Department of Mechanical and Aerospace Engineering

Performance analysis of fuel cell combined heat and power systems in buildings and their integration with renewable energy systems

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Abstract

The aim of this dissertation is to analyse the performance of fuel cell combined heat and power (CHP) systems in buildings and their integration with renewable energy systems in order to analyse their environmental and economic impact.

Even though, fuel cell technology is still in its research stage, improvements can be made in order for this technology to be cost-competitive for some applications in the future. A detailed review of the different types of fuel cells and the main companies developing them is carried out in the first part of this dissertation. A more thorough review has been carried out for the current fuel cell CHP systems. Outcomes of this research found out that the 750 W fuel cell CHP system developed in Japan through the ene.farm scheme is expected to be cost-competitive by 2015.

To analyse the performance of fuel cell CHP systems, existing commercial tools have been reviewed and analysed. The Simplified Building Energy Model (SBEM) tool has the ability to calculate the CO_2 emissions and operating costs of a CHP system that can represent a fuel cell. However, to design the system it is required to use a dynamic simulation tool. A model that consists of a fuel cell CHP unit, a hot water storage tank and a radiator that supplies the heating demand to an office, has been developed using the platform of ESP-r. From using this model it has been possible to define a methodology to select the best size of hot water storage tank to ensure that the fuel cell is not switched on and off intermittently for more than once a day. For the system that has been designed, the results have simulated the operating hours, the electricity generation, heat generation and the fuel consumption based on seasonal periods. The analysis of these results determined that a 5 kW fuel cell system can achieve significant reductions in CO_2 emissions and operating costs for an office between $250m^2$ and $500m^2$.

Fuel cell technology is also promising due to their potential to integrate renewable energy systems. For this reason, additionally, a modelling exercise has been carried out to encapsulate a system integrating wind and solar energy generation with an electrolyser to generate hydrogen, store it and supply a fuel cell when the renewable energy generation is not available. The software that has been used for this simulation is Homer Energy, which has been evaluated to analyse the performance of this system, obtaining interesting results and detecting some improvements that can be made.

Acknowledgements

I take this opportunity to express my gratitude to Dr Paul Tuohy for his help and guidance throughout the duration of this dissertation.

I also take this opportunity to tank James Thomson from Ramboll UK for his support with the ESP-r models and his good advice.

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1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) there is clear evidence that emissions of greenhouse gases (GHG) are causing global warming. According to their studies, global CO_2 emissions temporarily stabilized after the two oil crises of 1973 and 1979, however, growth returned thereafter and has continued to rise until the present day. (IPCC, 2007) In fact, recent data reveals that global CO_2 emissions were 150 times higher in 2011 than they were in 1850. (World Resources Institute, 2014)

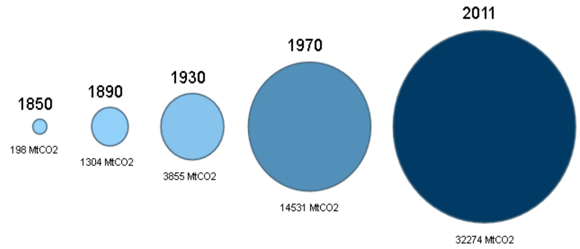


Figure 1: Global CO_2 Emissions 1850 to 2011.
Source: World Resources Institute, 2014

To stabilize the GHG concentrations in the atmosphere it is required to reduce the carbon emission from energy production and use, transport, building, industry, land use and human settlements. If successful in reducing these emissions, the IPCC's Fifth Assessment Report states that it would be possible to limit the increase in global mean temperature to two degrees Celsius above pre-industrial levels. (IPCC, 2014)

As can be seen in figure 2, in Europe, 26 % of the final energy consumption is used in buildings (European Comission, 2012), therefore an improvement in building services can represent a significant energy reduction in the total energy consumption. One of the technologies that can achieve significant energy reductions in buildings are Combined Heat and Power (CHP) energy systems. CHP systems are more efficient than conventional methods such as boilers and power stations; therefore they can deliver significant CO_2 emission reductions and cost savings. Due to power station and distribution losses, electricity supplied by the general grid in the UK has efficiency around 40%. As can be seen in figure 3, using a CHP system the overall efficiency of the system is around 75% due to avoiding transport losses as the electricity is generated on-site.

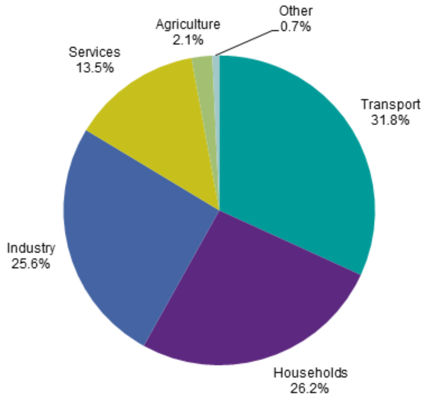


Figure 2: Final energy consumption, EU-28, 2012. Source: European Comission, 2012

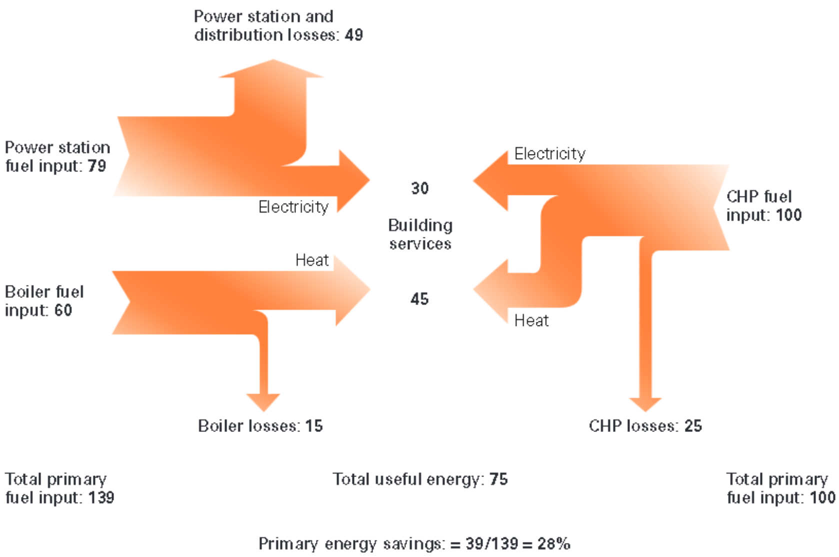


Figure 3: Energy savings through typical new small-scale packaged CHP compared to conventional sources. Source: (Carbon trust, 2010)

Using fuel cell technology, the efficiency of a CHP system can be increased up to 90% when all the heat generated is used. For this reason CHP fuel cell systems can contribute significantly to reduce energy consumption and carbon emission from buildings. Although the first fuel cell was developed in 1942, they remained nothing more than a scientific curiosity until the early 1990s. The interest in fuel cell technology was significantly increased in early 2000 based on a promise of a new energy revolution. Particularly, companies from Japan and the United States have been developing and improving the technology and even enabling commercial stages for some applications.

Due to the constant development of fuel cell technology and recent commercial production, the available information about its performance in real applications is currently limited to date, most of the commercial energy modelling tools available have not incorporated fuel cell functionalities and the utilization of research tools is required for this purpose.

Apart from the reduction of energy consumption due to their high efficiency, fuel cells are also promising due to their potential to integrate renewable energy systems in the future. Even though current applications of fuel cell CHP systems use natural gas to generate hydrogen to supply the fuel cell, hydrogen can also be generated from the excess of energy generated from a renewable energy source. In a future scenario where renewable energy generation systems substitute fossil fuel generation systems, one of the principal problems detected is the lack of control over when the electricity is generated. The integration of fuel cells in renewable energy systems can help to solve this problem as the excess of energy generated by renewable energy systems can be converted into hydrogen through a process of electrolysis and can be used later on when there is no renewable energy generation available.

In summary, the fuel cell CHP system can provide a more efficient way to produce electricity and heat to supply buildings' demands and have a potentially significant contribution for the future as they can be integrated with renewable energy systems.

1.1 Objective

The objective of this dissertation is to investigate the performance of fuel cell CHP systems to supply the demand of electricity and hot water of a building; to determine how fuel cell CHP systems can be simulated using existing tools and to develop a methodology to evaluate the environmental and economic impact of using fuel cell CHP systems; and to analyse their potential for integration with renewable energy systems.

1.2 Methodology

In order to achieve the objective described before, the steps described in this section have been undertaken in this dissertation.

The first step has been to understand the fuel cell technology, current context and state of art. The dissertation describes the main components common to the majority of fuel cell systems, emphasizing the ones that are critical for the system's performance and are object of current research. Each type of fuel cell has also been investigated to describe its characteristics and differences among other types. Some types of fuel cells are at a research stage while others are close to a commercial stage. For this reason, each type of fuel cell has had its manufacturing companies, actual or potential market and applications analysed.

From the current applications of fuel cells, this dissertation is focused on the CHP systems for buildings. Therefore, available fuel cell CHP systems in the market have been analysed. Different sizes of systems have been analysed from micro CHP systems of less than 1kW power output to big power stations of more than 10MW power output. Technical specifications of representative models available presently in the market have been exposed and, as examples, some installed systems in the UK have been illustrated. The future integration of fuel cell CHP systems has been also analysed as it has been considered that fuel cell technology has a huge potential in this area.

From this first section, it is possible to achieve a global understanding of fuel cells and, most importantly, the current models that can be found in the market and their applications.

The second step undertaken has been to analyse the available tools to simulate CHP systems and their potential to simulate fuel cells. The Chartered Institution of Building Services Engineers (CIBSE) guide has been used to understand the basics of CHP system design and the parameters that should be analysed when simulating CHP systems in order to determine the environmental and economic impact. The initial approach was to analyse simple available tools like the CHP Site Assessment Tool and the Simplified Building Energy Model (SBEM). From these tools it has been determined and calculated the necessary inputs and the outputs; but above all their capacity to simulate fuel cells has been analysed. Although the results obtained from these tools, especially SBEM, can provide the necessary information to carry out an environmental and economic analysis, the inputs needed depend on the system design.

ESP-r has been used to perform a dynamic analysis of the fuel cell CHP system in order to design the fuel cell CHP system and to obtain the results needed to analyse the economic and environmental impact. From an initial scoping of the fuel cell components developed in ESP-r and available models it has been decided to use an existing model from a former student as a starting point. At this stage it has been considered convenient to use a specific size of fuel cell which represents an existing fuel cell in the market and determine its performance for an appropriate scenario. Using the selected fuel cell, some simulations have been carried out to obtain several outputs:

- Heating demand of different scenarios to decide an appropriate case to study: two offices of 250 m^2 and 500 m^2 have been considered for subsequent simulations.

- Performance of the system with different tank sizes. A methodology has been developed to select the best tank size and it has been applied to the two scenarios analysed.
- Evaluation of the system designed to obtain the results: fuel consumption, operating hours, percentage of demand supplied by the CHP and the back-up system and electricity generated.

The third step undertaken has been to calculate the final results in order to analyse the environmental and economic impact of the system proposed. The annual results have been calculated using the outputs obtained from the ESP-r simulations. The results obtained have been validated comparing them to them to the results obtained in the verification of a similar fuel cell carried out by an independent agency. Finally, the CO_2 emissions and operating costs of the fuel cell CHP system has been calculated and analysed for the two scenarios proposed.

The forth step has been to analyse the potential of a commercial available tool in the market to simulate fuel cell CHP and renewable energy integrated systems. Even though it is not the main objective of this dissertation, it has been considered that fuel cells can provide important benefits in this area in the future. Some simulations have been carried out to determine the results that can be obtained with the software and the improvements that can be made in the future.

It has been also included a last step with the conclusions of the dissertation giving a critical point of view of the technology analysed and the results obtained, and exposing the future work identified.

2 Fuel cell technology

A fuel cell is an electrochemical device that converts the chemical energy from a fuel, combined with oxygen, into electricity, heat and water. Hydrogen is the most commonly fuel used and ambient air is usually used to supply the oxygen. The basic components of a fuel cell are:

1. A negative electrode (anode) to which the fuel is supplied.
2. A positive electrode (cathode) to which the oxygen is supplied.
3. An electrolyte that separates the two electrodes.

Electrons are produced in the anode and consumed at the cathode. An electric circuit is connected to the two electrodes to use the electricity provided by the fuel cell. The electrodes can contain a catalyst to improve the speed of the reaction. At the cathode, where the electrons are received, there is also generated heat which has to be taken away from the fuel cell and can be recovered to supply heating demand. The reactions that take place at the electrodes are:

1. Anode: $H_2 \rightarrow 2H^+ + 2e^-$
2. Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Figure 4 shows a schematic illustration of the basic components described above.

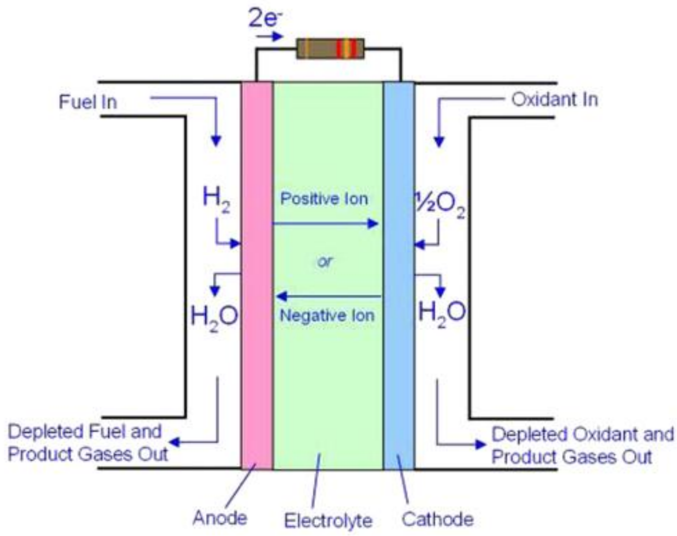


Figure 4: Schematic components of a fuel cell. Source: Hirschenhofe, et al., 2004 in Behling, 2013

The most critical part of the fuel cell is the interface. The interface is the area where the electrolyte and the electrodes meet and where the electrochemical reaction takes place. The design of the interface is critical and has been improved during the last 20 years increasing the performance of the fuel cells. (Behling, 2013)

2.1 Fuel cell systems

The fuel cell needs a set of external components to run properly which may differ according to the type of fuel cell used or the purpose of the installation; however, there are some common components to all the fuel cell types and some others which are used in the most common fuel cell applications.

2.1.1 Fuel cell stack

The fuel cell explained before represents only a single fuel cell. However, only one fuel cell generates a just a short amount of electricity; therefore multiple cells are assembled into a fuel cell stack which can contain hundreds of fuel cells. Increasing the number of fuel cells of a stack the voltage is increased while increasing the surface of the area of the cells the current is increased. (Ballard, 2013)

2.1.2 Fuel cell reformer

When the hydrogen used to supply the fuel cell is extracted from fossil fuels such as natural gas or methanol a reformer is needed. In the reformer the hydrogen is generated creating at the same time CO_2. After passing through the reformer, commonly, the hydrogen is sent to a reactor where other impurities, such as sulphur, are extracted in order to prevent the impurities to enter in contact with the catalyst reducing the efficiency and life expectancy of the fuel cell. (Ballard, 2013)

2.1.3 Air Supply

The ambient air is injected inside the fuel cell through an air compressor or blower. The air is filtered and, depending on the external conditions, it is humidified as well. (Ballard, 2013)

2.1.4 Thermal management

The temperature in the fuel cell stack has to be carefully controlled. The heat generated at the fuel cell stack is used to preheat the fuel and the air entering the fuel cell through heat exchangers. Due to the large amount of heat generated at the fuel cell, the excess of heat can also be recovered and used to produce steam and generate electricity or to supply a heating demand. When this energy is used, the efficiency of the fuel cell is largely increased. (Ballard, 2013)

2.1.5 Water management

Water is generated and at the same time needed in different parts of the fuel cell. A correct water management can provide the water needed from the one generated by the fuel cell reaction. (Ballard, 2013)

2.1.6 Power management

Fuel cells generate direct current electricity (DC); however in most of the applications of fuel cells alternating current (AC) is needed. An inverter to transform the electricity from DC to AC is installed along with converters and transformers. This increases the capital cost of the fuel cell and at the same time decreases the overall efficiency of the system around 2-6 %. (Logan Energy, 2011)

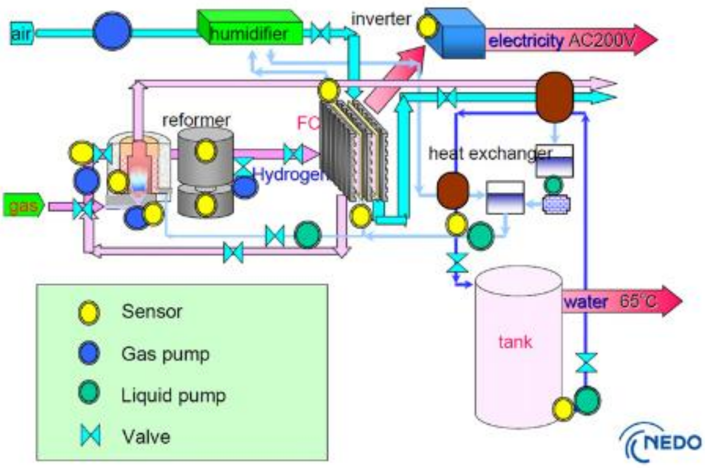


Figure 5: Fuel cell system schematic diagram. Source: Ujiie, 2006 in Behling, 2013

Figure 5 shows all the components described before and how they are connected to the fuel cell. It shows as well the flow of air, fuel and water and the electricity generated.

2.2 Types of fuel cells

There are different types of fuel cells which have been developed and produced since fuel cells where invented. In this section there are described all the types of fuel cells, their technical characteristics and their current state of development, current research and applications, companies producing them and main markets.

