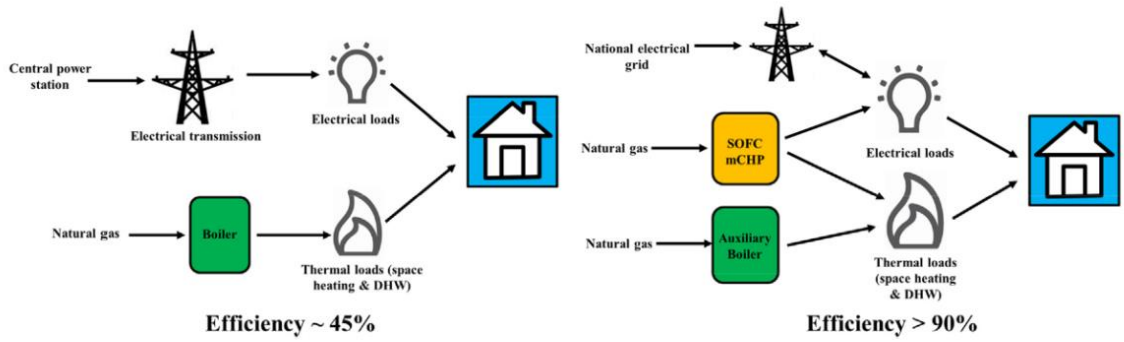


Figure 45. The assessment compares the base case scenario (left) with a SOFC-CHP scenario (right) with different control strategies.[43]

6.1. Sizing of the system

To analyze all the strategies in equal conditions, the sizing criteria of the system will be the same for all of them. The fact that there are strategies that operate connection to the power grid, implies a restriction in sizing: the system must have enough power to cover the building's electrical demand even on the days of greatest demand. To size the system, the maximum demand observed during the year has been taken for each building, and a 15% has been added as a safety margin (in the case of the TR8 building, the system has been sized according to the contracted electrical power, since it is positively known to be 70kW [4]).

6.2. Case studies

6.2.1. Case study 1: Current Situation (baseline case)

This case represents the current situation, in which the demand for thermal and electrical energy has to be met with supplies from the gas network and the power grid. For both supplies a tariff representative of those existing in the market is taken.

6.2.2. Case study 2: Heat-Driven operation strategy

In this case the building is considered to be connected to the power grid, and it is considered that the operation strategy of the fuel cell is to meet the demand for thermal energy. When the electricity generated does not match the electricity demand, it can be imported from the grid. The surplus of electricity can be exported to the grid. In the months when there is no demand for thermal energy for heating, the fuel cell remains shut down, and all the electrical energy is obtained from the grid.

6.2.2.1. Building TR14

The result of applying the operation strategy of follow heat demand can be seen in the following figure. Regardless of the sampling time used, a return on investment is not achieved in the analyzed time horizon of 10 years. In fact, cash flow is negative in the first three years, because the costs incurred are higher than in the baseline case. Only the increase in the prices of supplies makes the cash flow become positive from the fourth year (except the year of the replacement of the stack).

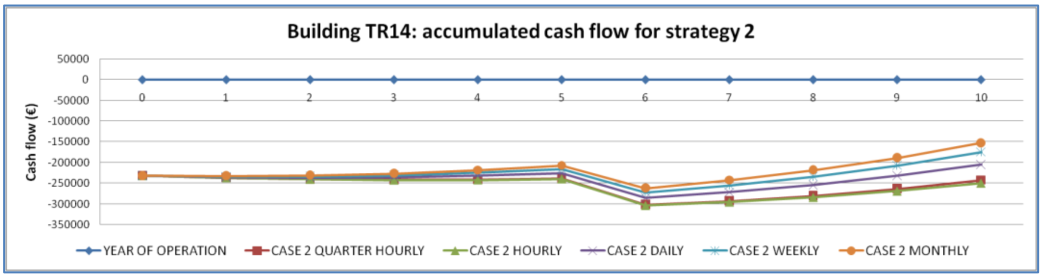


Figure 46. Accumulated cash flow for strategy 2 in building TR14 for different sampling times.

It is observed that the results are better when sampling time is greater. But even with the results obtained with data every 15 minutes, this mode of operation is far from offering a return on investment in less than 10 years.

6.2.2.2. Building TR8

In this case it is also appreciated, if the reader focus on the quarter hourly line, that the operation strategy does not offer a return on investment over the 10-year horizon. Although results are better, sufficient savings are not achieved. As in the previous case, it is observed that the results improve as the sampling time increases.

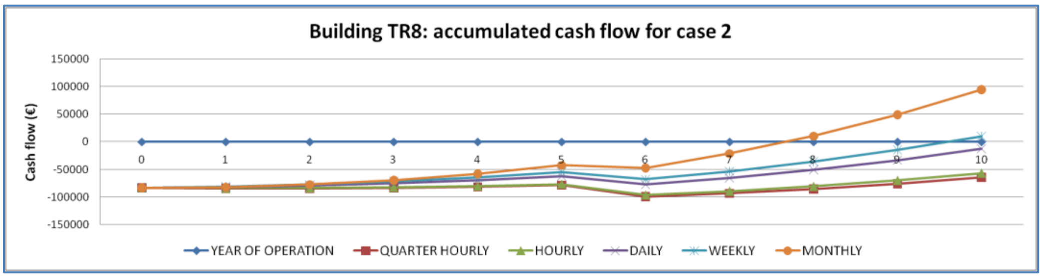


Figure 47. Accumulated cash flow for case 2 in building TR8 for different sampling times.

6.2.2.3. Building D7C

Neither in this case a return on investment is obtained in the established time horizon, although there is a positive cash flow from the second year onwards.

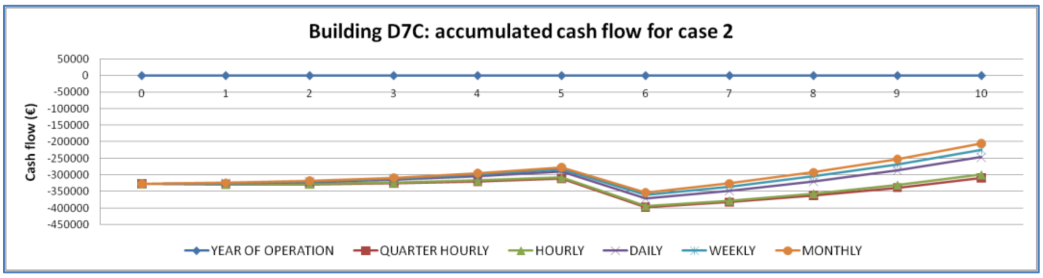


Figure 48. Accumulated cash flow for case 2 in building D7C for different sampling times.

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6.2.3. Case study 3: Maximum-Driven operation strategy

In this case it is considered that the operation of the fuel cell is adjusted to meet the higher demand for energy, be it heat or power. In the cold months, the demand for thermal energy will be greater than the demand for electrical energy in a large part of the working hours. On the contrary, in the warm months the demand for electrical energy will be higher than the demand for thermal energy throughout the day, since heating is not required.

This case has been divided into two sub-cases: in the first (Case 3A) it is considered that the building is connected to the power grid and, when the electric power generated by the fuel cell does not match the demand, energy is imported from the grid or the surplus is exported with the corresponding income.

In the second case (Case 3B), it is considered that the building operates disconnected from the power network. This allows saving the fixed costs of the electricity supply, but prevents the surplus of electricity from being exported to the network. This surplus is used to generate heat by means of resistances, so as to reduce the natural gas demand from the gas grid.

6.2.3.1. Building TR14

The result when the first operation mode is considered (Case 3A) is that the cash flow is positive from the second year onwards, but the return on investment is not achieved in the ten years considered, as can be seen in the following figure.

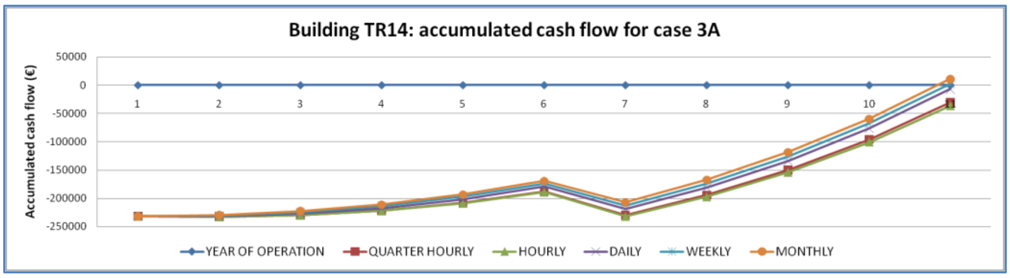


Figure 49. Accumulated cash flow for case 3A in building TR14 for different sampling times.