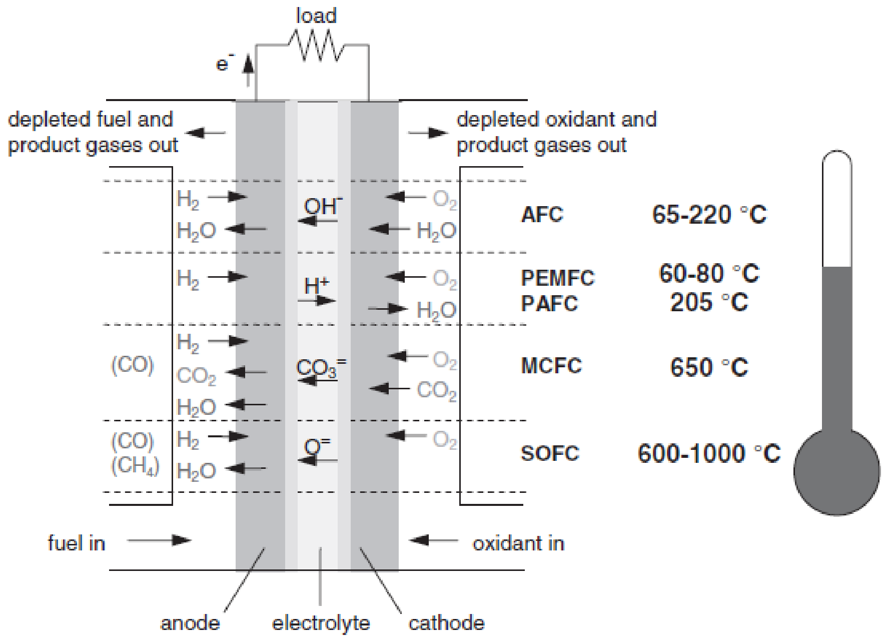


Figure 6: Types of fuel cells, their reactions and operating temperatures. Source: Barbir, 2012

Fuel cells are usually classified by the electrolyte used in the cell which can be aqueous, solid, or molten; alkaline, neutral, or acid; or polymer, chemical substance, or ceramic. As can be seen in the figure 6, the operating temperature of the fuel cell varies according to the type of electrolyte used. If the operating temperature of the fuel cell is low, fuels such as methane have to be reformed outside the fuel cell as the temperature required for its reformation is about 600-700 ºC. Conversely, if the operating temperature is high the fuel can be reformed inside the fuel cell. (Behling, 2013)

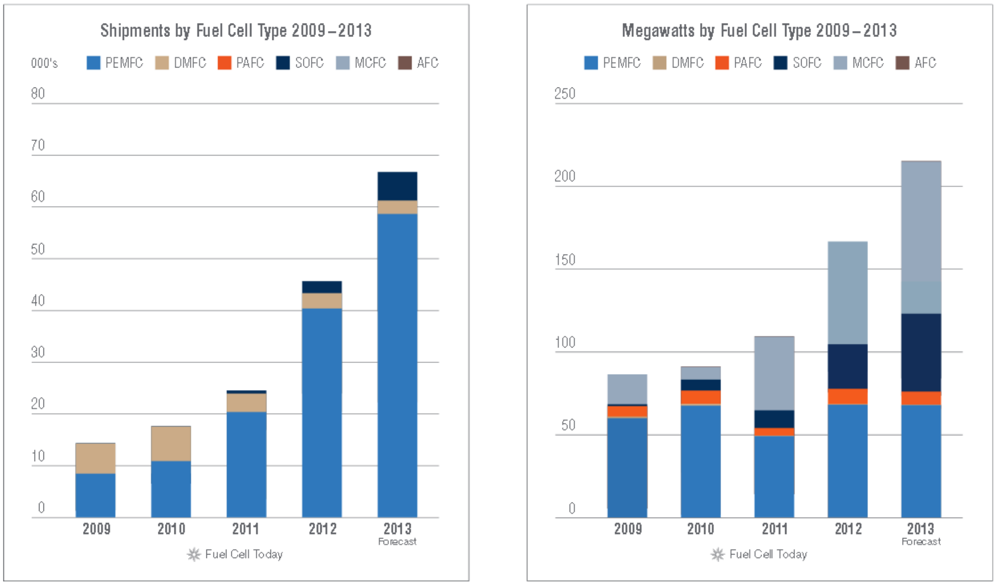


Figure 7: Shipments and Megawatts by fuel cell type. Source: Fuel Cell Today, 2013

Figure 7 shows the evolution of shipments and megawatts for type of fuel cell. It is interesting to highlight that PEMFC has been the most used type of fuel cell since 2009 and that in terms of megawatt produced the use of MCFC and SOFC has been increased in the last years.

2.2.1 Polymer electrolyte membrane or proton exchange membrane fuel cells (PEMFC)

PEMFC use a thin proton conductive polymer membrane as the electrolyte and the operating temperature is usually between 60ºC and 80 ºC. They are the most popular and versatile of all the types of fuel cells existing in the market. Systems can range from watt-scale up to MW stationary power generators. PEMFC can be used to power cars or busses, for backup power devices and for residential micro-CHP systems. Due to their popularity there have been strong efforts in their research reducing the costs and increasing the life time. (U.S. Department of Energy, 2011)

The automotive industry uses PEMFC technology and consequently the development of this technology is strongly affected by the results obtained in this sector. Component suppliers to the PEMFC markets are focusing their efforts in providing more automated solutions for the fuel cells. For example the company Tanaka is increasing its capacity to meet the future demand of catalyst demand for the also increasing micro-CHP sector.

Platinum is the main component used as a catalyst for PEMFC and its cost and scarcity has been identified as the main problem for a larger scale production of fuel cells. For this reason, a substitute catalyst is currently being researched by the main fuel cell companies. One of the alternatives is base metal or graphene-based systems which can operate either with hydrogen or with reformed natural gas or methanol. Another potential alternative is the one proposed by ACAL Energy, which replaced the cathode side of the fuel cell with a system similar to a redox flow battery. In this case there is no need of platinum in the cathode side of the fuel cell, but it is still used it in the anode side. The reduction of platinum loading with this technology is about 80%. If ACAL's technology can be proven commercially it can be a viable option to reduce the platinum loading which is nowadays identified as one of the main issues of PEMFC production. (Fuel Cell Today, 2013)

2.2.2 Molten carbonate fuel cells (MCFC)

The electrolyte of the MCFC is composed by a combination of alkali (Li, Na, K) carbonates, which is retained in a ceramic matrix of LiAlO2. The operating temperatures are between 600ºC and 700ºC. MCFC are in a research stage for large scale stationary power generation for industrial and military applications. Due to their high operating temperature they do not require an external reformer to convert the fuel into hydrogen and they can operate without a precious metal as a catalyst. When the heat produced at the fuel cell is used to create steam to run a turbine to produce electricity, the overall efficiency of the system can be as high as 85%. However, the high operating temperature accelerates its components corrosion and breakdown reducing the system's life. (U.S. Department of Energy, 2011)

The only commercial developer of MCFC is the US company FuelCell Energy, which is producing 300 kW, 1.4 MW and 2.8 MW stationary systems. Apart from the US market, currently they are experiment a growth in the market of the Democratic Republic of Korea. Another development related to MCFC is the DOE funded project aimed to capture the CO_2 emissions from a coal power station to supply the fuel cell in order to mitigate the environmental impact of the fossil-fuelled power plants. (Fuel Cell Today, 2013)

2.2.3 Solid Oxide Fuel Cells (SOFC)

SOFC use a solid, usually Y2O3-stabilized ZrO2 (YSZ), as the electrolyte. The operating temperatures are between 800ºC and 1000ºC. Like in the MCFC this type of fuel cells are in the research stage and their high temperature allows the non-utilization of precious metals as a catalyst, they do not need external fuel reformer and the efficiency is increased when the heat is used to produce electricity. They can also tolerate higher levels of sulphur than other types of fuel cells and this is why they can use gases made from coal. (U.S. Department of Energy, 2011)

One of the main companies developing SOFC is Bloom Energy which has been concentrating its efforts on the domestic market finding customers from the US who have a favourable incentive programs for fuel cells. The company has also received funding from the German utility E.ON, which is trying to introduce fuel cells in the European market. In Japan, Mitsubishi Heavy Industries is developing a SOFC system combined with a cycle gas turbine and is expecting to install hundreds of megawatts of power generation at efficiencies higher than 70%. (Fuel Cell Today, 2013)

2.2.4 Phosphoric Acid Fuel Cells (PAFC)

PAFC use concentrated phosphoric acid as the electrolyte. The operating temperatures are between 150ºC and 220ºC. They are 85% efficient when used for co-generation of electricity and heat. They are also less powerful than other fuel cells for the same size and weight; therefore, they are commonly used for stationary power generation or for big vehicles such as busses. Like the PEMFC, they need to use platinum as a catalyst which makes them expensive. (U.S. Department of Energy, 2011)

PAFC are considered as the first generation of modern fuel cells, and are almost in a commercial stage for stationary electricity generation and hundreds of units have been installed over the world. The leading company producing PAFC fuel cells has been for many years United Technologies Corp (UTC), recently acquired by ClearEdge Power (CEP). CEP has recently launched to the market (April 2014) two improved PAFC in two sizes: 5kW and 400kW. Fuji Electric is also developing a unit of 100 kW which is aiming to install at a number of its factories across Japan. (ClearEdge Power, 2014)

2.2.5 Alkaline Fuel Cells (AFC)

AFC use concentrated KOH as the electrolyte. The operating temperatures are between 120 ºC and 250 ºC. AFC and have been able to demonstrate efficiencies up to 60% in space applications. However, the fuel cell can be easy poisoned if CO_2 is present either in the fuel or the oxidant even in small amounts, making it necessary to purify both the hydrogen and the oxygen used and increasing the operation cost. Improvements in this type of fuel cells have increased the life up to 8,000 operating hours, however to be economically viable the life of the fuel cell should be increased up to more than 40,000 hours. (U.S. Department of Energy, 2011)

The development of the AFC is dominated by the UK-based company AFC Energy. The company is focussing its efforts on enlarging the life span of the fuel cell, which has increased from 3 to 12 months, and on increasing the power generation efficiency. The first commercial system will be sized at 250 kW and is being tested at the chlor-alkali facility of Industrial Chemicals Limited. (Fuel Cell Today, 2013)

2.3 Current applications of fuel cells CHP systems

Fuel cells can be applied for transport, stationary and portable energy generation. From all these applications, the stationary generation is the most used, finding applications across all scales: from micro-scale CHP systems for residential use, to off-grid back-up power systems providing uninterruptible power supplies for critical infrastructure, to prime power for buildings and even to megawatt-scale power stations. (Fuel Cell Today, 2013)

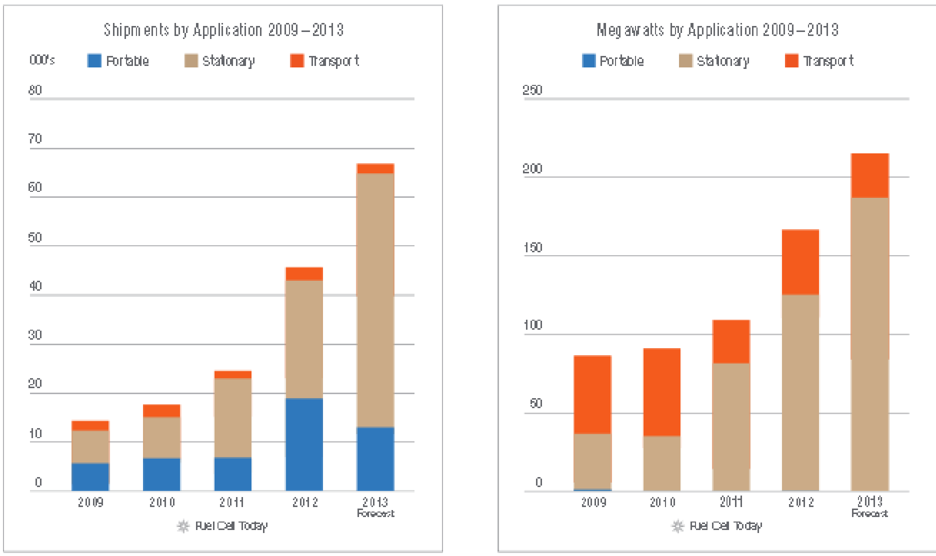


Figure 8: Shipments and Megawatts by Application. Source: Fuel Cell Today, 2013

In this section there have been analysed the fuel cell CHP systems avaliable in the market and the principal companies manufacturing them along with the technical specifications of representative models and they have been classified by their power output. There have been also described installed systems in the UK.

2.3.1 Fuel cell Micro CHP systems (<1kW)

Since 2009, the Japanese government has supported the fuel cell micro-CHP system through the Ene.farm program, providing subsidies to reduce the cost to the consumers. The subsides have been reduced since 2009 and the prevision is to remove them completely by 2015 as they expect that fuel cell unites will be cost-competitive by their own.

Two types of fuel cells are used for micro-CHP systems: PEMFC (80% used) and SOFC (20% used). PEMFC are able to switch of at night and operate at rated power during the day. SOFC units have a higher maximum efficiency but they need to operate continuously, so at night the efficiency is slightly scarified. In the case of PEMFC the cost of the unit has been reduced with a significant reduction of the platinum content. The durability of the fuel cell has also been increased up to 60,000 hours, which equals to an estimate life of 10-15 years if the unit is shut down during the night. (Institution of Mechanical Engineers, 2014)

Companies such as Tokyo Gas, Panasonic, Toyota and Toshiba are developing the technology usually sold at a rated power of 700-750W with a total efficiency from 80

% to 90 %. Japan installed about 50,000 micro-CHP units in 2013 and aims to have sold 1.4 million units by 2020 and 5.3 million by 2030. (Fuel Cell Today, 2013)

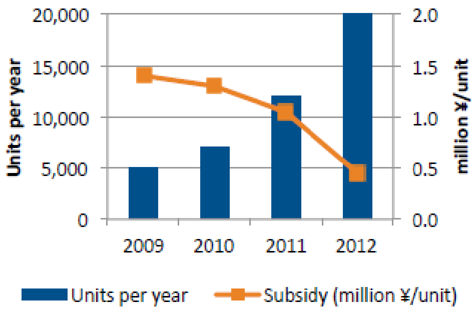


Figure 9: Ene.farm Scheme. Installed units per year, subsidy per unit. Source: Fuel Cell Today, 2013

In 2013, the ene.field project, funded by the EU and some private partners, was launched with the objective of installing 1,000 residential micro-CHP in five years in different locations across Europe. In Germany, the Callux program is installing 800 residential micro-CHP in 2014 and it is funded by the German government and nine partners from the industry. In Denmark, the Danish Micro Combined Heat and Power is also deploying fuel cells between 2010 and 2014. In UK there are some small projects also testing fuel cells such as the SOFT-PACK project and the AIMC4 project. (Curtin , et al., 2013) Recently Panasonic and the German company Viessmann started to sell a fuel cell system in Europe with the following characteristics:

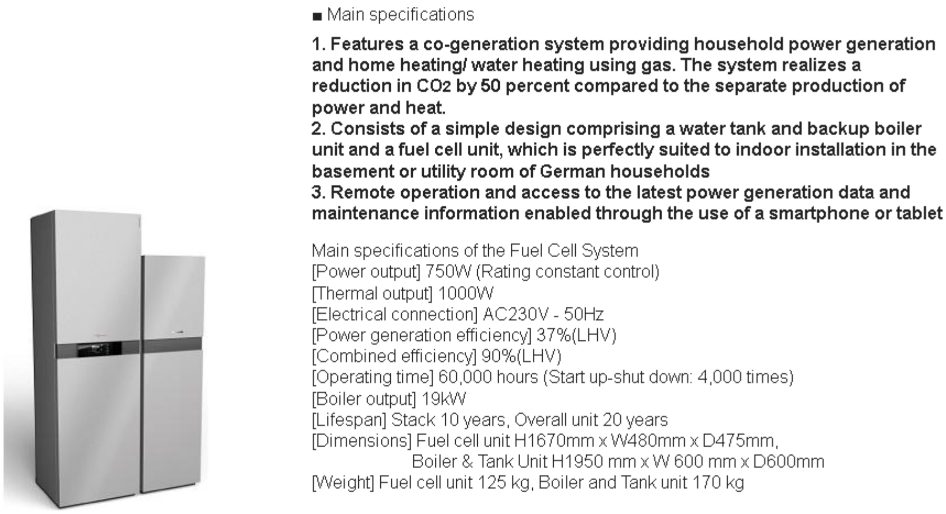


Figure 10: Specifications of a Panasonic 750W fuel cell. Source: Panasonic, 2014

2.3.2 Low power fuel cell CHP systems (5kW)

5kW CHP fuel cell systems have been developed by two US-based companies ClearEdge Power and Plug Power. ClearEdge Power has been selling residential CHP systems for several years and installing them mainly in California for commercial buildings. The units use natural gas as fuel and they can operate either independently or in parallel with the main grid. Plug Power has been installed fuel cell CHP systems since 2002 for residential and operational facilities at the US Army Research Centre. The systems can operate for a total of 80,000 hours and their plan is to reduce the cost to $ 1000/kW, which would make them competitive with diesel generators and micro turbines. (Curtin , et al., 2013) Figure 11 shows the technical Characteristics of the Plug Power PEMFC CHP plant:

Some Technical and Operating Characteristics of Plug-Power PEMFC Power Plant[a]

Continuous power rating	5 kWe (9 kWth)
Power output	2.5–5 kWe (3–9 kWth)
Power quality	IEEE 519
Voltage and frequency	120/240 V, 60 Hz
Fuel	Natural Gas
Emissions	< 1 ppm NO_x, < 1 ppm SO
Sound profile	Conversational level (60 dBA at 10 meters) acceptable for indoor installation
Operating:	
temperature	–18 °C through 40 °C
elevation	0 m through 1,800 m
installation	Outdoor
electrical connection	Grid parallel
Physical characteristics	Dimensions: 2.1 x 0.8 x 1.7 meters

Figure 11: Specifications of Plug-PowerFC Power plant. Source: Srinivasan, 2006

2.3.3 High power fuel cell CHP systems (20kW – 10MW)

The market for high power CHP fuel cells is mainly situated in US and since the last years in Korea and their production is dominated by three US-based companies: FuelCell Energy, Bloom Energy and ClearEdge Power.