In the case 3B, a positive cash flow is achieved from the first year and a return on investment in the ninth year.

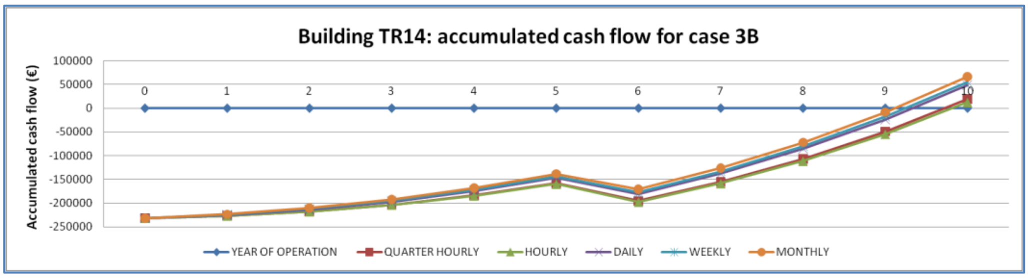


Figure 50. Accumulated cash flow for case 3B in building TR14 for different sampling times

6.2.3.2. Building TR8

With operation mode 3A there is a return on investment in the eighth year. Cash flow is positive as of the first year, and its value grows as supplies prices increase year after year.

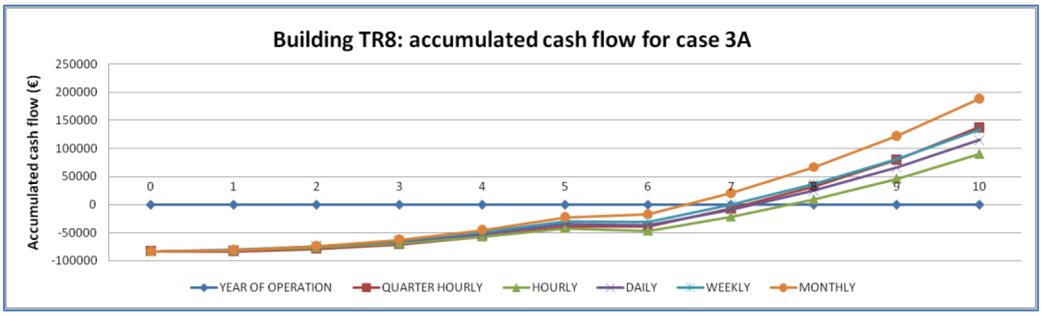


Figure 51. Accumulated cash flow for case 3A in building TR8 for different sampling times.

With the 3B mode of operation the results are slightly worse: although a return is also obtained in the eighth year, the cash flow is lower.

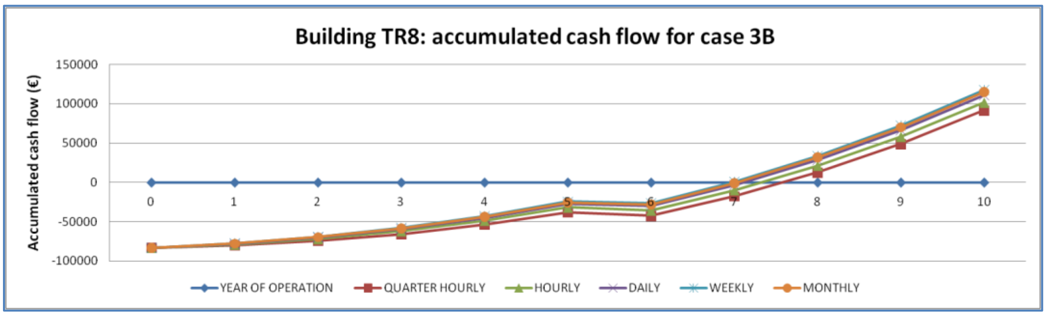


Figure 52. Accumulated cash flow for case 3B in building TR8 for different sampling times.

6.2.3.3. Building D7C

For this building, the 3A mode of operation does not provide a return on investment, although the cash flow is positive from the first year onwards. The investment to be made is too large due to the size of the fuel cell that is required to cover all the electricity demand.

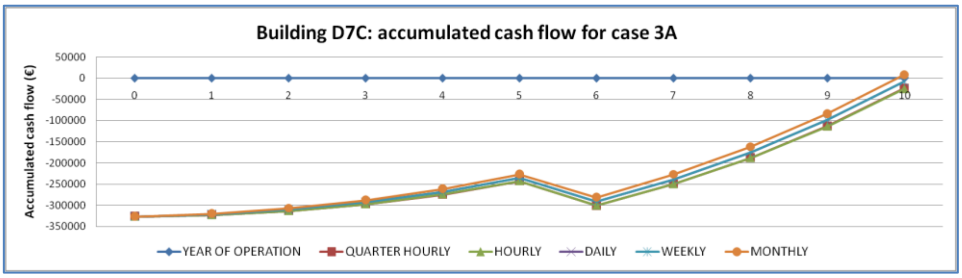


Figure 53. Accumulated cash flow for case 3A in building D7C for different sampling times.

With the 3B mode of operation the results improve because less natural gas is needed to meet the heat demand, due to the use of excess electricity to generate heat. In addition, the savings of not being connected to the power grid exceed the losses from the sale of energy to the grid. This is because the fixed term of electricity is high is Spain, on the one hand, and because the price of exported electricity is 1/2 compared to the price of the imported one with the rate used. Even so, a return on investment in the tenth year is very little attractive to make the investment.

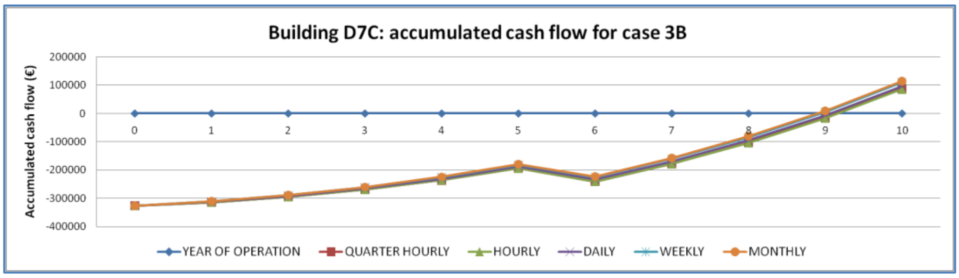


Figure 54. Accumulated cash flow for case 3B in building D7C for different sampling times.

6.2.4. Case study 4: Electric-Driven operation strategy

In this case it is considered that the fuel cell works according to the demand for electricity, and the system is sized to meet peak demand. When the thermal energy generated does not cover the demand, natural gas is taken from the gas grid.

This case has been divided into two sub-cases: in the first, the building is connected to the power grid and the corresponding contracted power and connection costs are assumed, even if all the electric power comes from the fuel cell. In the second sub-case, the building works without connection to the power grid. This saves the fixed costs of connection.

6.2.4.1. Building TR14

Operation strategy 4A does not have a return on investment over the 10-year time horizon. In case 4B, with the savings of the costs of connection to the electricity grid, the cash flow improves and a return on investment is achieved in the last year.

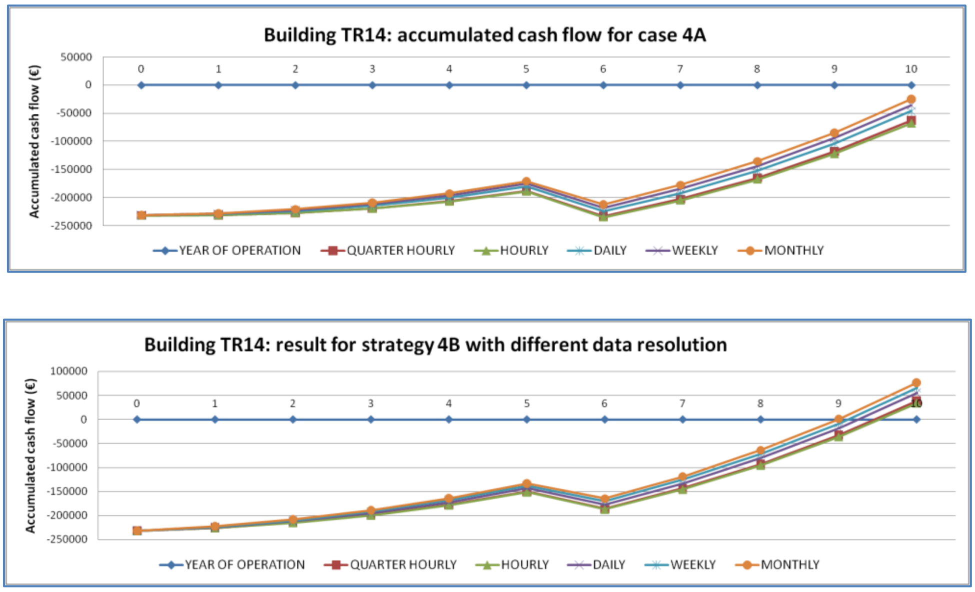


Figure 55. Accumulated cash flow for cases 4A, 4B in building TR14 for different sampling times.