ClearEdge Power (ex-UTC Power Energy) designed the 200 kW PAFC power plant which was the first of all types of fuel cell to reach the commercialization stage for combined heat and power. The company has installed over 500 units and is positioned as the most experienced innovator in the fuel cell industry. In 2014, the company launched an improved 400 kW PAFC CHP unit. (ClearEdge Power, 2014)

Figure 12 shows the specifications of a 200 kW power plant:

TABLE 10.1
Some Specification and Operational Performance Characteristics of UTC Fuel Cells 250-kW PC-25 Power Plant[a]

Rated electrical capacity	200 kW / 235 kVA
Voltage and frequency	480/227 V, 60 Hz, 3 phases 400/230 V, 50 Hz, 3 phases
Fuel consumption	Natural gas: 991 liter/min
Efficiency (LHV basis)	87% total: 37% electrical, 50% thermal
Emissions	< 2 ppmv CO, < 1ppmv NO_x, negligible SO_x (on 15% O_2 dry basis)
Thermal energy available: standard: high heat options:	2,638 W @ 60 °C 131,900 W @ 60 °C 131,900 W @ 120 °C
Sound Profile	Conversational level (60 dBA at 10 meters) acceptable for indoor installation
Modular power	Flexible to meet redundancy requirements as well as future growth in power requirements
Flexible siting options	Indoor or outdoor installation Small foot print
Power module	Dimensions 3 x 3 x 5.5 meters Weight 18,000 kg
Cooling module	Dimensions 1.2 x 4.2 x 1.2 meters Weight 770 kg

Figure 12: Specifications of UTC fuel cells 250 kW power plant. Source: Srinivasan, 2006

Bloom Energy is producing a SOFC 200 kW unit and is progressing in the US market with limited orders. (Fuel Cell Today, 2013)

FuelCell Energy is probably the most successful company producing fuel cells to date. The company is increasing its production in US and at the same time is entering into the Korean market since 2014. They have installed the biggest fuel cell power station in Connecticut with 14.9 MW power. The technology used was invented by the company and it is called direct fuel cell (DFC), in which the fuel is reformed in the cathode chamber using a catalyst on the backside of the electrode. In the DFC the cell stacks and the reformer are together and the electrical efficiency of the system is enhanced. (FuelCell Energy, 2013) Annex A shows the technical specifications of a 1.2 MW DFC power plant.

The company Ballard is also producing a 250-kW PEMFC Power Plant. Although the major activity of Ballard is focused on the electric vehicles, since 1994 they have been developing a CHP system based on the same type of fuel cell used for electric vehicles. The efficiency reached by this system is 34% for electric power generation and 42% for heat generation. (Srinivasan, 2006)

2.3.4 Installed fuel cell CHP systems in the UK

In Woking Park there was installed the first fuel cell CHP system of the UK in December 2002. The system installed is a 200 kW fuel cell which provides power, heating and cooling to the leisure centre. Although the cost of the system was very high, it achieved a very good environmental performance according to the programme CHPQA explained later. (Woking Borough Council, 2007)

The company Logan Energy based in Edinburgh and established in 1995 has installed some fuel cell CHP systems for commercial buildings. One example is a PAFC 200kW manufactured by UTC which operates on natural gas and provides power and heat for an SSE's customer service centre. The fuel cell provides two thermal energy streams which are used to drive a 90kW absorption chiller and to supply the heating demand. Another example is a similar system installed at the Palestra building in London. The results of the system have been analysed obtaining: 20% reduction of carbon emission compared to the grid supplied electrical energy, saving approximately 400 tons of CO_2 pa and annual saving in energy costs about £53,000. (Logan Energy, 2011)

2.4 CHP Standards

CHPQA Good Quality CHP standards measure how efficient is a CHP system on a Quality Index (QI). The QI measures the overall efficiency of the CHP and the level of primary energy saving that it can deliver compared to alternative forms of separate heat and power generation. (Carbon trust, 2010)

The QI is calculated with the following formula:

$$QI = X \cdot nelec + Y \cdot nheat$$

The X and Y values depend on the CHP fuel, technology and size; their values are detailed in the Annex B. Fuel cells are considered a special case and for all types and sizes of fuel cells and the values are: X=180 and Y+120. Knowing the electrical and thermal efficiencies of fuel cell systems it is possible to determine the QI. For example, for the cases described above the QI are:

Table 1: Quality Index Results

Fuel cell system	η elect	η heating	QI
700 W Panasonic Vitovalor 300-P	37%	53%	130.2
250 kW UCT fuel cell PC-25	37%	50%	126.6

In all cases the QI index obtained by the fuel cells is high as a QI index above 100 is considered a good QI, and it only depends on the efficiencies which in all types of fuel cells are higher than conventional CHP systems. The financial subsides applicable to the CHP installations are higher when the QI is higher.

2.5 Future integration of fuel cells with renewable energy systems

The capacity to integrate fuel cells with renewable energy systems has also been analysed in this dissertation. One drawback of the renewable energy generation systems is their variability: wind is usually blowing intermittently and solar power is only available during daytime. For this reason, if a system wants to be designed to rely only on renewable energy systems it has to be over-sized to take into account this factor, or it has to rely on back-up systems which are usually based on fossil fuels. In a higher scale, natural gas and other fossil fuels are used to compensate the supply and the demand of electricity. If in the future, renewable energy systems replace fossil fuel generation systems, a technology to balance the generation to match the demand has to be developed. One solution is to store the excess of renewable energy during times of plenty to use it when sufficient energy is not available. However, the storage of electrify in large scale conventional batteries or other technologies is a difficult task. Hydrogen can be a solution for this future problem. (Fuel Cell Today, 2012)

2.5.1 Storage of electricity as hydrogen

To transform the excess of electricity into hydrogen an electrolyser is required. An electrolyser cell is like a fuel cell run in reverse, using electricity to produce hydrogen. Two commercial electrolyser types can be found in the market: proton exchange membrane and alkaline. The principal drawback of current commercial electrolysers systems is that they may be too small to take advantage of the potential high volume of electrify produced by wind. (National Renewable Energy Laboraory, 2004)

The hydrogen generated by the electrolyser is stored in tanks at high pressure. Hydrogen is a widely used industrial gas with a well-developed set of codes and standards for its storage. However, large storage systems are required in integrated renewable energy systems, therefore the pressure at which the hydrogen stored is increased to reduce the size of the storage tanks; some applications can use pressure levels up to 875 bar. This higher pressure requires additional testing and certification of high-pressure vessels. (Lipman, 2011)

Figure 13 is a schematic representation of how fuel cells can be integrated with renewable energy systems in the future. Hydrogen can also be obtained from biomass and can be used for transport or it can be injected in the natural gas grid.

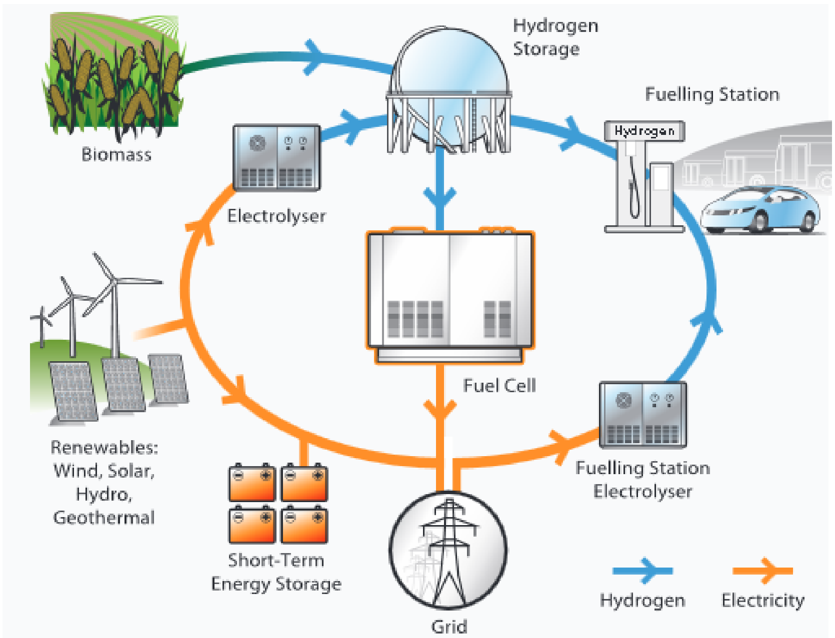


Figure 13: Integration of fuel cell with renewable energy systems. Source: Fuel Cell Today, 2012

2.5.2 Case studies

There are some experimental projects trying to evaluate the performance of integrated hydrogen and renewable energy systems.

In Germany, there was opened a hydrogen-power plant on October 2011 which is primarily a 6 MW wind power plant. When more wind power is available than required, the electrolysers generate hydrogen which is stored on site. The hydrogen can be also mixed with biogas and used in the cogeneration power plants, which produce electricity when no wind is available; the heat is fed into a district heating network, increasing the efficiency of the hybrid power plant. (Carter, 2012)

In the French island of Corsica, in the Mediterranean Sea there is installed the project Mission hYdrogen & Renewable for the inTegration on the Electrical grid (MYRTE), which combines solar power with electrolysers, hydrogen and storage fuel cells. PV panels can provide energy during the day but, using the electrolyser and hydrogen energy storage, excess of electricity can be stored and returned when required, for example during the night. The initial plan of the project is to prove the concept, but there are future plans to integrate the energy system housing electrolysers, fuel cells, fuel storage and heat management systems inside a standard container. (Fuel Cell Today, 2012)

The hydrogen office at Methil consists in a building powered by wind energy and a hydrogen energy system. The system includes a 750 kW wind turbine, 30 kW electrolyser, 10 kW hydrogen fuel cell and a geothermal source heat pump. It also uses a 5 kW hydrogen boiler and a public electric vehicle charging station. The project uses the excess of energy from the wind turbines to create hydrogen, store it and use it when no wind is available. Heating is supplied by a heat pump in the building. (Bright Green Hydrogen, 2014)

All these examples aim to demonstrate the potential integration of hydrogen and renewable energy systems to rely less on fossil fuels and reduce the emissions of CO_2. Although, all these projects are for research purposes, they are contributing to the technology development and probably their number will increase in the coming years.

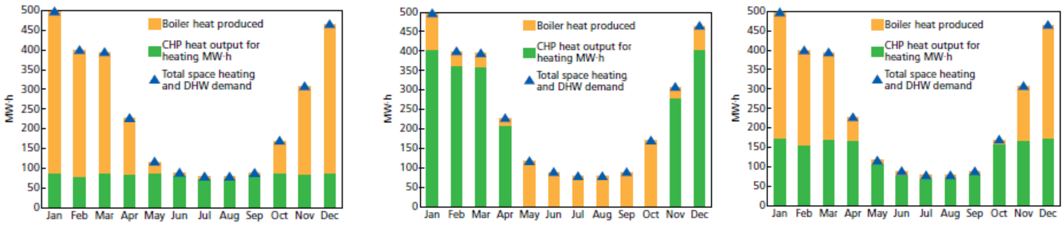
3 Fuel cell CHP simulation tools analysis

In order to understand the performance of the fuel cell CHP systems different sizing recommendations and energy simulations tools have been analysed in this section. The Chartered Institution of Building Services Engineers (CIBSE) recommendations have been used to comprehend different sizing strategies and their advantages and drawbacks. Tools such as the CHP Site Assessment tool, the Simplified Building Energy Model (SBEM) and ESP-r have been analysed regarding their potential to simulate fuel cells in order to obtain the adequate results to analyse their performance and calculate the environmental and economic impact of the system.

3.1 CIBSE CHP sizing guide

CIBSE recommendations (CIBSE, 2013) have been analysed with the purpose of understanding how a CHP system has to be designed. CIBSE is an international Chartered Institution of Building Services Engineers based in London which publishes several guides for building services design recommendations and standards. Although the guide developed by CIBSE is referred to conventional CHP systems, the principles can be applied also to fuel cell CHP systems.

The relevant information for this dissertation can be found in the chapter *4.4 Principles of CHP sizing* of the CIBSE guide. The first recommendation suggests that the CHP system should be sized according to the heating and hot water demand. There are three strategies which define how the CHP system is operate and the percentage of the heating demand that is supplied by the CHP system. Figure 14 represents the three strategies defined:



Base-load sizing On/Off sizing Part-load sizing

Figure 14: CHP sizing strategies

When the CHP is designed to meet the base load, it runs at rated power during all the year and results in a smaller CHP. Therefore, the payback period of the installation is short but the influence to the overall cost of energy supply is low. An On/Off sizing strategy allows installing a bigger size CHP system which is completely turned off when the heating demand is low. In this case the payback period is longer but the cost of the heating supply is considerably reduced. When applying a part-load strategy the heating demand supplied by the CHP system is increased in relation to its size. However, the efficiency of the system is reduced when the CHP system is not operating at its rated power and the maintenance costs are increased as they usually depend on running hours and not on the heat or electricity generated.

The three different sizing strategies can be evaluated, according to CIBSE recommendations, through two criteria:

1. Economic aspects: calculation such as internal rate return, net present value or payback period should be carried out to determine the cost or the savings of each proposed design.
2. CO_2 saving: CO_2 emission of each option should be compared in order to determine its environmental impact.

To carry out an economical and environmental analysis there is some data which has to be collected or calculated.

- Heating and power demand of the case study.
- Fuel and electricity prices.
- Operation of the CHP: heating and electrical output, fuel consumption.
- Cost of the CHP system.

To determine all these values the system has to be designed and sized using simulation tools. In the following sections of this dissertation there have been analysed different existing tools and their potential to simulate fuel cell CHP systems.

3.2 CHP Site Assessment Tool

The first tool analysed is the CHP Site Assessment Tool. This tools is developed by the UK's Department of Energy & Climate Change (DECC) which works to make sure that UK has secure, clean, affordable energy supplies and promote international action to mitigate climate change. (UK Government, 2014)

This tool gives an indicative assessment and potential options for installing CHP systems on a particular site. It is a simple tool which gives the 5 best options for the site analysed and shows:

1. CHP capacity.
2. Capital cost.
3. Payback period.
4. Net Present Value.
5. Cost Saving.
6. Primary energy savings.

A simulation has been carried out to analyse the results given by this tool than can be useful for the objective of this dissertation. The Annex C shows the CHP systems proposed by the tool and the monthly electrical and heating demand of the case studied. This tool is not a sizing tool and all the CHP systems recommended are based on reciprocated engine (not fuel cells). However, it can be used to have an approximate idea of the ranges of sizes of fuel cell that can be analysed in more detail in dynamic analysis and an approximate value of the heat and electricity generated the economic costs and the CO_2 emissions.

In conclusion the CHP Site Assessment Tool can be used to have an idea of the appropriate size of a CHP system for a given site. After analysing this tool it has been detected the necessity of a more powerful simulation tool in order to analyse the real performance of a fuel cell and its economic and environmental impact.

3.3 Simplified Building Energy Model (SBEM)

The second software tool analysed is the SBEM, developed by the Building Research Establishment (BRE). This tool provides an analysis of the building's energy performance to determine the CO_2 emission rates in compliance with the UK building's regulations and to generate Energy Performance Certificates for commercial buildings. (BRE, 2014)

In this dissertation, it has been used the version 4.1 of iSBEM (user interface of SBEM), as it is the version that has to be used for the Scottish building's regulation. Using an exemplar provided by the software as a baseline, it has been added a conventional CHP system and a fuel cell CHP system. In SBEM the CHP system can be configured according to the electrical and thermal efficiencies, the quality index and the percentage of heating demand supplied by the CHP system. To simulate a conventional CHP system the thermal efficiency has been set up at 45% and the electrical efficiency at 25% and the Quality Index at 100 which can be considered as standard values for a conventional CHP system. (Carbon trust, 2010) To simulate the fuel cell CHP system the heating efficiency has been set up at 50% and the electrical efficiency at 37%. These values are defined by the 200kW UTC fuel cell CHP plant described before. In both cases the percentage of heating demand supplied by the CHP system is 70%. The results for the three systems analysed are (Detailed results are shown in the Annex D):

Table 2: SBEM analysis results

	Baseline	Conv. CHP	Fuel cell CHP
Building CO2 emission rate (Kg CO2/m2.annum)	58	55	49
Heating Energy Consumption (kWh/m2.annum)	67	112	94
Electricity produced by CHP (kWh/m2.annum)	0	23	27
Electrical Demand (kWh/m2.annum)	378	357	325

Results show that CO_2 emissions are reduced with a conventional CHP system and they are even more reduced with a fuel cell CHP system as the efficiency of the system is higher. However, as in a fuel cell the conversion of energy takes place through an electrochemical process, the emissions of other ait pollutants (NO_x, SO_2 and CO) are significantly reduced. In fact the emission of NO_x can be considered negligible. As fuel cells are not totally represented in SBEM calculations, these reductions in the emissions are not taken into account in the calculations. (ClearEdge Power, 2014)

The other output of the tool is the heating and electricity consumption. From the results it is possible to see that the energy consumption is increased when a CHP system is installed. This is because SBEM takes into account the amount of fuel consumed by the heating system. In the case of the CHP system the fuel used is producing heat and power and for this reason the fuel consumption is higher. The total electrical demand of the building is reduced as part of it is directly supplied from the CHP system. In this case, the values are correct for a fuel cell as they depend on the efficiencies which are an input of the tool.

As explained before, the criteria to analyse different options of fuel cells is based on the environmental and the economic aspects. Using SBEM, the CO_2 emissions of fuel cells can be calculated but the reduction of emissions of other pollutants is not considered. The economical saving can be calculated comparing the cost of the fuel consumption (increased when a CHP system is installed) with the cost of the electricity (reduced when a CHP system is installed). However, one of the inputs used for the SBEM calculations is the percentage of heating demand supplied by the CHP system. In this case the value for all the calculations has been estimated at 70%, but its real value has to be calculated. Therefore, it can be concluded that SBEM can be used to calculate the energy performance of CHP systems but it requires some input data which depend on the design and size of the components; and has to be calculated with a dynamic simulation analysis using a more powerful tool.