6.2.4.2. Building TR8

With operation strategy 4A the system offers a positive cash flow every year and the return on investment is obtained in the ninth year. In operation mode 4B the return on investment is advanced one year.

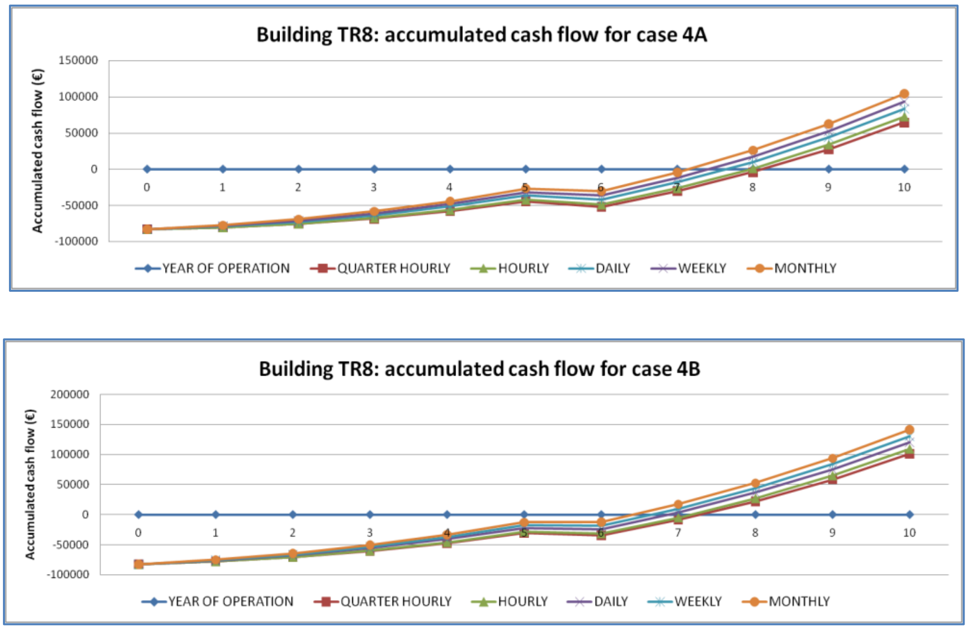


Figure 56. Accumulated cash flow for cases 4A, 4B in building TR8 for different sampling times.

6.2.4.3. Building D7C

With operation strategy 4A, the system offers a positive cash flow every year but there is no return on investment over the 10-year horizon, due to the amount of the initial investment, since a very large fuel cell is needed to cover all electricity demand. In mode of operation 4B, a return on investment is obtained in the last year.

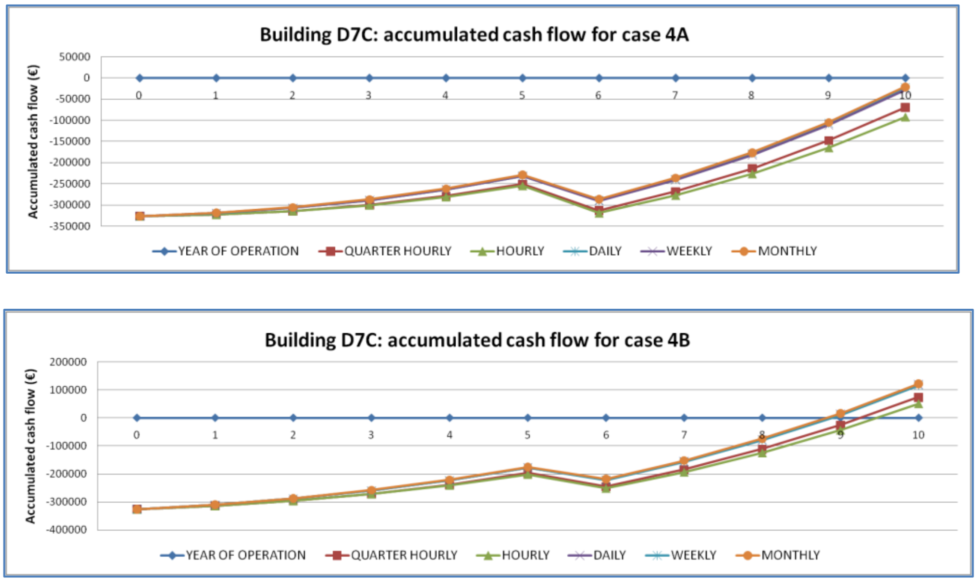


Figure 57. Accumulated cash flow for cases 4A, 4B in building D7C for different sampling times.

6.3. Effect of data sampling time

As can be seen in the previous paragraphs and in the following figure, the sampling time affects the results of the model. For the building TR14, the costs calculated with monthly data are up to 7% lower than those calculated with data every 15 minutes. This means that, if only the 12 data corresponding to the monthly demand for gas and electricity are available, it is necessary to provide a corrective factor to the cost resulting from the model.

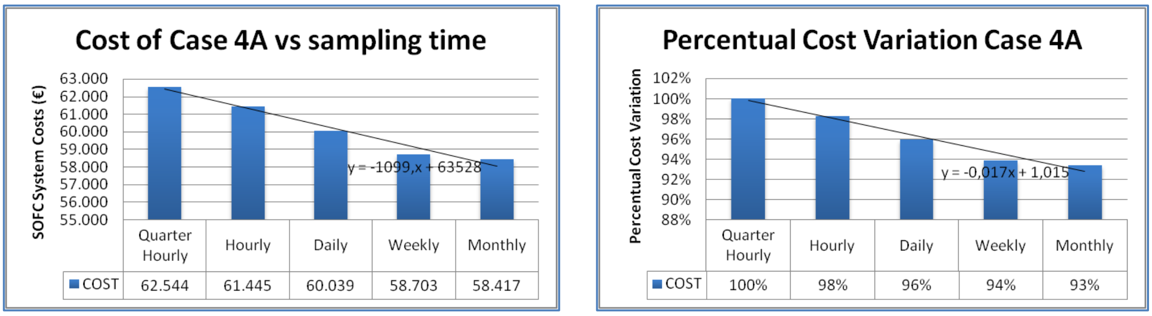


Figure 58. Variation of costs results with sampling time.

The figures show the system costs in absolute and percentage value, when applying the model with different sampling data. The best situation is to have data every 15 minutes, which means that a total of 35.040 observations are available. The resulting value is taken as a reference to compare the rest of the results. The worst resolution is the extreme case of having only the monthly consumption data, in which case only 12 observations are available for the model.

The results for the TR8 building follow a similar pattern. In this case, a difference of 8 percent can be seen in the calculation of costs in the case where less data is available. The following table contains the differences obtained for the test case and for each sampling time used.

Table 10. Costs of the system (€) for the different cases and sampling times used. The costs obtained with 15 minutes resolution are considered 100%.

	Annual cost of SOFC-CHP System									
	Building TR14 (heat to power demand near 1)									
	Case 2	%	Case 3A	%	Case 3B	%	Case 4A	%	Case 4B	%
Quarter Hourly	66111	100%	61937	100%	55483	100%	62544	100%	56463	100%
Hourly	64675	98%	61510	99%	55048	99%	61445	98%	55364	98%
Daily	64399	97%	61098	99%	54421	98%	60039	96%	53958	96%
Weekly	63296	96%	60119	97%	53682	97%	58703	94%	52622	93%
Monthly	62697	95%	59755	96%	53341	96%	58417	93%	52336	93%
	Building TR8 (heat to power demand near 2)									
	Case 2		Case 3A		Case 3B		Case 4A		Case 4B	
Quarter Hourly	53.326	100%	54.078	100%	51.286	100%	51.238	100%	49.042	100%
Hourly	53.866	101%	54.953	102%	52.573	103%	54.637	107%	52.441	107%
Daily	53.217	100%	51.366	95%	48.876	95%	50.152	98%	47.956	98%
Weekly	51.332	96%	50.433	93%	47.851	93%	48.891	95%	46.695	95%
Monthly	51.962	97%	50.930	94%	47.936	93%	47.734	93%	45.538	93%
	Building D7C (heat to power demand near 1/2)									
	Case 2		Case 3A		Case 3B		Case 4A		Case 4B	
Quarter Hourly	78.224	100%	74.060	100%	65.273	100%	71.117	100%	62.550	100%
Hourly	79.343	101%	73.224	99%	64.419	99%	68.090	96%	59.523	95%
Daily	76.507	98%	72.144	97%	63.300	97%	72.769	102%	64.202	103%
Weekly	75.567	97%	72.144	97%	62.545	96%	70.571	99%	62.004	99%
Monthly	75.882	97%	71.962	97%	63.129	97%	70.990	100%	62.423	100%

The results indicate that, taking as reference the results of the model when maximum demand information is available, the greatest deviation occurs when only weekly or monthly consumption data is available, resulting in a lower system cost than in the case of reference (3-7% less). In the case of daily consumption data, the deviation is smaller but can occur in both directions (from 3% higher to 5% lower), and in the case of hourly consumption data, the deviation can occur in both directions (from 7% higher to 5% lower).