3.4 ESP-r

ESP-r has been analysed in this dissertation to determine its potential to carry out dynamic simulations of fuel cells CHP systems in buildings and determine their performance.

The ESP-r tool is developed by the University of Strathclyde Energy System Research Unit (ESRU). It is an integrated modelling tool which can be used to simulate thermal, visual and acoustic performance of buildings. It analyses the energy use and the associated gaseous emission to determine their environmental impact. The tool is able to assess the heat, air, moisture, light and electrical power flow based on the user's specifications. (ESRU, 2007)

ESP-r allows the user to define a building geometry with its associated zones. It is possible to specify all the characteristics of the zones according to their construction details such as U values or glazing types, the internal gains generated by the occupancy or the appliances, the climate conditions according to the location of the building. All the plant components associated to the building can be defined specifying the heating and cooling systems, the ventilation, the lighting and it is possible to install renewable energy generation systems like a PV panel. The controls of all the plant components can be set up controlling the conditions which want to be achieved inside the building and the operating hours of the systems. Results show dynamic analysis of any of the components of the system and their operating conditions. It can be analysed the energy demand (fuel and electricity) and the zone's environment quality.

For its functionality, ESP-r can be considered a relatively similar tool than the commercial IES. The main difference is that ESP-r is mainly used for the academic purposes. For this reason, ESP-r has a larger amount of components developed, even if they do not exist in a commercial stage. This is the case of fuel cells which are not developed for IES but they have already been developed in ESP-r. This is the reason why ESP-r is used to carry out the simulations in this dissertation. Although the potential of ESP-r is higher than the potential of IES, it is also a more complex tool to use. Its constant development involves, sometimes, a lack of information of its functionalities and the users' guides for the new developments are usually not created. For this reason, the first stage of this dissertation when using ESP-r has been to carry out a detailed analysis of the fuel cell potential and a set of simulations to ensure that the results obtained where correct.

3.4.1 Fuel cells in ESP-r

Bearing in mind that the objective of the utilization of ESP-r in this dissertation is to analyse the performance of fuel cells in buildings, an analysis of the fuel cell components already developed in ESP-r has been carried out. There have been also analysed available exemplars using fuel cell CHP systems.

3.4.1.1 Available Fuel cell component models in ESP-r

Fuel cell components available in ESP-r can be found in the component's database of ESP-r. The characteristics detailed for each component are the description, number of nodes and all the variables related to the component with their default value and their accepted range of values. Table 3 shows all the fuel cell components found in the database.

Table 3: ESP-r fuel cell components

Type	Description	Insertion date	No. of nodes
fuel cell	three node description of a residential fuel cell	8 Aug 01	3
PEM CHP fuel cell system	PEM fuel cell system supplying WCH loop; 1 node model	12 Apr 02	1
2-node PEM hydrogen fuel cell model	Empirical PEM hydrogen cogeneration fuel cell	18 Jan 05	2
3-node residential SOFC with 2 connections	three node description of a residential fuel cell	8 Aug 01	3
3-node residential SOFC with 2 connections	three node description of a residential fuel cell	8 Aug 01	3
14-node FC-cogeneration model	IEA/ECBCS Annex 42 FC-cogeneration model	24 Mar 05	12

The information detailed in the table above, is all the information that can be collected directly from the database of ESP-r for the fuel cell components. They can be installed as plant components for a model to analyse its performance. When they have more than 1 node, the model must be better understood. This can be done through the information detailed in the source code of ESP-r.

From the fuel cells types available in ESP-r, the one selected to use for this dissertation is the “PEM CHP fuel cell system”. This type of fuel cell has been selected to carry out the simulations because it can represent a PEM fuel cell type, which is the most used type of fuel cell in the industry. Moreover, it has been recently used in a model developed by a former student with good results obtained as explained later. Even though this type of fuel cell has only one node and is more simple than other available in ESP-r, it is still a good model, which has an accurate level of detail and can proportionate interesting results for this dissertation. The following table shows its description, the variables that can be configured and the results that can be obtained.

Table 4: Fuel cell component description, variables and outputs

Component Description			
Generic type : PEM CHP fuel cell system			
Description: PEM fuel cell system supplying WCH loop; 1 node model			
Insertion date : 12 Apr 02 15:55			
Nodal Scheme Description			
Number of nodes : 1 No of nonzero matrix elements : 1			
Node connections : 1,			
Variables:	**Value**	**Min**	**Max**
1 Fuel type (1=methane, 3=methanol)	1	1	3
2 Nominal rated output (W, electrical); Value = 5000.0; Range (Min Max):0.0000 2000.0	5000	0	5000
3 Turn-down ratio (-)	0.1		
4 Electrochemical efficiency at rated output (-)	0.47	0.0000	1
5 Activation polarization (-)		0	0.5
6 Power conditioning efficiency (-)	0.92	0.85	1
7 Reformer thermal loss coefficient (W/deg C)	0	0	0.3
8 Fuel cell stack thermal loss coefficient (W/deg C)	0	0	40
9 HTWS thermal loss coefficient (W/deg C)	0	0	0.3
10 LTWS thermal loss coefficient (W/deg C)	0	0	0.3
11 PROX thermal loss coefficient (W/deg C)	0	0	0.3
12 H2 Burner thermal efficiency (-)	1	0.8	1
13 Auxiliary burner efficiency (-)	0.95	0.8	1
14 Air compressor isentropic efficiency (-)	0.76	0.5	1
15 Natural gas compressor isentropic efficiency (-)	0.76	1	
16 Pump efficiency (-)	1	1	
17 Electric motor efficiency (-)	0.92	0.5	1
18 Evaporative cooling system performance (COP)	18.6	5	30
19 Reformer fuel utilization (-)		0.8	1
20 Stack fuel utilization (-)		0.6	1
21 Auxiliary burner fuel utilization (-)	1	0.9	1
22 Hydrogen burner fuel utilization (-)		0	1
23 Steam-to-carbon ratio (#H20:#C)		4	
24 Cathode excess air ratio (-)	2	1	4
25 PROX excess air ratio (-)	2	1	4
26 Auxiliary burner excess air ratio (-)	1.1	1	2
27 Hydrogen burner excess air ratio (-)	1.1	1	2
28 Reformer shift percentage (-)	0.47	1	
29 HTWS shift percentage (-)	0.84	0	1
30 LTWS shift fraction (-)	0.84	0	1
31 PROX shift fraction (-)	1	0	1
32 Reformer inlet temperature (deg C)	750	500	900
33 HTWS inlet temperature (deg C)	430	350	550

34 LTWS inlet temperature (deg C)	230	200	300
35 PROX inlet temperature (deg C)	130	100	300
36 Stack operating temperature (deg C)	80	60	100
37 Process heat recovery minimum temperature. (deg C)	50	0	200
38 Space heat recovery minimum temperature (deg C):		0	20
39 Ambient temperature (deg C)	20	-20	50
40 Compressor outlet pressures (kPa)	110	101.32	600
41 Anode operating pressure (kPa)	110	101.32	600
Additional output variables:			
1 Fuel consumption (kg/s)			
2 Gross electrical output (kW)			
3 Net electrical output (kW)			
4 Thermal production (kW)			
5 Electrical efficiency (-)			
6 Thermal efficiency (-)			
7 Overall efficiency (-)			

Table 4 shows that the fuel cell can be configured in detail. The values for variables such as fuel type, rated output, electrochemical efficiency and stack operating temperature can be changed according to the technical specification of the fuel cell that is represented. Outputs such as fuel consumption and thermal and electrical production of the fuel cell can be also obtained. These outputs are necessary for the final results obtained in this dissertation.

3.4.1.2 Available Building and Plant models with fuel cells in ESP-r

From all the exemplars available in ESP-r, there are none using fuel cells. However, using the ESP-r users' mail list it has been discovered that there are two tester exemplars available that contain fuel cells. This exemplars where developed in the Final Report of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme. (Her Majesty the Queen in Right of Canada, 2008)

The two tester models "plt_pre_A42_PEMFC_model" and "plt_pre_A42_SOFC_model" contain a 1.5 kW PEMFC and a 3kW SOFC respectively. However, the model available has been prepared to analyse the electrical performance of the fuel cell but not the thermal performance. Therefore, to analyse the thermal performance of the fuel cell some changes in the model have to be applied.

Another model analysed in this dissertation is a model developed by a former student of the University of Strathclyde. This model is made from two exemplars available in ESP-r: a CHP exemplar and a wet central heating exemplar. Both models are put together resulting in a model composed by a zone, which can represent a living room or an office, where the heating demand is supplied by a wet central heating radiator. The hot water is supplied to the radiator from a hot water storage tank. A fuel cell CHP unit is providing the hot water to the storage tank. This was considered as a very interesting model for this dissertation as it can provide information of the performance of a fuel cell CHP unit for different size of fuel cells and storage tanks. However, the firsts simulations carried out using this model detected some problems:

1. The temperature in the zone was not properly controlled. It was detected that in some specific periods the heating system was heating the zone even if the temperature was above the setting point of 22 ºC.
2. Increasing the fuel cell size was not producing any difference in the total heat supplied to the zone.

The first problem was solved changing the control settings of the model. The new control was set up to run the pump that connects the water storage tank to the radiator when the temperature of the zone drops below 21 ºC and to stop it when the temperature is higher than 23 ºC.

Regarding the second problem described, it was detected that the flow of the pumps defined in the system was too small and therefore the heat which was transferred from the fuel cell to the water storage tank was not increased when the size of the fuel cell was increased.

After solving the problems detected, this model has been considered as the best one for this dissertation and it has been used as a baseline in the next simulations carried out.

3.5 Conclusions of the simulation tools analysis

From the tool analysis carried out in this section it has been determined that a dynamic simulation tool such as ESP-r is needed to represent the performance of a fuel cell CHP system. The CHP Site Assessment Tool can be used to calculate the appropriate CHP system size for a given scenario, but all the results are based on conventional CHP systems. SBEM can be used to calculate CO_2 emissions and demands of the system but the inputs required depend on the design of the system and its performance. ESP-r has the capacity to simulate dynamically the performance of fuel cells and for this reason it has been considered for subsequent analysis. For the simulations it has been considered a model composed by a room where the heat is supplied by a CHP system. The CHP system is composed by a 1 node fuel cell. Even though there are more complex fuel cells available in ESP-r, the 1 node component was selected for this dissertation because it can represent a PEM fuel cell which is the most used type of fuel cell and it has a high level of detail in the variables that can be configured and the results that can be obtained.

4 ESP-r simulations

In this section there is described the model used for ESP-r simulations, its components and control systems. There are also described the results obtained for the scenarios proposed and an analysis of the environmental and economic impact of the system is carried out.

The fuel cell selected for the simulations is a 5 kW PEMFC. This represents an existing commercial fuel cell which uses a PEM fuel cell; the most used type of fuel cell in the market. For this fuel cell, there have been determined the scenarios where it can be used to obtain significant reductions in operating costs and CO_2 emissions.

Simulations have been carried out in order to analyse the performance of the system. From this analysis it has been defined a methodology to select the best hot water storage tank. After deciding the size of the storage tank results have been obtained: fuel consumption, operating hours, percentage of demand supplied by the CHP and the back-up system and electricity generated.

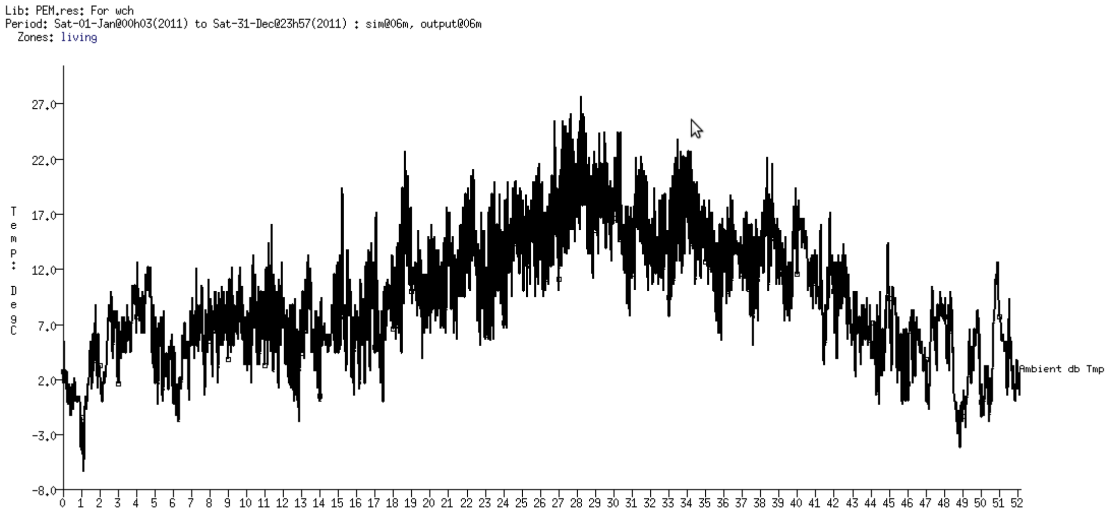
Finally, the results are calculated and validated to perform an environmental and economic analysis of the system.

4.1 Description of the model

The model used is composed by a zone that represents a big office inside a building. The heat generated by a CHP system is recovered and collected into a storage tank. A wet central heating uses the heat stored in the tank to supply the heating demand of the zone. In all simulations the control system is configured to maintain the zone within acceptable values for office activity. The parameters that have been set up in ESP-r to carry out the simulations are explained in the following section.

4.1.1 Climate

The climate used in the simulation is the default one provided by ESP-r. This climate corresponds to the climate of an area in England (Latitude: 52N, longitude: 0). Variation of the ambient temperature is represented in the following graph:



Graph 1: Annual ambient temperature

From this climate data, there have been identified summer and winter days and spring/autumn representative days. These are the periods used for the simulations.

- Summer days:
  - Period: 12 Jul – 13 Jul.
  - T_{max}= 26.1 ºC ; T_{min}= 13.3 ºC ; T_{mean}= 19.24 ºC.
- Winter days:
  - Period: 8 Jan – 9 Jan.
  - T_{max}= 0.5 ºC ; T_{min}= -6.4 ºC ; T_{mean}= 2.6 ºC.
- Spring/Autumn days:
  - Period: 6 May – 7 May.
  - T_{max}= 13.3 ºC ; T_{min}= 6.6 ºC ; T_{mean}= 9.2 ºC.

There have been also carried out simulations from the 1st of July to the 20th of July representing the warmest period of the year.

4.1.2 Plant components

Figure 15 shows a schematic representation of the components of the model:

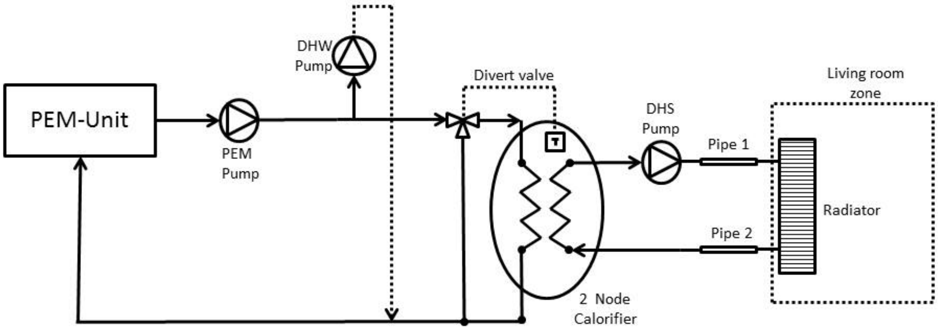


Figure 15: Component's schematic representation

The components represented in the figure and relevant for the current dissertation are:

- PEM-Unit: Represents the PEM 5 kW fuel cell system developed by the company Plug-Power (technical specifications are listed in the figure 11). It has been used the 1 node PEM CHP fuel cell system available in ESP-r with the electrical rated power set up at 5kW and the output temperature set up between 60 ºC and 90 ºC.
- PEM pump: This pump moves the water through the PEM-Unit extracting the heat generated by it, and storing it in the hot water tank. The flow of the pump has been set up at 1 kg/s.
- Calorifier/hot water storage tank: Stores the hot water supplied by the PEM-Unit and supplies the hot water used for heating the zone.
- DHS pump: Pumps the water from the hot water tank to the radiator placed inside the zone. The flow of the pump has been set up at 0.8 kg/s.
- Radiator: Provides heating to the zone. The power output of the radiator has been set up at 10 kW.

4.1.3 Control system

The entire heating system is switched on during the day (7 am to 10 pm) and switched off during the night (10 pm to 7 am). This includes the fuel cell and the DHS pump, which supplies the heat to the radiator.

There are two controls set up for the model:

1. Temperature in the hot water tank. The temperature in the water tank is set up between 40 ºC and 75 ºC. When the temperature is above 75 ºC the PEM-Unit is switched off and when the temperature is below 40 ºC the PEM-Unit is switched on. The purpose of this control is to maintain the temperature in the tank below a maximum of 75 ºC to prevent damage of the tank and at the same time to switch off the fuel cell when the heat produced is not used at heat the zone.
2. **2.** Temperature in the office. The heating system is set up to maintain the temperature inside the zone between 21ºC and 23ºC, which are the standard values given by CIBSE recommendation for an office. (CIBSE, 2006) When the temperature of the office is below 21ºC the DHS pump is switched on and when the temperature of the office is above 23ºC the DHS pump is switched off.

4.1.4 Zones description

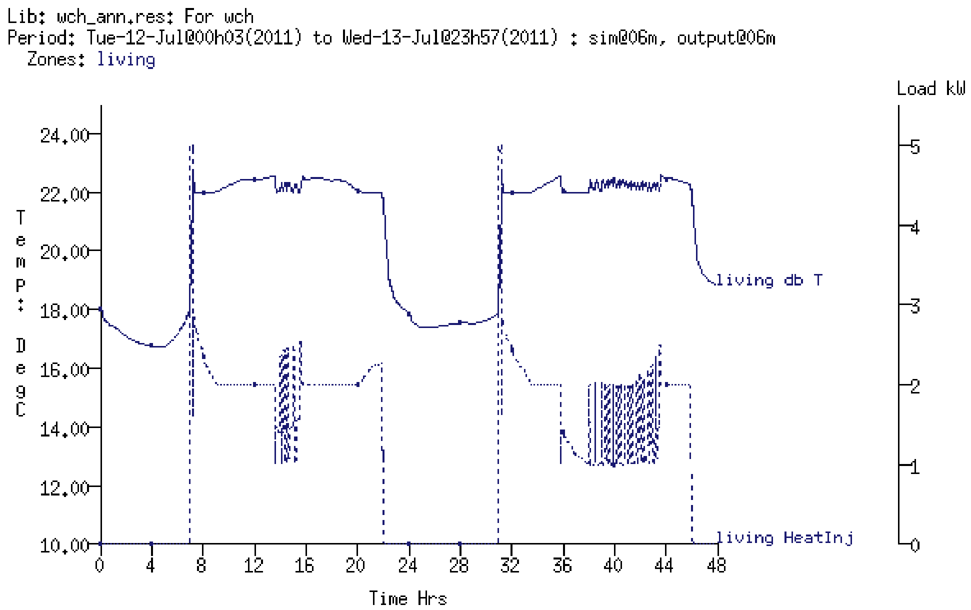
One of the objectives of the simulations carried out in ESP-r is to determine which one is a good scenario to use a 5kW fuel cell. A first set of simulation have been carried out for different sizes of offices. From the values obtained in these first simulations; it has been detected that interesting results can be obtained for a small office (250m^2) and a large office (500m^2). For smaller sizes of office it is considered that the demand is too low for the system proposed. Conversely, for larger sizes it is considered that the heating demand is much higher than the heating provided by the fuel cell and therefore the impact of the CHP system for this is scenario is not significant.

To analyse the heating demand in the office, a control which maintains the temperature at 22 ºC from 7 am to 10 pm has been set up. In this case, the heating demand is perfect (the technology used is not relevant) and has enough power to maintain the correct temperature in all conditions.

4.1.4.1 Small office heating demand

An analysis of the heating demand for the representative winter, summer and spring/autumn days has been carried out:

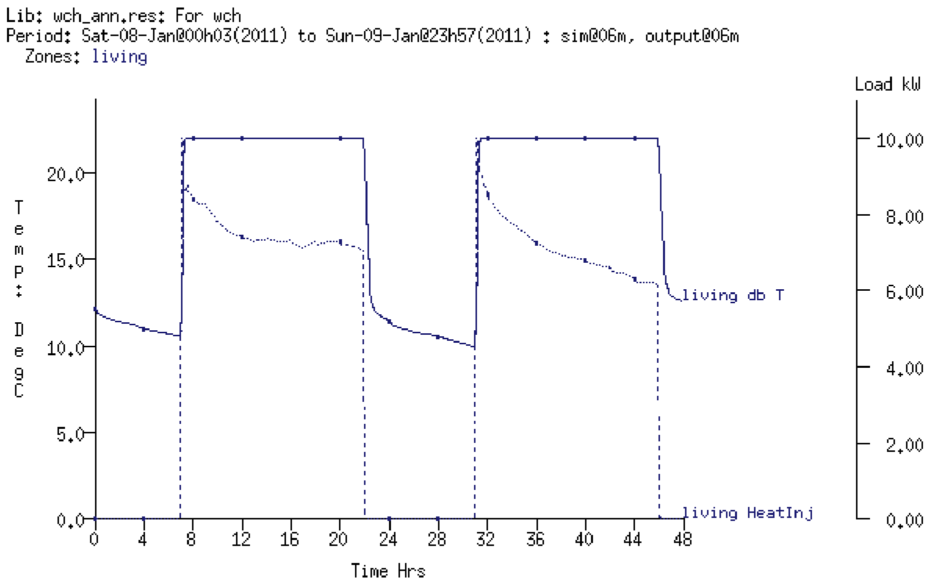
Summer



Graph 2: Summer heating demand. 250m^2 office

Total heating demand during two summer days is 56.8 kWh.

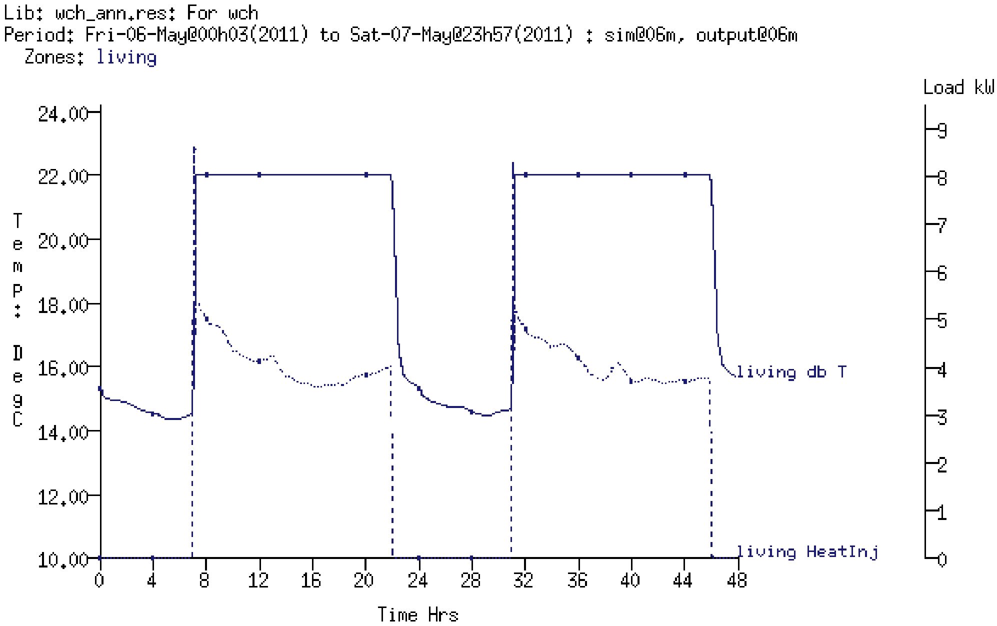
Winter



Graph 3: Winter heating demand. 250m^2 office

Total heating demand during two winter days is 219.6 kWh

Spring/Autumn 123.4 kWh 30h



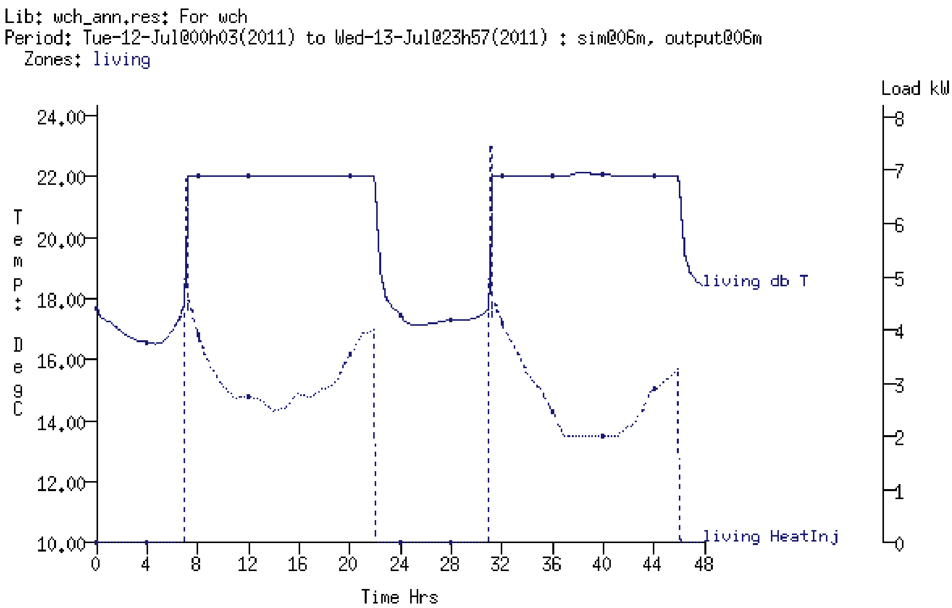
Graph 4: Spring/Autumn heating demand. 250m^2 office

Total heating demand during two spring/autumn days is 123.4 kWh.

4.1.4.2 Large office heating demand

An analysis of the heating demand for the representative winter, summer and spring/autumn days has been carried out:

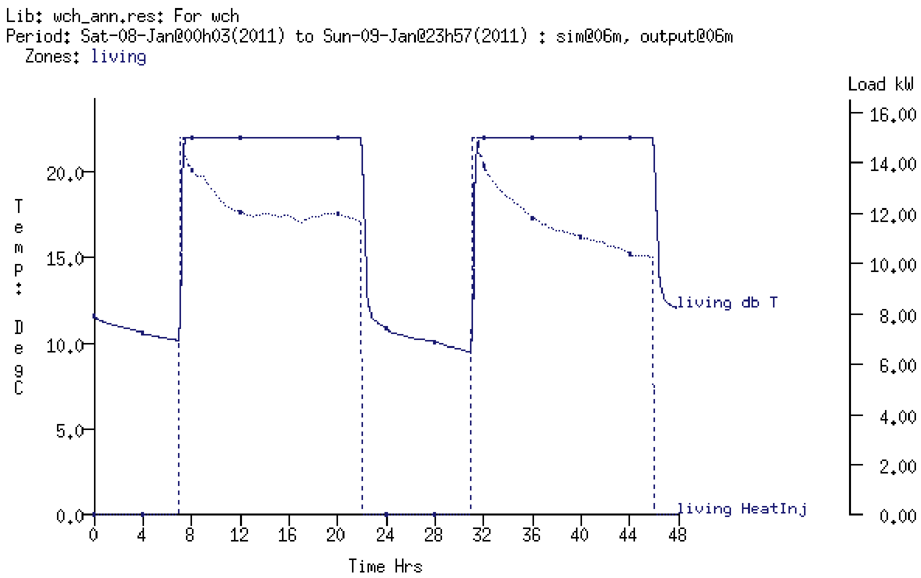
<u>Summer</u>



Graph 5: Summer heating demand. 500m^2 office

Total heating demand during two summer days is 88.8 kWh.

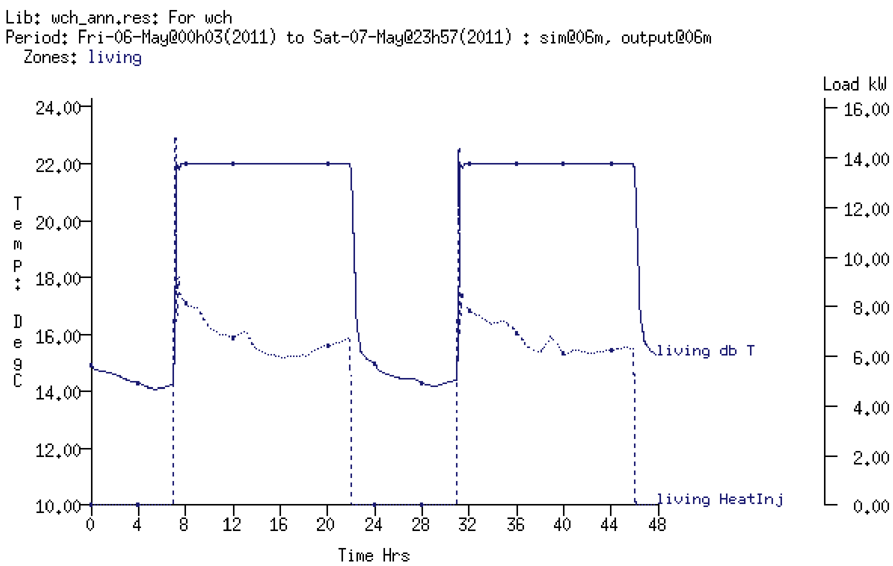
Winter



Graph 6: Winter heating demand. 500m^2 office

Total heating demand during two winter days is 356.5 kWh

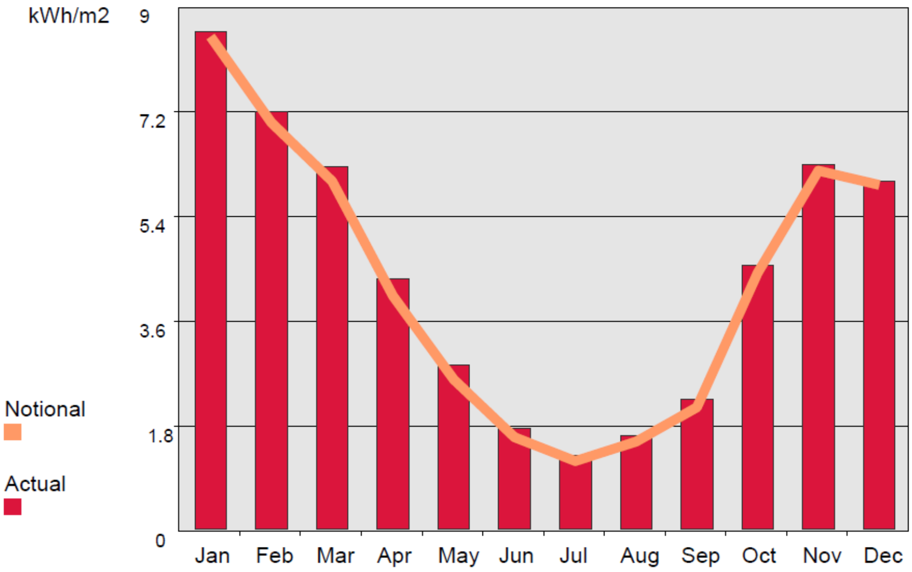
Spring/Autumn



Graph 7: Spring/Autumn heating demand. 500m^2 office

Total heating demand during two spring/autumn days is 204.1 kWh.

Casual gains, infiltration, and construction specifications of the model have not been changed to carry out the simulations. However, as all these parameters affect the heating demand of the model, the results obtained in ESP-r simulations have been compared with the demands obtained in the notional building that represents an office in SBEM. Results are detailed in the graph 8.



Graph 8: SBEM calculated heating demand

Comparing the values it is possible to determine that the small office used in ESP-r has approximately the same heating demand than an office of 250m^2 in SBEM. Similarly, the large office used in ESP-r has approximately the same heating demand than an office of 500m^2. For this reason, in subsequent simulations the small office is considered as a standard 250m^2 office and the large office is considered as a standard 500m^2 office. Nevertheless, the results obtained for both offices analysed are useful for any scenario with a similar demand and the same methodology applied in this dissertation can be applied for different scenarios to calculate the environment and economic impact of fuel cell CHP systems.

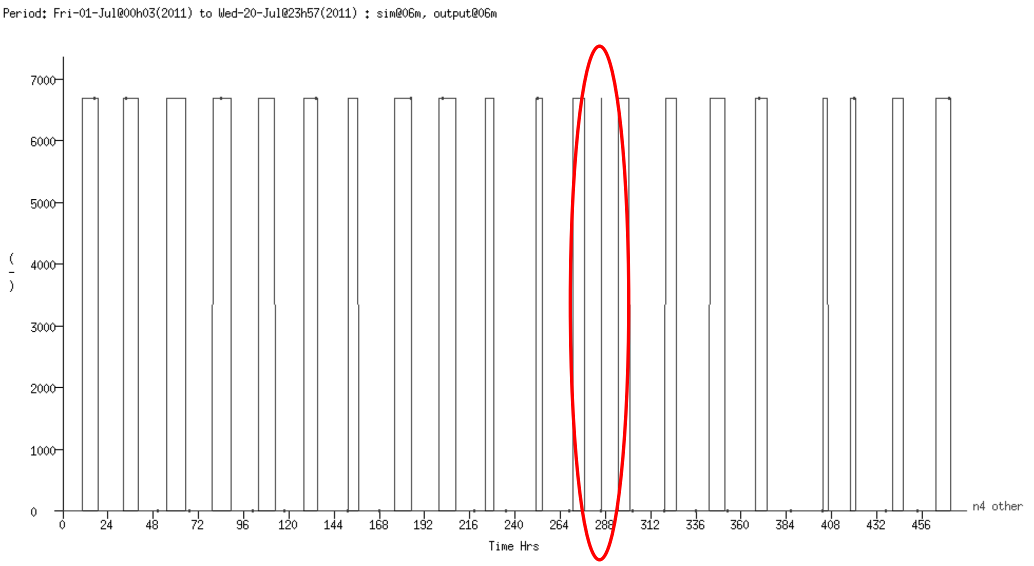
4.2 Fuel cell CHP simulations

The simulations carried out using the model have a double objective. The first objective is to analyse the performance of the fuel cell during the representative days and ensure that it is not switching on and off multiple times during a day reducing the efficiency of the system and the life of the fuel cell stack. Changing the size of the tank can modify the performance of the fuel cell to avoid this effect. The second objective is to determine the total heat supplied to the office, the fuel consumed by the fuel cell and the electricity generated by the fuel cell. These simulations are carried out for office's size of 250m^2 and 500m^2.

4.2.1 250m^2 office's fuel cell CHP simulations

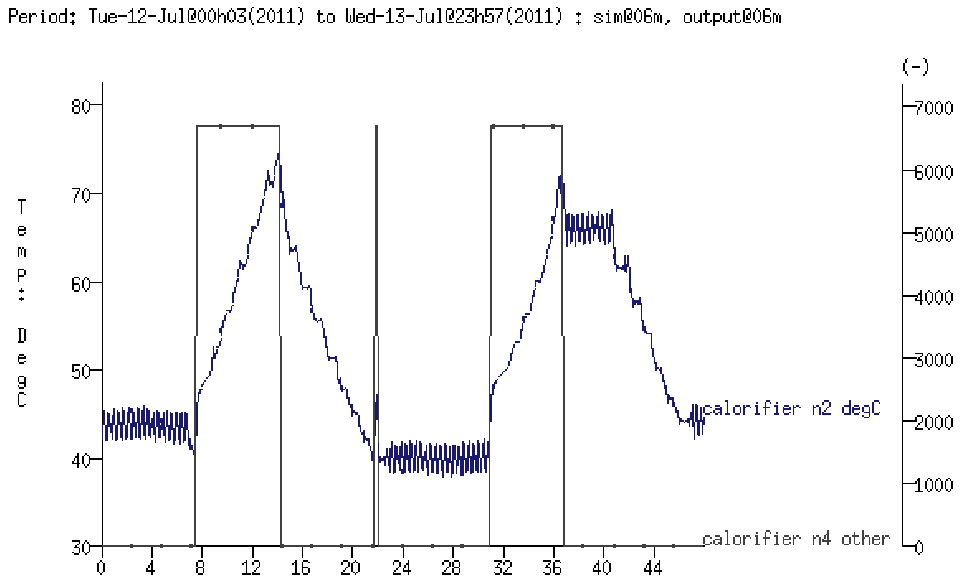
4.2.1.1 Influence of tank sizing in system performance (250m^2 office)

As explained before one purpose of this simulations is to ensure that the fuel cell is not switching on and off repeatedly during a day. At summer, when the heating demand is lower, is when this undesired effect can occur as the fuel cell is not operating during all day. To analyse this, a simulation of the output of the fuel cell for the warmest period of the year has been carried out.