These different results are produced because of the logic implemented in the model, which for every observation uses the magnitude of the thermal and electrical demands to make calculations. It calculates the additional demand of heat or electricity if the system does not provide enough energy, or determines what demand the system must follow (cases 3A and 3B).

The fact that the data is aggregated causes the calculations to lose accuracy. For example, taking the aggregate daily demand, it could be concluded that the heat demand is greater than the electricity demand for a given day. However, if the data are compared hourly or every 15 minutes, it can be appreciated that the demand of heat is not always greater than that of electricity.

7. Comparison of results, analysis and discussion

7.1. Comparison

The results show that for a building with a heat to power ratio close to one (building TR14), none of the strategies provide a return on investment in less than 9 years, with the best mode of operation being electric-driven and disconnected from the power grid, thus getting the greatest cost savings and therefore the best cash flow. Maximum-driven and off-grid yields also good results.

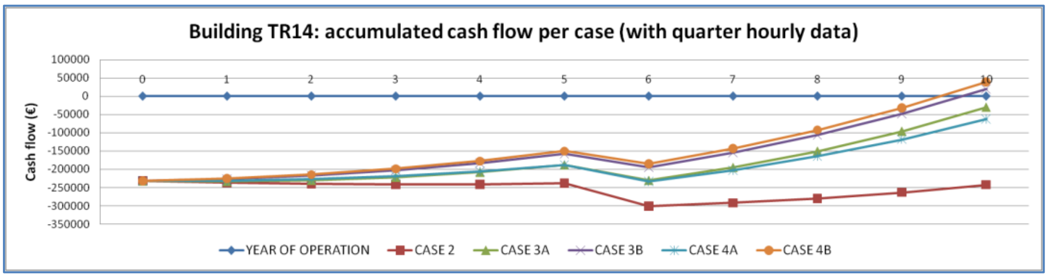


Figure 59. Results of every case study for TR14.Only two of them lead to a payback, in the ninth year.

In the case of a building with heat to power ratio close to two (building TR8), the strategy of following thermal demand offers clearly the worst result. This can be attributed to the fact that the system works the fewest hours and therefore is not possible to get the most return of investment. The rest of the strategies offer similar results with payback times in the eighth year, with case 3A (grid-connected, maximum demand-driven) offering the best cash flow at the end of the time horizon.

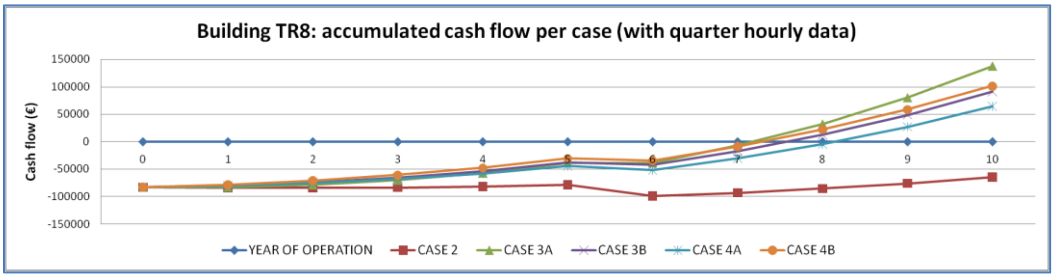


Figure 60.Results of every case study for TR8. Three of them lead to a payback in the seventh year.

In the case of the D7C building, with heat to power ratio close to 1/2, neither of the strategies offers a return on investment until the 10^{th} year, and the two best strategies are those that contemplate the disconnection of the electricity grid, which provide savings of more than 8,000€ per year in terms of fixed costs, due to the fixed term for the large contracted power. Even so, this savings added to the one of the electrical energy that is not imported from power grid, cannot compensate fast enough for the high investment made.

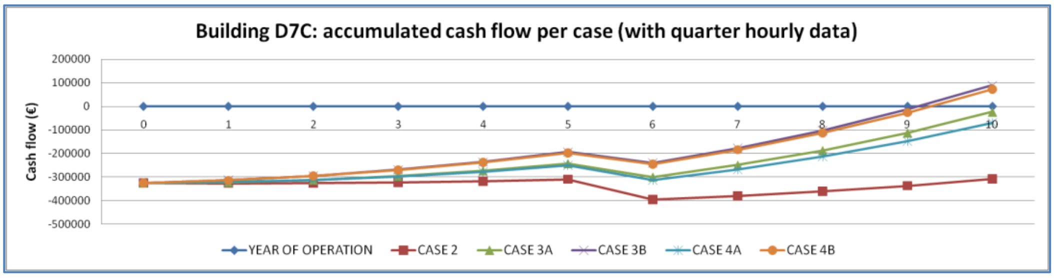
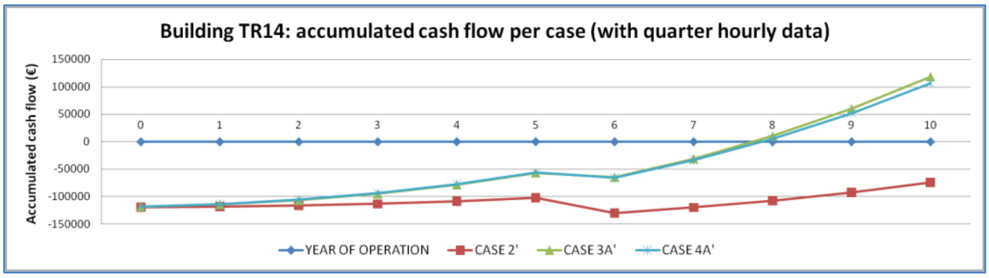


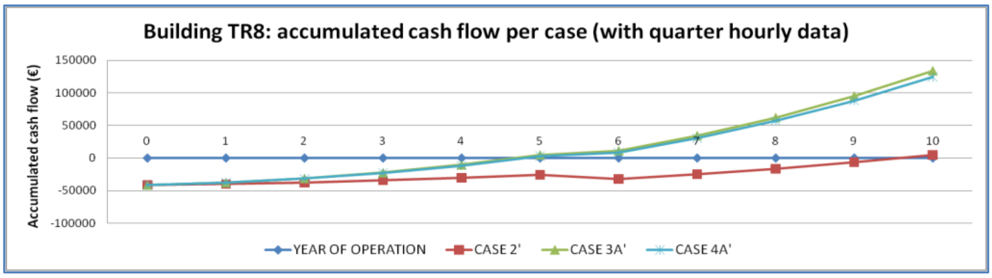
Figure 61.Results of every case study for D7C.Only two of them lead to a payback, in the ninth year.

So far in this assessment, the strategies used have been "peak load", that is, following the maximum demand, be it thermal, electrical or the greater of both. Further analysis can be carried out with "base load" strategies, that is, by sizing the system to supply a base load and use the power grid and/or a boiler when the electrical or thermal demand exceeds what the system can supply. A range of fuel cell sizes can be chosen to assess the tradeoffs between capital costs and utility savings.

Following this idea, another scenario has been assessed: it consists of sizing the system to cover only a 50% of the maximum power demand and thus have a lower initial investment. This forces the system to always work connected to the power grid, since the system alone is not able to meet the electrical demand. Case studies 3B and 4B must be discarded.

For the other case studies, the results can be seen in the following figures, labeled as case 2 ', case 3A' and case 4A '. It is appreciated that for the cases 3A' (follow maximum demand) and 4A' (follow electrical demand) is obtained a faster payback than with previous cases.





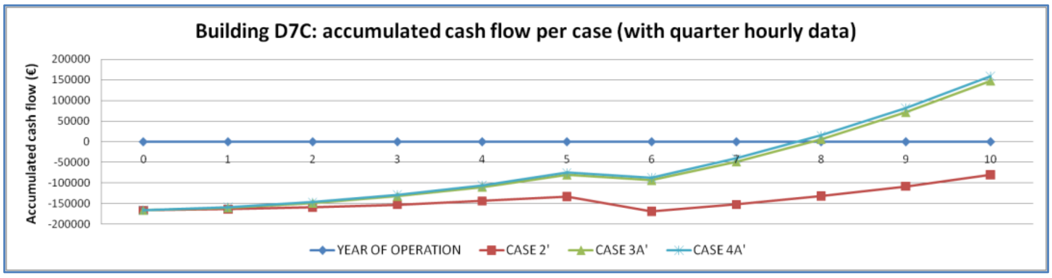


Figure 62. Results for a system sized to give 50% of the maximum electric power needed. For control strategies 3A' and 4A' the payback is faster.

The following table summarizes the results obtained. The table show that:

- The best results are for building TR8 (heat to power ratio near 2), for the cases with a system half the size of the maximum power demand. All cases work better for this building except case 2.
- Case 2 is the worst one for every building in payback time. It is not advisable to use the "heat demand-driven" control of the system.
- The cases with the system sized to cover half the power demand give best payback results for all buildings. These are the only cases with payback of 5 years. It is not advisable to size the system to cover the peak demand of electricity.
- Cases 3B and 4B give slightly better economical results than cases 3A and 4A. This means that with the current price composition, it is preferable to work off-grid if the control of the system is "maximum demand-driven" or "power-driven". This is because of the high costs of connection to the grid combined with the low retribution for exported electricity.
- Case 3A yield second best emission reduction and best primary energy reduction. From the environmental point of view, this is the operation strategy recommended.

Table 11. Results for each combination of operation mode and operation strategy. Green indicates payback of five years or less. Yellow indicates payback between 6 and 10 years.

Building	Case	SOFC-CHP electricity produced (MWh/year)	SOFC-CHP thermal energy produced (MWh/year)	Electricity imported from the grid (MWh/year)	Electricity exported to the grid (MWh/year)	Annual CO_2 reduction (TCO_2/year)	Annual primary energy reduction (tep/year)	Payback time (years)
TR14	Case 2	244	195	222	177	34	25	+10
	Case 3A	461	368	0	173	25	31	10
	Case 3B	461	299	0	0	-18	45	10
	Case 4A	294	235	0	0	1	11	+10
	Case 4B	294	235	0	0	1	11	10
	Case 2'	122	98	239	63	17	12	+10
	Case 3A'	316	253	36	67	10	20	8
	Case 4A'	252	202	39	0	0	11	9
TR8	Case 2	108	87	156	71	17	11	+10
	Case 3A	472	378	0	277	11	34	8
	Case 3B	472	267	0	0	-9	57	8
	Case 4A	186	148	0	0	1	7	9
	Case 4B	186	148	0	0	1	7	8
	Case 2'	59	48	144	18	8	6	10
	Case 3A'	185	148	22	17	3	10	5
	Case 4A'	165	132	22	0	0	9	5
D7C	Case 2	231	185	284	120	32	24	+10
	Case 3A	231	184	284	120	20	29	+10
	Case 3B	517	372	0	0	-7	37	10
	Case 4A	396	317	0	0	5	22	+10
	Case 4B	396	317	0	0	5	22	10
	Case 2'	152	122	278	45	21	16	+10
	Case 3A'	377	301	11	37	8	29	9
	Case 4A'	55	284	15	0	5	22	8

The effect of the increase in gas and electricity prices can be seen in the following figures. In the first year some strategies are more expensive than the baseline case, but as prices increase year after year, the advantage of the CHP system becomes evident. In the tenth year, the difference is very favorable for all strategies.

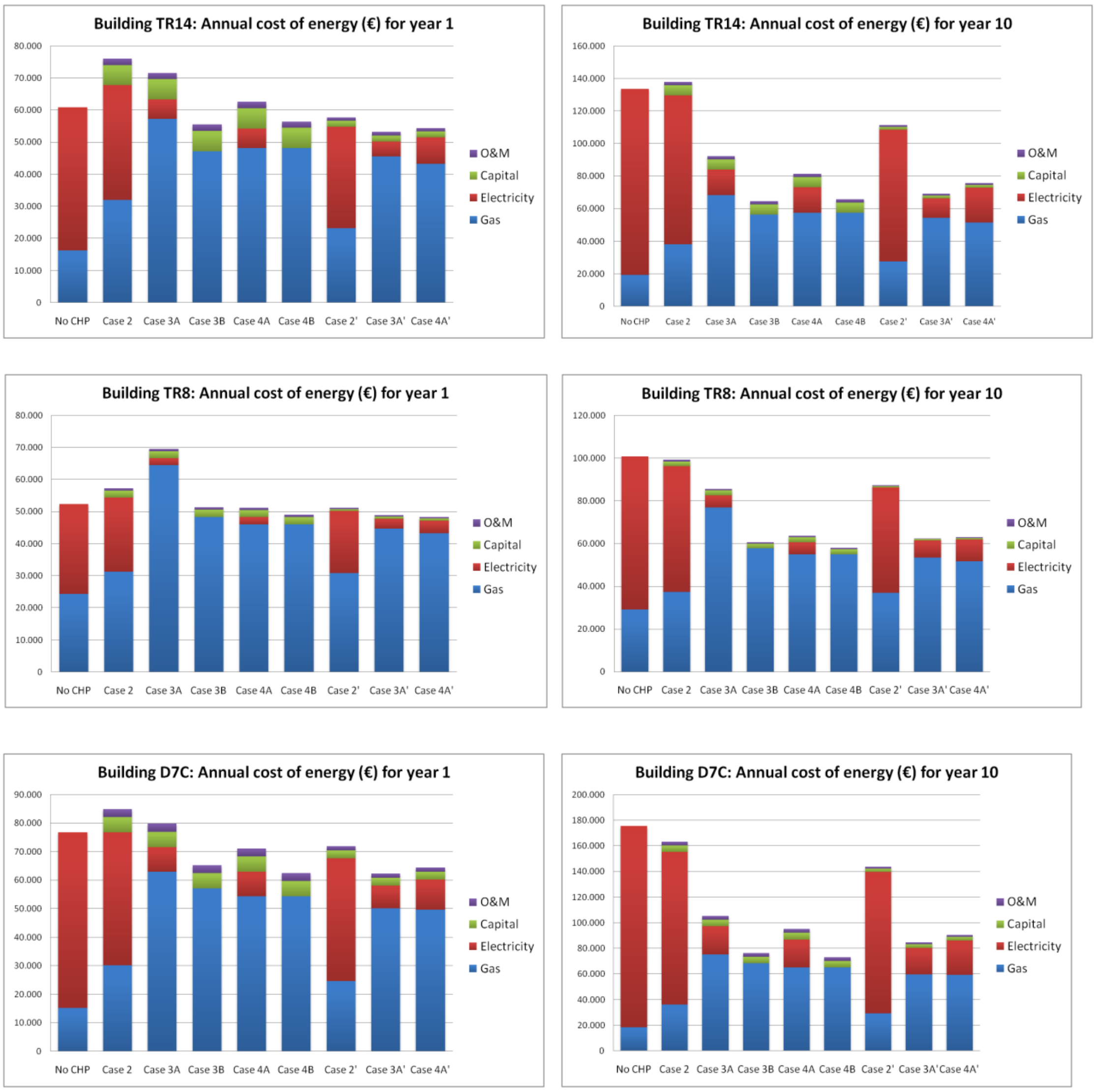


Figure 63.Comparison of annual cost (€) of energy at the beginning and at the end of the period considered. The increases in prices of natural gas and electricity favour the use of the SOFC-CHP system.

Regarding CO_2 emissions, it can be seen that improvements are obtained in all three buildings, but especially in cases 2 and 3A. In cases where the operation strategy is electricity-driven, the emissions are just slightly better the baseline case. In case 3B the emissions result worse than the baseline case.