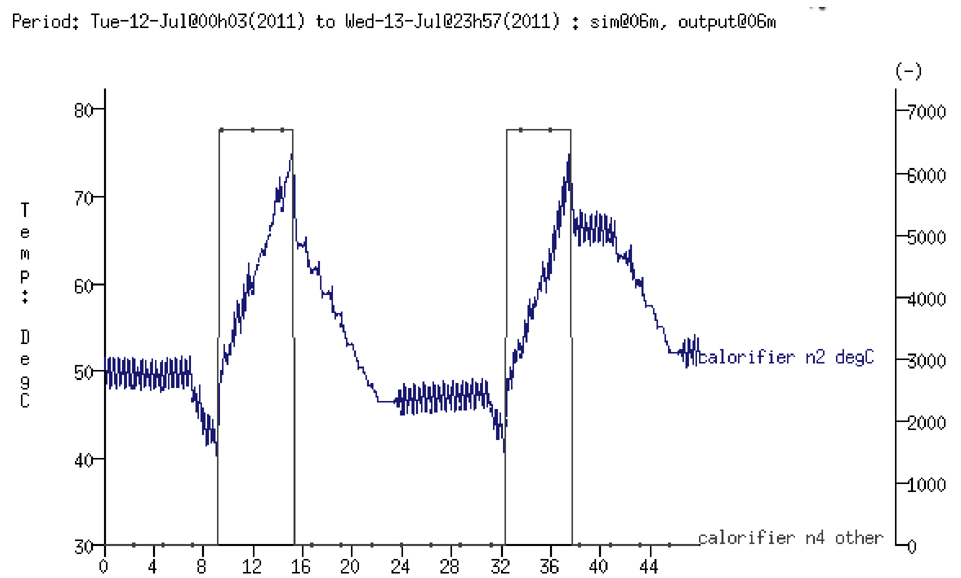
Graph 9: Fuel cell heat generation. Warm period. Small office

The graph 9 shows that, on the 12th of July, the fuel cell is switched on just for some minutes. This effect is analysed in more detail in the following graph.



Graph 10: Fuel cell heat generation and tank temperature. Summer day. 600 l tank. Small office

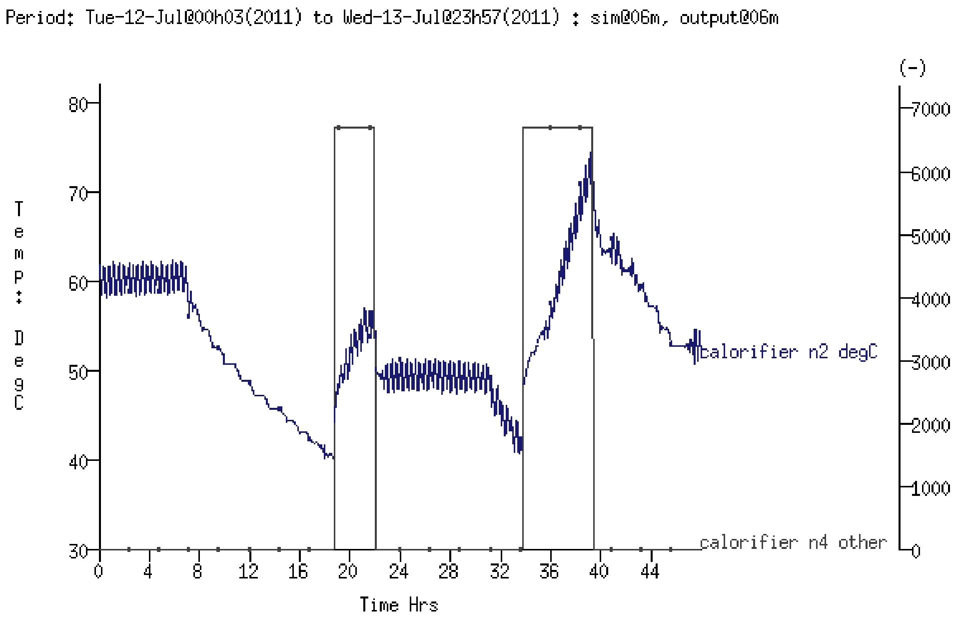
Graph 10 shows that when the temperature in the storage tank reaches the set point (75 ºC) the fuel cell is switched off and therefore it is not producing heat. When the fuel cell is switched off the office is heated using the hot water stored in the tank. In this case the temperature of the tank drops below the cold set point (40ºC) and therefore the fuel cell is switched on. However, it is switched on just for a few minutes as the heating system is operating until 10 pm. To avoid this effect, a larger storage tank has been installed passing from 600 litres to 750 litres. The same simulation has been repeated with the new tank size.



Graph 11: Fuel cell heat generation and tank temperature. Summer day. 750 l tank. Small office

Graph 11 shows that in this case the fuel cell is switched on once per day.

It has been also analysed the effect of installing a larger storage tank to determine its effect. In this case a 1000 litres tank has been installed.



Graph 12: Fuel cell heat generation and tank temperature. Summer day. 1000 l tank. Small office

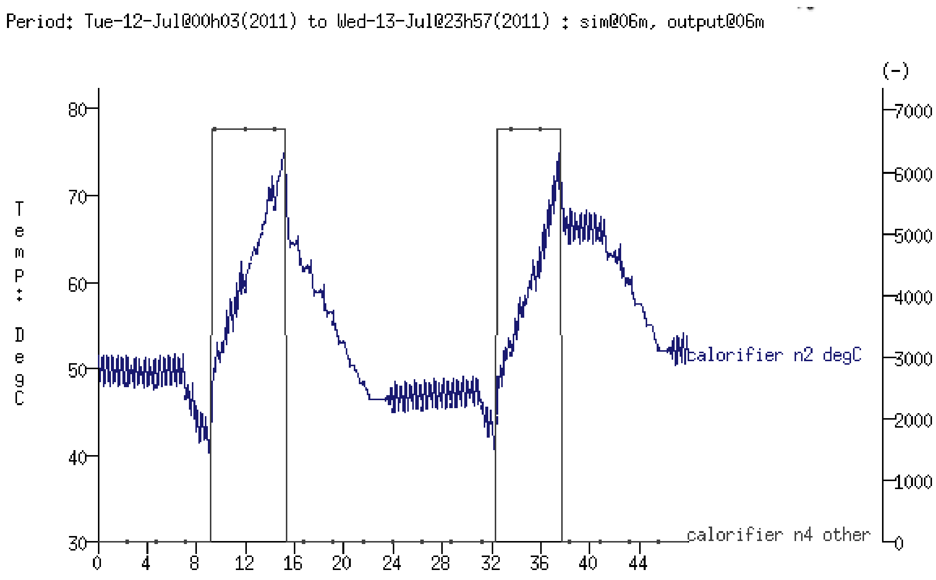
Graph 12 shows that from 7 am to 6 pm the fuel cell is switched off and the heat used to supply the heating demand of the office is provided by the storage tank. This is an undesired effect as the fuel cell is running during evening hours and not during the morning. If the running hours of the CHP system are displaced on this way, the CHP is producing electricity at hours when the electrical demand is usually lower. A part from that, the temperature of the tank at night is higher and therefore the heat losses are higher as well.

Comparing the three tanks sizes analysed (600, 750 and 1000 litres) it can be concluded that a 600 litres tank is too small as the fuel cell may be switched on and off twice per day, 1000 litres is too large as the hours when the fuel cell is switched on are changed and the heating losses are increased. For this reasons, 750 litres is considered as the best size for the model proposed and it is used for the subsequent simulations.

4.2.1.2 Simulation's results (250m^2 office)

<u>Summer</u>

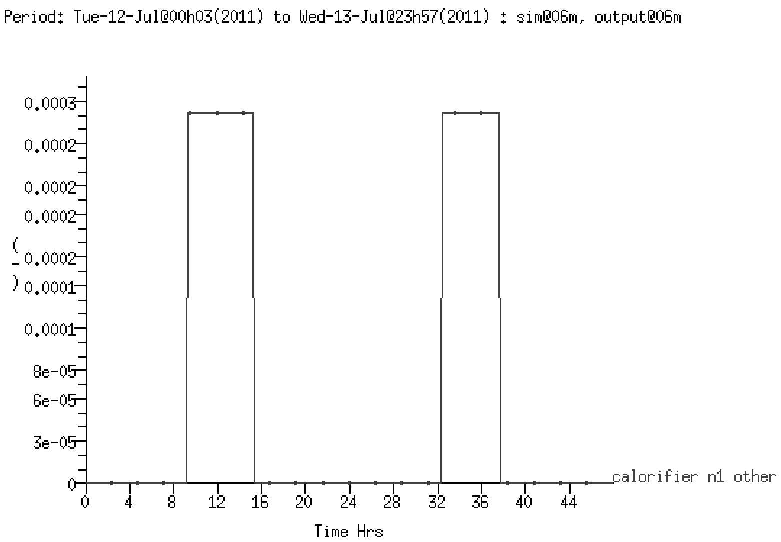
Graph 13 shows the temperature of the tank and heat generated by the fuel cell.



Graph 13: Fuel cell heat generation and tank temperature. Summer day. Small office

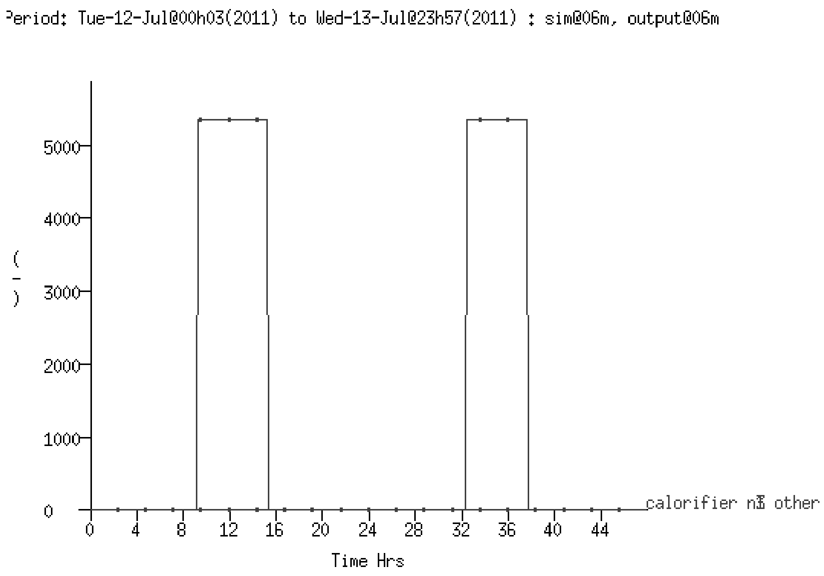
Analysing the graph 13 it is possible to determine the operating hours of the fuel cell during the period analysed. In this case, the fuel cell is switched on from 9 am to 3 pm during the first day and from 8 am to 2 pm during the second day.

In ESP-r, it is possible to analyse as well the fuel demand of the fuel cell during the operating hours. The graph 14 shows that the fuel consumption is completely constant at 0.0003 kg/s when the fuel cell is operating. As in all the simulations carried out the fuel cell used is always the operating at rated power, it is considered that the fuel demand is always same when the fuel cell is operating.



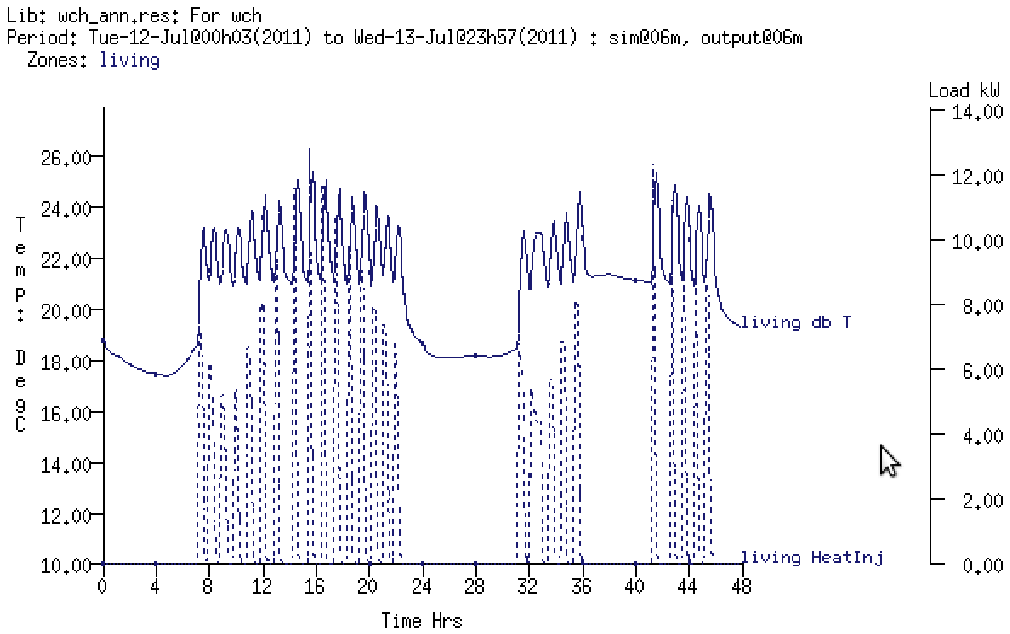
Graph 14: fuel consumption of the fuel cell

The graph 15 shows the electrical generation of the fuel cell. Similarly as for the fuel demand, the electricity generated by the fuel cell is constant at 5,000 kW when it is operating. This value is considered correct for all the simulations carried out in this dissertation as the fuel cell used is always the same.



Graph 15: electricity generation of the fuel cell

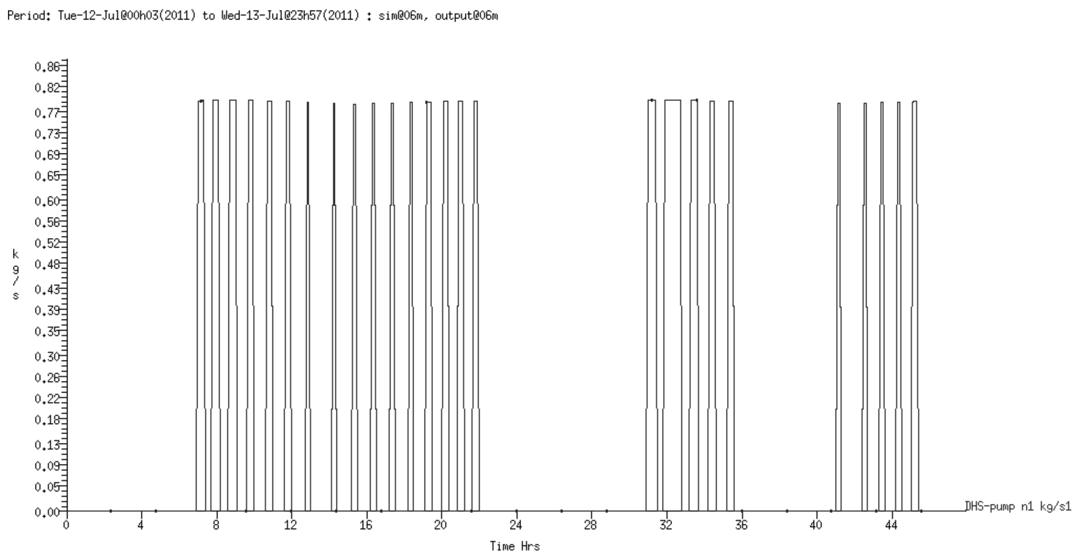
To analyse how successful is the heating system in maintaining the temperature inside the office between the set points (21 ºC – 23 ºC) it has been generated the following graph:



Graph 16: Office temperature and energy supplied. Summer day. Small office

Graph 16 shows that the temperature is always above 21 ºC. However, for some minutes it is above 23 ºC. This is caused by the inertia that the radiator has when it is switched off which makes the temperature rise up. During these moments of the day there are also some solar gains which warm up the office. The heat output of the radiator (10 kW) is also a problem as it is too high for the heating demand during this period of the year. However, during the winter this size of radiator is needed to supply all the heating demand of the office. The total heat supplied from the fuel cell CHP system to the office for the period analysed (two summer days) is: 73.7 kWh.