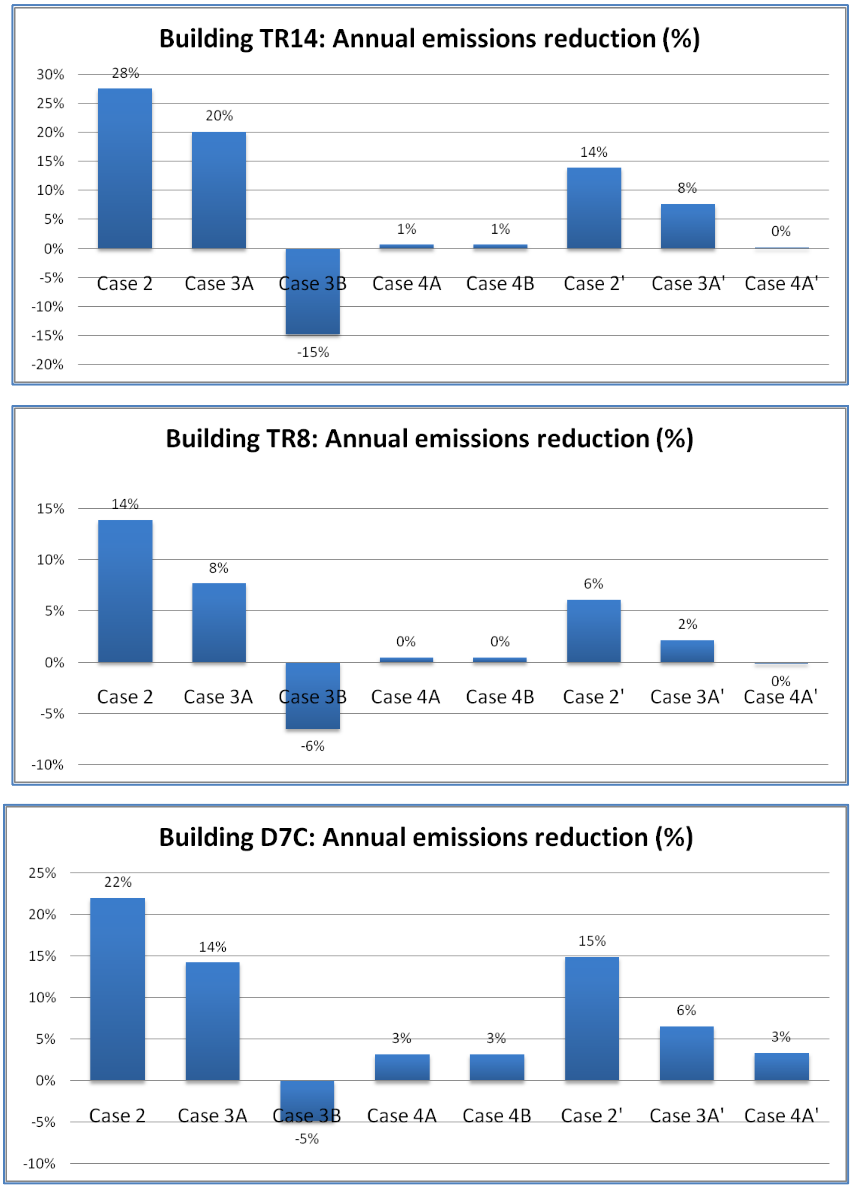


Figure 64.Emissions reduction compared with the current situation for every case study, for the three buildings.

Regarding primary energy consumption, it can be seen in the following figures that it is better than the baseline case for every case study, particularly for cases 3A and 3B ("maximum demand-driven"). Building TR8 show the best results. The conversion factors to calculate primary energy from the final energy consumed are taken from [45].

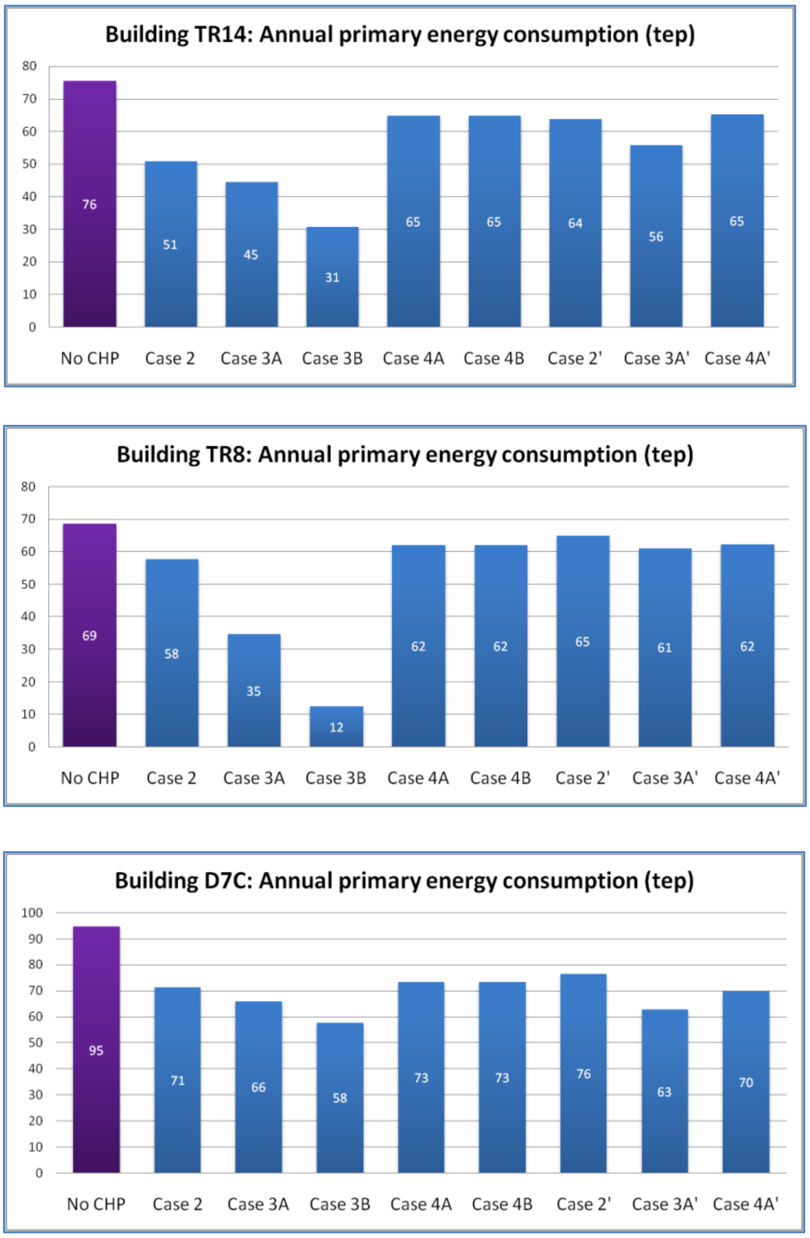


Figure 65. Annual primary energy consumption for every case study compared to the current situation (first column on the left).

7.2. Sensitivity analysis

7.2.1. Effect of government grant

The magnitude of the initial investment has a great influence on payback time. If an investment reduction of 50% is possible, for example thanks to a government subsidy, the payback time is considerably reduced, as can be seen in the following figures. For building TR14 the payback is 6 years, 4 and 6 respectively for TR8 and D7C.

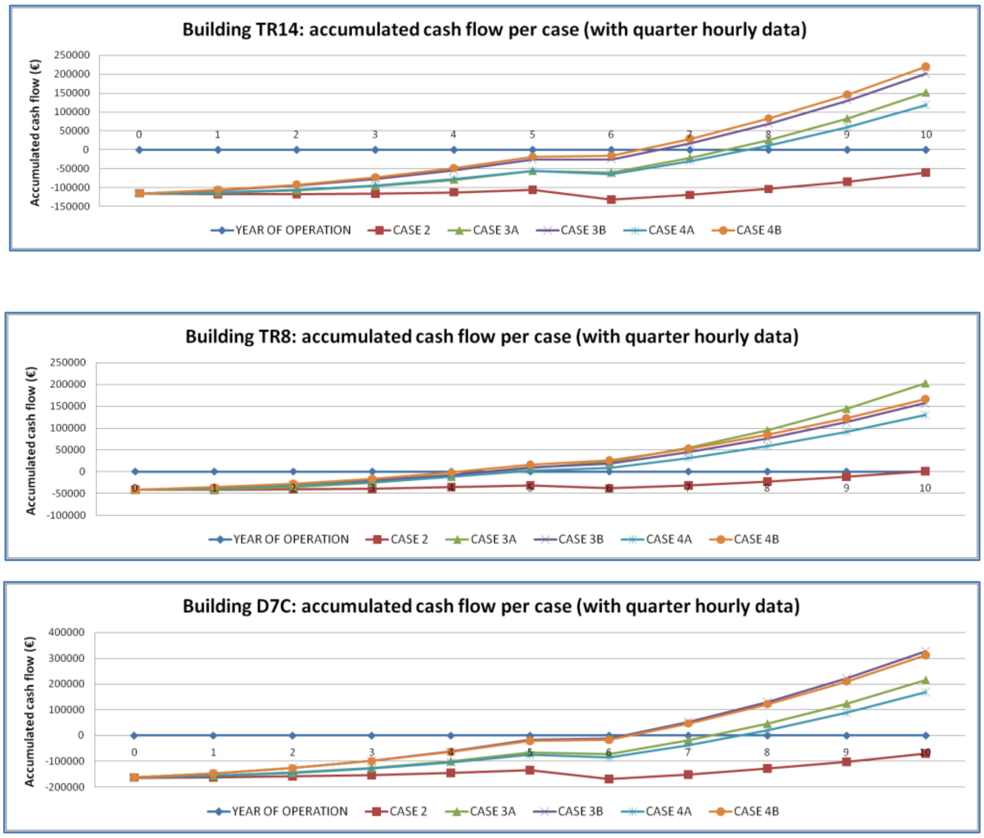


Figure 66. Effect of a government grant of a 50% of CAPEX. The payback is significantly improved for every case study.

7.2.2. Effect of electricity and gas price trend

The expected behavior of gas and electricity prices has a marked effect on the cash flow generated during the lifetime of the system. The greater the cash flow, the better the results are, because it shortens the payback time. The following figures show the effect in three scenarios: 1. the current scenario, 2. a optimistic scenario in which prices rise at 50% of the current trend, 3. a pessimistic scenario in which they rise at 150% of the current trend.

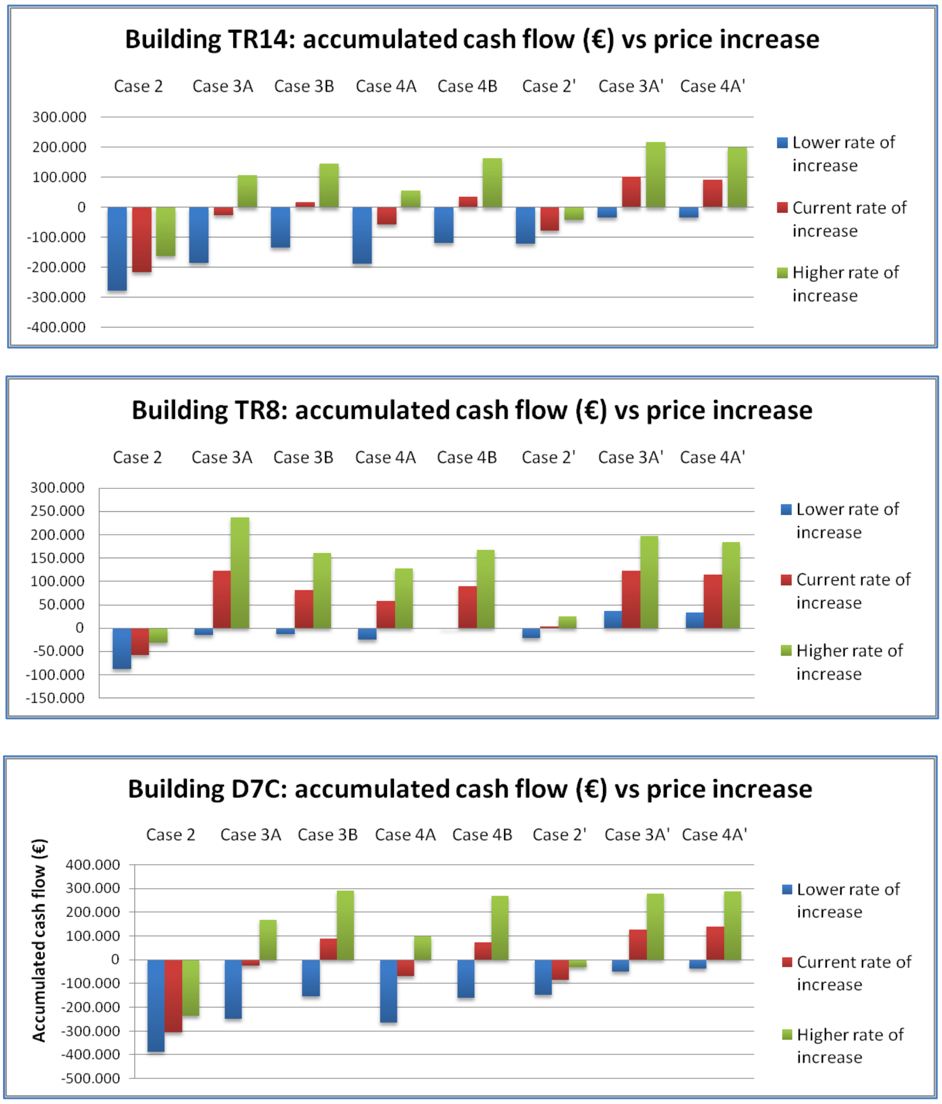


Figure 67.Expected cash flow at the end of 10-year use phase as a function of the evolution of electricity and gas prices.

The graphics show that operation strategy 2 is not recommended, because always has a negative cash-flow at the end of the lifetime of the system. The results of the other operation strategies depend on the expected evolution of prices: the current trend has to be maintained or augmented to obtain positive values.

The following table summarizes the results of the sensibility analysis. It shows the payback time with government grants of 25 and 50%. It also shows the payback time for the optimistic an pessimistic scenarios of the prices (lower and higher rate of increase than expected, respectively). The last two columns show another interesting effect: what happens when changes the relative distance between the prices of natural gas and electricity (spark spread).

Table 12. Results of the sensitivity analysis: government grant and price trend for electricity and natural gas. Green color indicate payback of 5 years or less. Yellow indicates payback between 6 and 10 years.

Building	Case	Payback time with initial assumptions (years)	Payback time with 25% grant (years)	Payback time with 50% grant (years)	Payback time with lower price increment (years)	Payback time with higher price increment (years)	Payback time with lower increment of electricity only (less spark spread) (years)	Payback time with lower increment of gas only (more spark spread) (years)
TR14	Case 2	+10	+10	+10	+10	+10	+10	+10
	Case 3A	10	10	8	+10	8	+10	9
	Case 3B	10	9	7	+10	8	+10	9
	Case 4A	+10	9	8	+10	9	+10	10
	Case 4B	10	9	7	+10	8	+10	8
	Case 2'	+10	+10	10	+10	+10	+10	+10
	Case 3A'	8	7	5	+10	7	+10	8
	Case 4A'	9	7	5	+10	8	+10	8
TR8	Case 2	+10	+10	10	+10	+10	+10	+10
	Case 3A	8	7	5	+10	7	+10	7
	Case 3B	8	7	5	+10	7	+10	8
	Case 4A	9	7	5	+10	8	+10	8
	Case 4B	8	7	5	+10	7	+10	8
	Case 2'	10	9	7	+10	9	+10	10
	Case 3A'	5	5	4	8	5	8	5
	Case 4A'	5	5	4	8	5	8	5
D7C	Case 2	+10	+10	+10	+10	+10	+10	+10
	Case 3A	+10	9	8	+10	9	+10	10
	Case 3B	10	8	7	+10	8	+10	9
	Case 4A	+10	10	8	+10	10	+10	+10
	Case 4B	10	8	7	+10	9	+10	10
	Case 2'	+10	+10	9	+10	+10	+10	+10
	Case 3A'	9	7	5	+10	8	+10	8
	Case 4A'	8	7	5	+10	7	+10	8

The results show that building TR8 (heat to power ratio near 2) offers the best payback in several case studies, especially with a system sized to cover half the maximum power. The effect of a government grant is also positive for all buildings, especially in the cases with a system sized to cover half of the electricity demand.

On the other hand, if prices of gas and electricity increase slowly than expected in the time horizon of 10 years, it is difficult to have an acceptable payback time in any building. The table shows also that if the spark spread increases, the payback is faster.

7.3. Possible support policies

The following figure contains a summary of possible support schemes, with distinction between investment support (as capital grants) and operating support (as feed-in-tariffs).

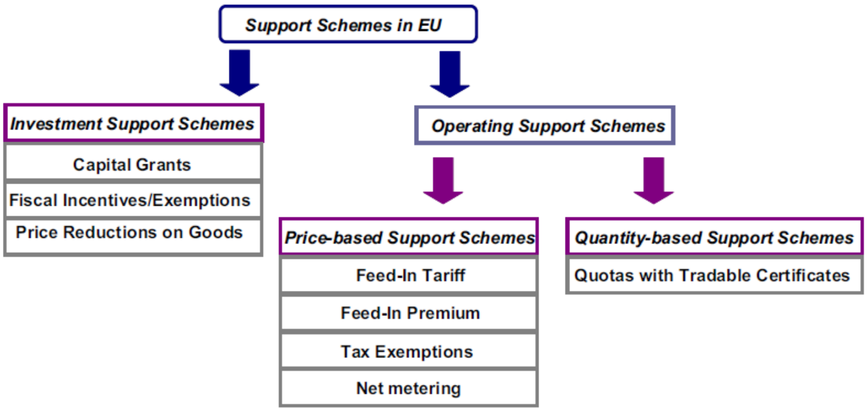


Figure 68. Possible support schemes, both for investment and operation of new technologies[46].