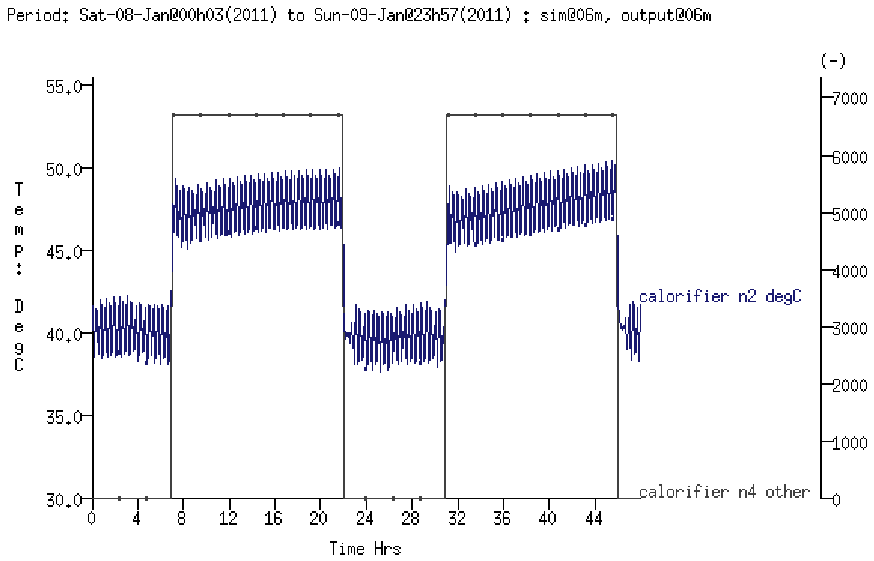
Graph 17 shows that the pump supplying the heat to the radiator is switched on and off repeatedly during the day. This is a normal performance of the system when it is trying to maintain the temperature between a certain values and the capacity of the system is higher that the demand.



Graph 17: DHS performance. Summer day. Small office

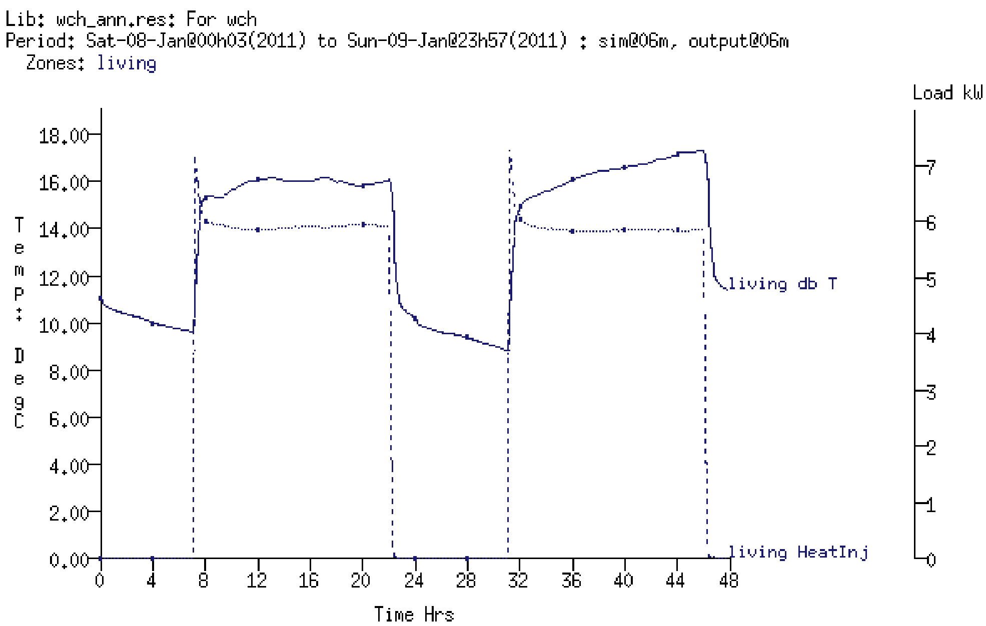
Winter

For all the following simulations carried out, it has been analysed the heat output of the fuel cell, the temperature of the tank, the operating hours of the fuel cell, the temperature inside the office and the heat supplied to the office.



Graph 18: Fuel cell heat generation and tank temperature. Winter day. Small office

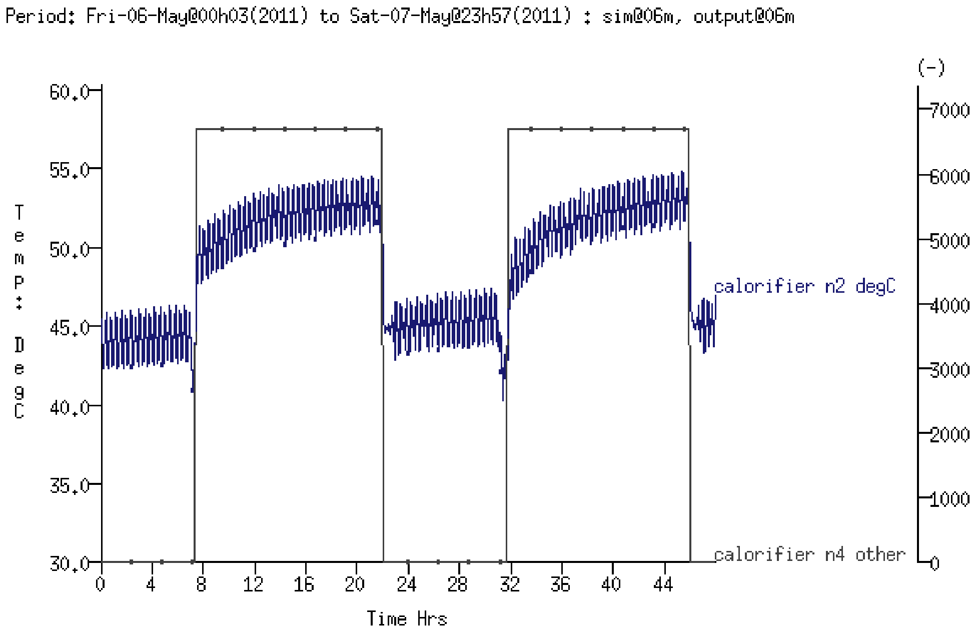
Graph 18 shows that the temperature in the tank during the winter days analysed is not reaching the set point (75 ºC) at any moment. Therefore, the fuel cell is operating during all day (7 am – 10 pm).



Graph 19: Office temperature and energy supplied. Winter day. Small office

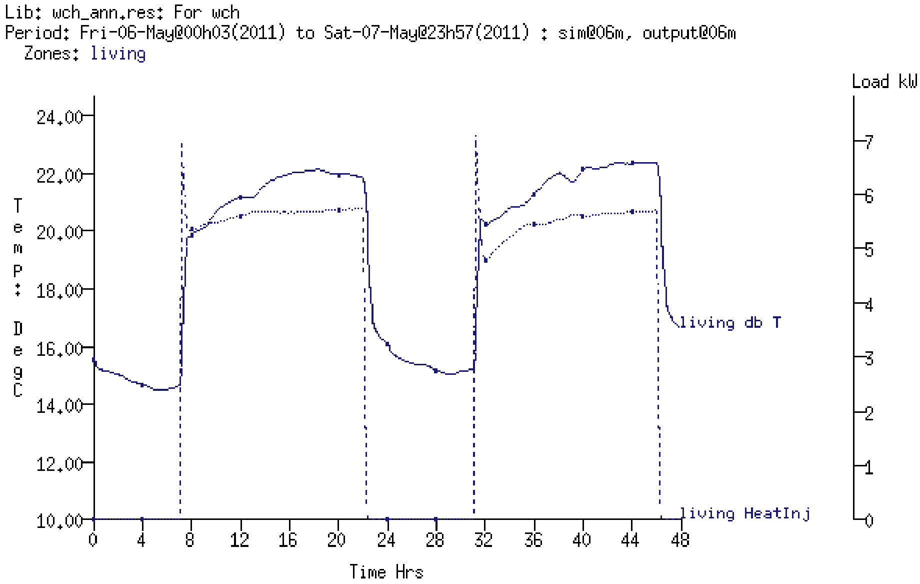
Graph 19 shows that the temperature inside the office is always below the set point (21 ºC). This means that the capacity of the CHP system is not enough to match all the heating demand for this period and part of it has to be supplied by the back-up system. The total heat supplied from the fuel cell CHP system to the office for the period analysed (two winter days) is: 178.4 kWh.

Spring/Autumn



Graph 20: Fuel cell heat generation and tank temperature. Spring/autumn day. Small office

Graph 20 shows that the temperature in the tank during the winter days analysed is not reaching the set point (75 ºC) at any moment. Therefore, the fuel cell is operating during all day (7 am – 10 pm).



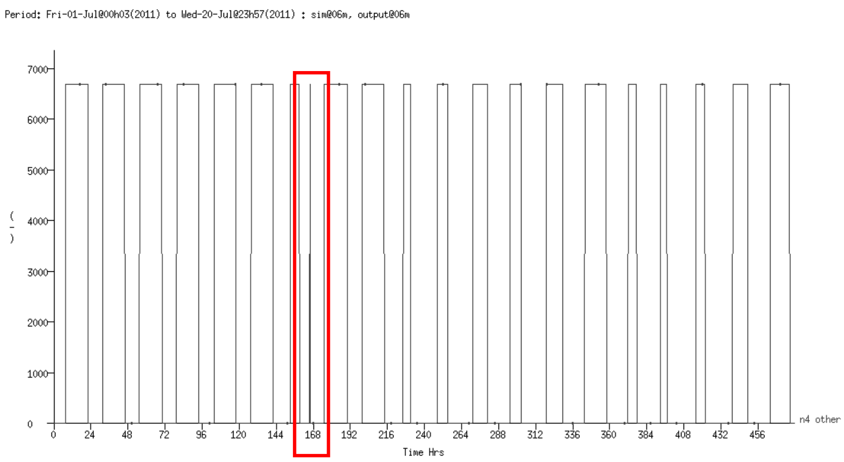
Graph 21: Office temperature and energy supplied. Spring/Autumn day. Small office

Graph 21 shows that the temperature is below the set point (21 ºC) only during the first hours of the morning. This means that the back-up system is shortly used for this period. The total heat supplied from the fuel cell CHP system to the office for the period analysed (two spring days) is: 168.4 kWh.

4.2.2 500m^2 office's fuel cell CHP simulations

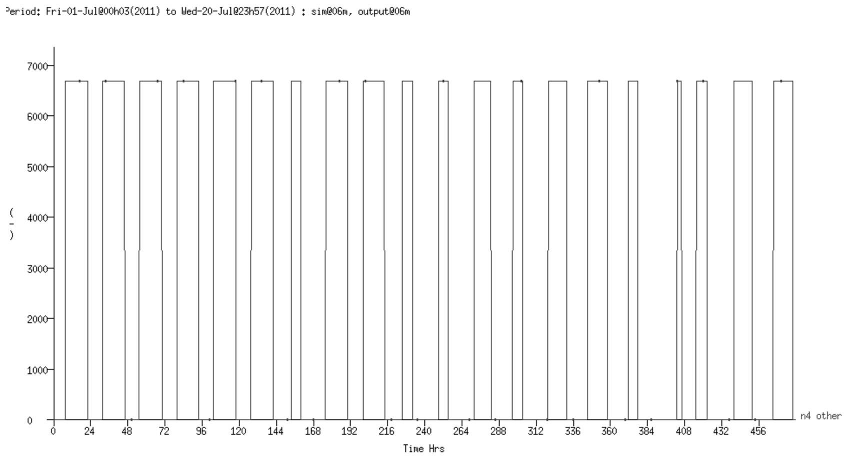
4.2.2.1 Influence of tank sizing in system performance (500m^2 office)

Similarly as for the 250m2 office, it has been analysed the operating times for the fuel cell during the warmest period of the year (1Jul – 10 Jul).



Graph 22: Fuel cell heat generation. Warm period. Large office. 750 l tank

Graph 22 shows that the fuel cell is switching on and off twice during one day when the size of the tank is 750 litres. Graph 23 shows that this effect is not occurring when the size of the tank is increased to 900 litres. Therefore, this has been considered the best size of the tank for the 500m^2 office.

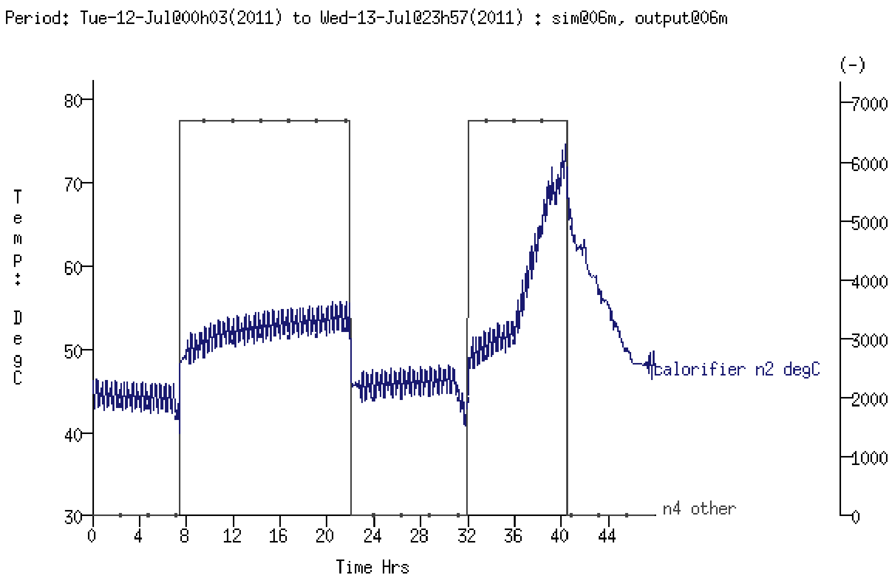


Graph 23: Fuel cell heat generation. Warm period. Large office. 900 l tank

4.2.2.2 Simulation's results (500m^2 office)

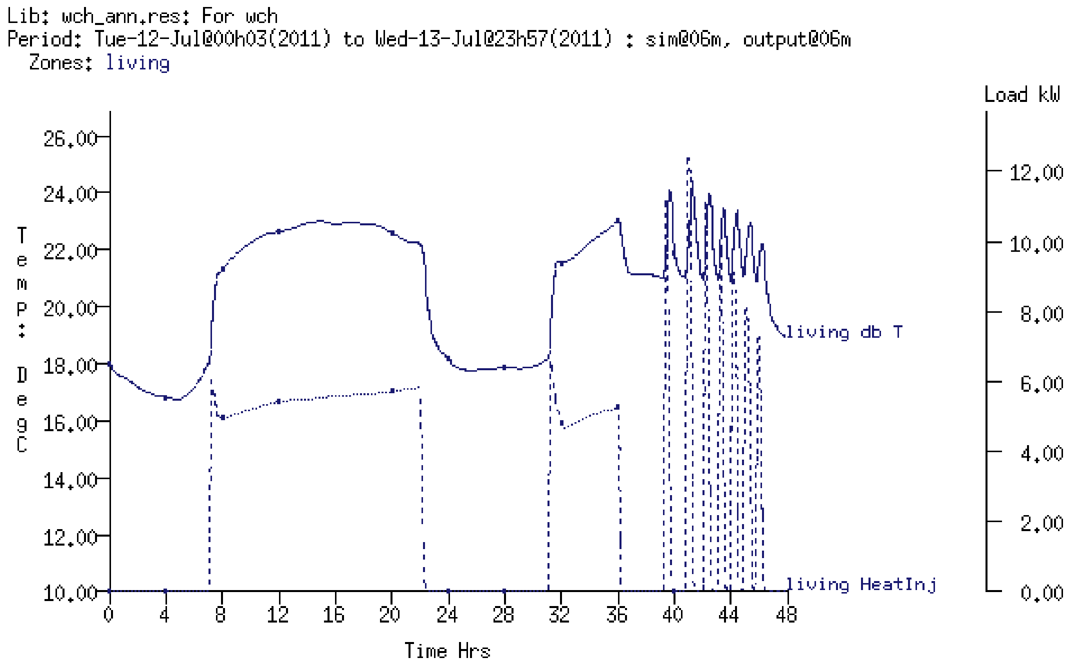
Summer

Graph 24 shows that the fuel cell is switched on during all the first day and it is switched on from 7 am. to 5 pm. during the second day because the temperature in the tank reaches the set point temperature.



Graph 24: Fuel cell heat generation and tank temperature. Summer day. Large office

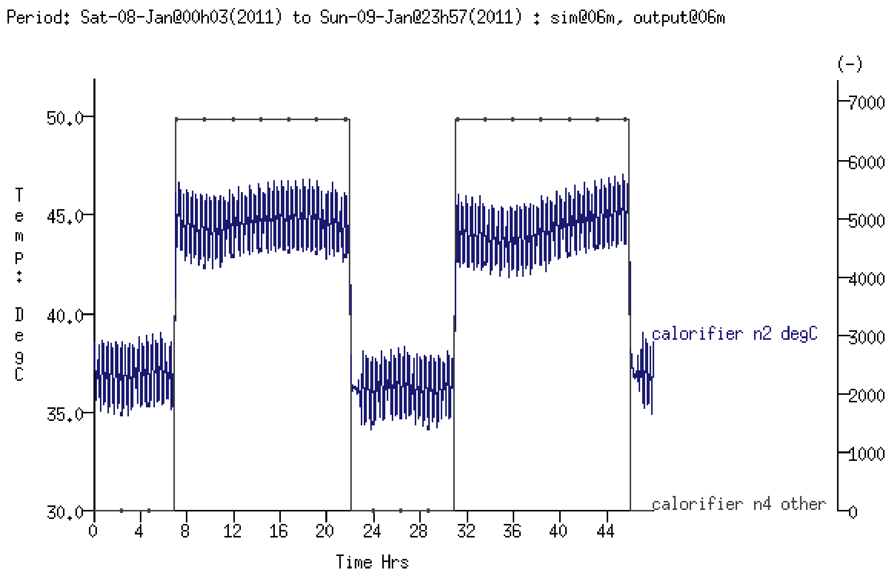
Graph 25 shows how successful is the CHP system in maintaining the temperature between the set points (21ºC – 23ºC). The total heat supplied from the fuel cell CHP system to the office for the period analysed (two summer days) is: 135.1 kWh.