The economic analysis carried out demonstrate the great influence of the initial investment in the economic results after a 10-years use phase. With this in mind, Government incentives could be designed to support penetration into the market of new technologies that have social benefits (e.g., more energy efficiency and environmental benefits), only for a period of time when the technology is not yet cost-competitive. Without incentives, the high investment cost of a SOFC-CHP system hinders its competitiveness in the market. The simulations show that a reduction of 50% in the initial investment cost is enough to recover it in a reasonable time of 5 to 7 years in several cases.

Japan constitutes an example with its Ene-Farm Programme, which provides subsidies for purchase of residential fuel cell systems for domestic CHP. The total number deployed was approaching 300.000 at the end of 2018, with a year-on-year gain of 50.000 [17]. National support schemes covering a percentage of the initial cost are preferable, as for example the ones applied in Germany for the Ene-field Project [7].

Another example of policy support is the introduction of an feed-in-tariff (FIT) for the generated energy, as was made in the UK [47].

7.4. Possibilities for improvement and further assessment

Listed below are a series of approaches that can be assessed to improve the economic viability of the SOFC-CHP system.

- Improving the utilization of waste heat, for example, by producing cold using absorption chillers. This is known as combined cooling heat and power (CCHP) or trigeneration. This has been successfully used in data and communications centers [48]. Also in building applications as the ones seen in this project, the demand for cooling coincides with a reduction in heating demand, enabling these CCHP systems to operate near full load for a greater period of time over the course of a year compared to conventional CHP systems.

- Use the SOFC-CHP technology in buildings integrated into a district heating network, in order to optimize the use of the heat energy generated, thus reducing the primary energy demand of the group of buildings involved. In [49] it is stated that SOFC systems can lead to significant reduction in primary energy use at district level when combined with appropriate building thermal storage, materials and district heating technologies, and also offer significant savings in CO_2 emissions. By distributing the cost of investment among several buildings, the project can be much more economically attractive. In particular, this option may interest the UPC, which already has a cold and heat distribution network operational on the Diagonal Besós campus (Districlima).

- Reducing costs by reducing the contracted electrical power, because part of the power is supplied by the SOFC-System. Obviously this rules out the off-grid operation mode, and the building must remain connected to the power grid to receive electrical energy when the fuel cell is not supplying enough electricity.

- Consider the possibility of sell the extra electrical energy through an aggregator, in order to maximize the benefits, instead of simply compensate it at the price indicated by retailers in the free market (or at 0,05€/kWh, which is the price indicated by REE for prosumers in the regulated market) [50][44].

- Remove the fuel processor. Analysis estimate that 80% of the balance of plant cost is due to the fuel processor, so removing this system in particular would have the greatest impact, halving total system costs. An option is to directly supply the fuel cells with hydrogen, rather than converting it on-site in an expensive and complex chemical reactor. Interest in centralized hydrogen production is growing, and thousands of kilometers of pipeline exist across Europe and the US. The obvious barrier to extending this ‘hydrogen economy’ is the cost of developing infrastructure. However, if networks of hydrogen production and distribution are developed to serve hydrogen vehicles, it could be possible for FC-CHP customers to piggy-back on that development, eliminating the need for thousands of dollars of equipment per unit [11].

- Change the business model to a leasing. Clients may be deterred due to the large upfront initial costs and the anticipation of replacement of costly components in the medium and long term. To counteract this, the product can be offered as a lease with a monthly price for 10 years. This price should include maintenance costs and spare parts during those 10 years. A utility company may own the stationary fuel cell unit and simply charge the end user for electricity and heat usage. This approach would make the financing and maintenance of the unit an easier task [22].
- Change the business model offering a PPA (Purchase Power Agreement). This could secure a more attractive return on investment, because the customer does not invest in the FC system (no CAPEX), and in compensation agrees to purchase natural gas at an established rate for a given period of time [51][52].

Conclusions

The present work offers a tool to estimate the economical viability of a FC-CHP system, based on a techno-economical model that can be applied to different types of buildings with different demand patters. The parameters of the model can be changed and be adapted to a varied number of scenarios.

The model has been applied to address the feasibility of stationary SOFC-CHP systems for buildings of the UPC, with its particular energy needs and under the conditions of the energy market in Spain. The model considers the heat and electrical demand of the buildings, operational modes and operational strategies of the system, investment costs, O&M costs, interaction with the power grid and evolution of market price conditions. Different combinations of operational modes and operational strategies have been analyzed to see how they result in terms of payback time,CO_2 savings and energy efficiency. This work also considers the influence that the sampling time of the data available has in the results of the techno-economical model.

A state-of-the-art SOFC-CHP system has been compared to the current situation, in which the buildings cover all its electricity demand from the power grid and all its thermal demand from the natural gas grid. The capital cost for a SOFC-CHP system is currently high. However, the operational cost can be competitive in several scenarios. Consequently, SOFC-CHP systems can offer an interesting value proposition as long as capital costs can be reduced so as to allow an acceptable payback time.

Nowadays, government subsidies have great influence in the economic viability of this systems. They will be necessary only while the price of SOFC-CHP systems remains high. As the technology expands and economies of scale in manufacturing costs grow, subsidies may gradually decrease until they disappear. The second most important factor is the expected trend in natural gas and electricity prices. If the current trend is maintained or increased, the operating costs of the CHP system are better than the baseline case costs.

The amount of consumption data available is relevant when performing the simulations. The more data available for unit of time, the more reliable the model will be. The results obtained, such as the quantity of natural gas needed to meet the energy demand, can change in a not-negligibly way depending on the level of detail of the data. In the tested scenarios, different sampling times can lead to differences of +/- 7% in the system's operating costs.

When the operation strategy is to follow heat demand, the fuel cell works less hours because on the hotter months it is stopped. This means that the economic benefits of the system are lower and that the payback time is unacceptably long. Although the duration of the system in this case should be greater than 10 years, the payback time is too long. The results show that this operation strategy is not recommended for the buildings assessed.

When the operation strategy is to follow electricity demand or follow the maximum demand, the fuel cell can generate electricity constantly during the whole year. The capacity of the system (number of kW to be installed) for each specific case study is conditioned by the operation mode, that is, if the fuel cell is designed to operate off-grid or not. The capacity of the system strongly conditions the investment to be made and the payback time.

The analysis show that the better results are achieved in building TR8, with a heat to power ratio near 2. In this building, a payback time of 5 years or less can be achieved with several operation strategies. If the SOFC-CHP system is sized to cover the 50% of the electric energy demand, the payback time for this building is five years even without government grant. Other buildings with similar heat-to-power ratio are good candidates to have a SOFC-CHP system, for example TR123, ETSAV and C6-DAC. The other buildings assessed can also have a payback of five years in the same scenario, but only if a government grant covers 50% of the investment.

In terms of CO_2 emissions reduction, the SOFC-CHP system can provide an improvement up to 28% compared to the current situation, given the emissions factor of the power grid, the gas boiler, and the CHP system. The operation strategies "heat-driven" and "maximum-driven" give the best reduction. Operation strategy "electric-driven" is just slightly better than the current situation. The system gives also a reduction in primary energy consumption for all case studies, especially in "maximum-driven" operation strategies.

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Further reading

Rifkin, Jeremy, "La economía del hidrógeno". Translated to Spanish by Ramón Vilà Vernis. Ediciones Paidós Ibérica, S.A., 2010.

I would like to reproduce an excerpt from the document "Fuel cell technology for domestic built environment applications: State of-the-art review" by Theo Elmer, Mark Worall, Shenyi Wu and Saffa B. Riffat, published in "Renewable and Sustainable Energy Reviews" in 2015, because I think that the expectations of FC-CHP systems cannot be better expressed:

> *"If [...] countries are serious about their aspirations of a low carbon future, the built environment and the domestic sector in particular will play a critical role. In order to create a real transformation, both operational and technological changes need to occur. Nations can no longer rely on technologies of the past to help arrive at the destination of a low carbon sustainable society. Fuel cells are a technology of the future here today, providing a change in the way heat and power are supplied to end users. Fuel cells operating in CHP and tri-generation systems could finally provide the means by which energy generation can transfer from centralized to decentralized locales in a sustainable and effective manner."*

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