Graph 25: Office temperature and energy supplied. Summer day. Large office

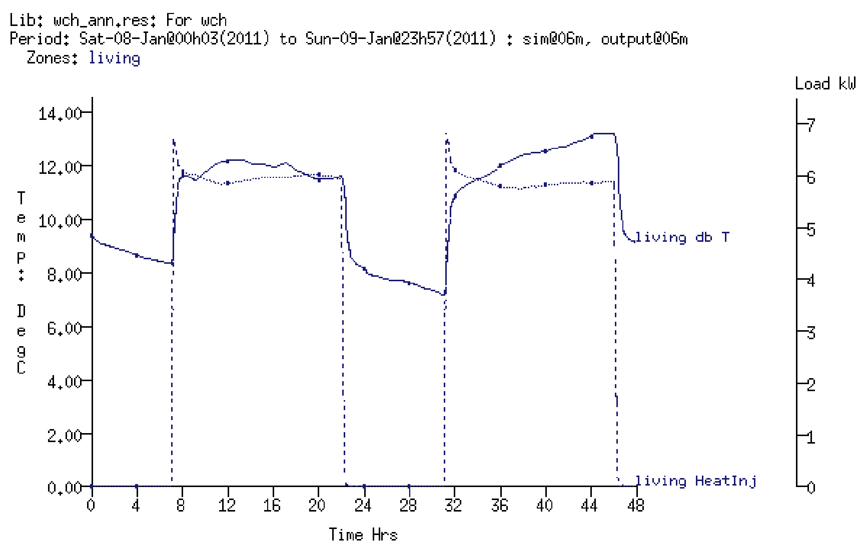
Winter

Graph 26 shows that the temperature in the tank during the winter days analysed is not reaching the set point (75ºC) at any moment. Therefore, the fuel cell is operating during all day (7 am – 10 pm).



Graph 26: Fuel cell heat generation and tank temperature. Winter day. Large office

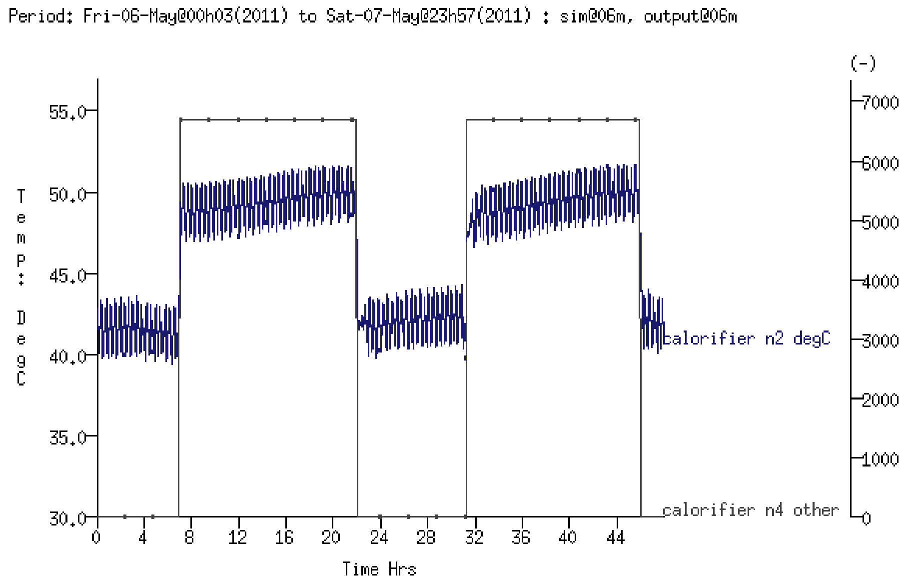
Graph 27 shows that the temperature inside the office is always below the set point (21ºC). This means that the capacity of the CHP system is not big enough to match all the heating demand for this period and part of it is supplied by the back-up system. The total heat supplied from the fuel cell CHP system to the office for the period analysed (two winter days) is: 179.1 kWh.



Graph 27: Office temperature and energy supplied. Winter day. Large office

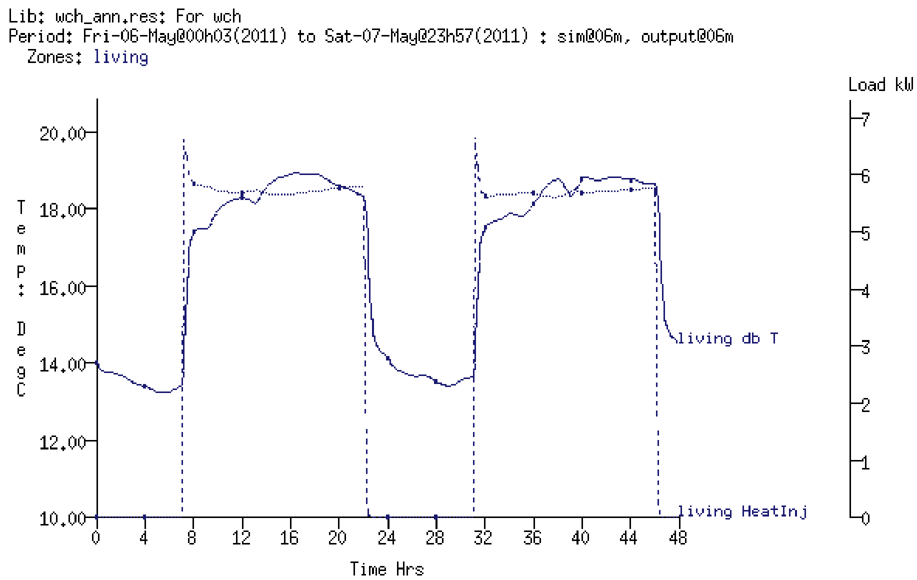
Spring/Autumn

Graph 28 shows that the temperature in the tank during the winter days analysed is not reaching the set point (75ºC) at any moment. Therefore, the fuel cell is operating during all day (7 am – 10 pm).



Graph 28: Fuel cell heat generation and tank temperature. Spring/autumn day. Large office

Graph 29 shows that the temperature inside the office is always below the set point (21ºC). This means that the capacity of the CHP system is not enough to match all the heating demand for this period and part of it has to be supplied by the back-up system. The total heat supplied from the fuel cell CHP system to the office for the period analysed (two winter days) is: 178.4 kWh.



Graph 29: Office temperature and energy supplied. Spring/Autumn day. Large office

4.3 Analysis of Results

Results obtained in the simulations are analysed in this section.

Firstly, there is described how the results are obtained, specifying the assumptions made and the equations used. Before analysing the final values, there has also been made a validation analysis, comparing results obtained from ESP-r simulations with results obtained from a performance analysis of a similar fuel cell carried out by an independent agency.

Finally, and bearing in mind that the main objective of the simulations is to carry out an economical and environmental analysis of the performance of the fuel cell, there are detailed the final results: CO_2 emissions and operating cost of the system proposed for the two scenarios analysed.

4.3.1 Simulation's results calculation

The results have been obtained from the simulations using the following procedure:

- Operating hour of the fuel cell (one day): from the graphs of the heat generated by the fuel cell is possible to determine the operating hours of the fuel cell per day. For winter and spring/autumn representative days the fuel cell is operating during all day resulting in 14 hours per day. During the summer period, the fuel cell is operating an average of 5 hours per day for the 250m2 office and 11 hours per day for the 500 m^2 office.
- Number of days: there has been made the assumption that there are 60 summer days, 90 winter days and 180 spring/autumn days during a year.
- Operating hours per season or per year have been calculated multiplying the number of operating hours per day by the number of days.
- Heat generated: is considered constant at 6,800 kW when the fuel cell is operating. This value is calculated from the graph 9.
- Electricity generated: is considered constant at 5,000 kW when the fuel cell is operating. This value is calculated from the graph 15.
- Fuel consumption: is considered constant at 1.08 kg/s when the fuel cell is operating. This value is calculated from the graph 14.

The results obtained are detailed in the following table:

Table 5: Fuel cell generation and consumption

	250m2			500m^2		
	Summer	Winter	Spring/ Autumn	Summer	Winter	Spring /Autumn
Operating hours (one day)	5	14	14	11	14	14
number of days	4	90	180	90	90	180
Operating hours (season)	20	1,260	2,520	990	1,260	2,520
Operating hours (year)	3,800			4,770		
Heat generated (kWh/year)	25,840			32,436		
Electricity generated (kWh/year)	19,000			23,850		
Fuel consumption (kg)	4,104			5,152		

Table 5 shows that the fuel cell CHP system is used during more hours in the 250m^2 office than in the 500m2. Therefore, the heat generated, electricity generated and fuel demand is higher.

To calculate the percentage of heat supplied by the CHP system and by the back-up system is has been determined:

- Total heating demand for 2 representative days: heating demand of the offices when there is installed a perfect heating system which is able to supply all the demand.
- Heating supplied by CHP: Calculated from the heating delivered to the offices by the system when the CHP is installed.
- Back-up demand: when the total heat supplied by the CHP system is lower than the total heating demand it is assumed that the back-up system is used to match this demand. In some cases the heating supplied by the CHP system is higher than the total heating demand. It has been assumed that in these cases the back-up demand is equal to 0. This effect is commented later in the results validation.
- Seasonal and annual demand: the total demands have been calculated assuming that there are 60 summer days, 90 winter days and 180 spring/autumn days during a year.

- The percentage of heating supplied by the CHP and by the back-up has been calculated taking into account the annual heat supplied by each system.

The results obtained are detailed in the following table:

Table 6: Fuel cell and back-up heating supplied

		250m2			500m^2		
		Summer	Winter	Spring/ Autumn	Summer	Winter	Spring /Autumn
2 days	Heating demand (kWh)	57	220	123	89	357	201
	Heating supplied by CHP (kWh)	74	174	168	135	179	178
	Back-up demand (kWh)	0	45	0	0	177	23
	Number of days per year	90	90	180	90	90	180
Season	Heating demand (kWh)	2,556	9,882	11,106	3,996	16,043	18,126
	Heating supplied by CHP (kWh)	3,318	7,848	15,156	6,080	8,060	16,056
	Back-up demand (kWh)	0	2,034	0	0	7,983	2,070
Year	Heating demand (kWh)	23,544			38,165		
	Heating supplied by CHP (kWh)	26,322			30,195		
	Back-up demand (kWh)	2,034			10,053		
	% heating supplied by CHP	92.83%			75.02%		
	% heating supplied by Back-up	7.17%			24.98%		

Results show that the percentage of heating supplied by the CHP is higher in the smaller office. This is a coherent result as the demand of the smaller office is lower; therefore, the CHP system is able to match a higher percentage of the demand. For the 250 m^2, it is possible to observe that the heating supplied by the CHP in one year is higher than the total heating demand. This effect is commented later in the results validation.

4.3.2 Results validation

Although ESP-r is a consistent tool which has been widely validated, some calculations have been made to evaluate how precise are the results obtained. Some of the results have been compared to an external analysis of the performance of a similar fuel cell. It has been also analysed why, in some cases, the heating supplied the CHP is higher than the total heating demand.

4.3.2.1 CO_2 emissions validation

An analysis of the performance of a 5 kW PEMFC developed by Plug Power has been carried out by the The U.S. Environmental Protection Agency (EPA) through the environmental Technology Verification (ETV). (EPA, 2003)

The CO_2 emissions determined by this analysis are:

$$CO_2 emissions = 1.66\, lb/kWhe = 0.752\, kg/kWhe$$

From the results obtained in ESP-r is possible to determine that the fuel cell is consuming 0.0003kg/s of methane when it is producing 5kWe. Therefore, it can be calculated the fuel cell consumption:

$$fuel\ consumption = 0.0003\, kg/s = 1.08\, kg/h = 0.216\, kg/kWhe$$

The emissions of CO_2 when the methane is reformed to generate hydrogen are 2.75 kg CO_2 for 1 kg of methane. (The energy collective, 2011)

Therefore, the CO2 emissions are calculated:

$$CO_2 emissions = 0.216\, kg/kWhe \times 2.75 = 0.594\ kg/kWhe$$

Comparing the CO_2 emissions from the EPA report and the ones obtained in ESP-r, it can be seen that the results are similar. EPA report's calculations where made with different range of power output and the value represents an average, while ESP-r CO_2 emissions are calculated at rated power. For this reason, CO_2 emissions obtained from ESP-r simulations are considered correct.

4.3.2.2 CHP heating supplied validation

During the results analysis it has been detected that in some simulations the energy delivered by the CHP system is higher than the energy demand for the period analysed. This effect can be seen, for example, in the summer simulations for the 250m^2 office: the heating demand is 57 kWh and the heating supplied by the CHP system is 74 kWh. Analysing the graph 16 it is possible to see that the temperature in the zone is oscillating between the set point values. Conversely, in the graph 2 it is possible to see that the temperature is almost constant during all the period when it is used a perfect heating system to supply the heating demand. In summary, when the zone is heated by the CHP, the average temperature is higher and therefore the energy demand is higher.

Although this error in the results has been detected, it has been assumed that its effect on the total results is not significant. The error is only occurring when the CHP system is able to meet all the heating demand; it is switched on and off repeatedly during a day and its inertia makes the temperature inside the office rise up above the set point. When the CHP system is not able to meet the demand, it is operating constantly, and the temperature in the office is always below the set point. In this case, the value of the total heat supplied by the CHP is correct, and it is assumed that the energy missing to meet the total demand is supplied by the back-up system.

4.3.3 Environmental and economic analysis

From the CIBSE guide it has been determined that an analysis of the environmental and economic evaluation of the CHP system has to be made in order to compare it with other solutions.

4.3.3.1 Environmental analysis

To evaluate the annual environmental impact is has been calculated the CO_2 emissions of the system proposed for the two sizes of office analysed. The CO_2 emissions have been calculated according to the natural gas consumption taking into account the percentage of heating demand supplied by the CHP system and supplied by the back-up. It has been assumed that the back-up system used is a conventional natural gas boiler.

The results obtained are detailed in the following table:

Table 7: CO_2 emissions calculation

Symbol	Units	Description	Value	250m2	500m^2
Q total	kWh	Annual Heating Demand		28,356	40,248
M	%	Percentage of heating demand meet by CHP		93	75
Q h	kWh	Annual heating supplied by CHP	Q total x M	26,323	30,194
h	hours	Full hours run		3,800	4,770
Re	kW	Rated electricity output CHP		5	5
Qe	kWh	Net electricity generated	Re x h	19,000	23,850
Cfe	kGCO$_2$/kWh	CO_2 factor for grid-displaced electricity	0.445		

Ce	$kgCO_2$	CO_2 saved owing to electricity from CHP	Qe x Cfe	8,455	10,613
Rf	$kgCO_2/h$	Rated fuel consumption	1.08		
Qfchp	kg	Annual fuel consumption of CHP	Rf x h	4,104	5,152
CFfchp	$kgCO_2$/Kgfuel	CO_2 factor for fuel supply	2.75		
Cchp	kg	CO_2 emissions due to fuel consumed by CHP	Qfchp x CFfchp	11,286	14,167
Econ	%	Seasonal efficiency of conventional boiler	86%		
N	kWh	Percentage of heating demand meet boiler	1 -M	7	25
Qcon	kWh	Annual fuel consumption of boiler	Qtotal x N / Econ	2,308	11,700
Cffcon	$kgCO_2/kWh$	CO_2 factor for fuel supply to conventional boiler	Gas=0.194		
Ccon	kg	CO_2 emissions due to fuel consumed by boiler	Qcon x Cffcon	448	2,270

A part from the emissions of the CHP and the back-up system, it has been also calculated the CO_2 emissions saved for the electricity which is generated by the CHP system and therefore it is not supplied by the grid. CO_2 emissions of the electricity supplied from the general have been assumed as 0.445 $kgCO_2/kW$. (Carbon Trust, 2013)

Total CO_2 emissions for each office are:

$$CO_2 emissions = C_{chp} + C_{con} - C_e$$

Total emissions are equal to the emissions generated by the CHP system and the back-up system minus the emissions saved due to the reduction of the electricity used from the grid.

A summary of the results is detailed in the table below:

Table 8: CO_2 emission

	250m^2	**550m^2**
Cchp	11,286	16,437
Ccon	448	2,270
Ce	8,455	10,613
Total CO_2 emissions	3,279	5,823
Emissions with boiler	6,397	9,079
Reduction of emissions	49%	36%

Table 8 shows total emissions for each office. These emissions can be compared to emissions generated by other solutions. For example, if they are compared to the emissions of the same scenario with a conventional natural gas boiler to supply the heating demand and the electrical grid to supply the electricity, it is possible to see that CO_2 emissions are reduced by 49% for the 250m^2 office and 36% for the 500m^2 office. In conclusion, if the heating demand is higher, the impact of the CHP system in the CO_2 emissions is lower as the percentage of heat demand supplied by the CHP system is lower.

4.3.3.2 Economic analysis

To calculate the net present value or the pay-back period of the system proposed, the initial cost and the maintenance cost of a fuel cell has to be defined. Due to its constant development and its early commercial stage, the cost of the fuel cell is variable and, currently, it is too high to be competitive with alternative solutions. For this reason, in this dissertation, it has been only calculated the operating cost of the fuel cell which depends on the prices of fuel and electricity. The following values have been assumed: natural gas=4.21 pence/kWh, electricity=13.52 pence/kWh. (Natural Gas-delivered by Envestra, 2013) (Energy Saving Trust , 2014)

The total operating cost of the system has been calculated with the following equation:

$$Total\ cost = CHP\ gas\ cost + Backup\ gas\ cost - Electricity\ cost$$

In this case, it has been assumed that all the electricity is consumed on site. Therefore, the cost of buying this electricity from the grid is discounted from the total cost. If part of the electricity is sold to the general grid is has to be taken into account the price at which it is sold.

Total results are calculated for both offices analysed:

Table 9: Costs results

	250m^2	**550m^2**
gas CHP (£)	2,544	3,194
Back-up gas (£)	113	573
Total gas cost (£)	2,657	3,767
Cost of (£)electricity	2,569	3,225
Total cost (£)	89	542
Cost with boiler (£)	1,388	1,970

The results from the table 9 show that the cost of the gas consumption is increased when a CHP system is used. However, if all the electricity is used on site and its cost is discounted from the cost of the gas, CHP operating costs are cheaper.

4.4 Conclusions of ESP-r simulations

From the simulations carried out in ESP-r it can be concluded that significant reductions of CO_2 emissions and operating costs can be achieved when a 5 kW PEM fuel cell CHP system is installed to supply the heating demand of an office between 250 m^2 and 500 m^2.

The first simulations carried out have been used to develop a methodology to size the hot water storage tank. This methodology consists in analyse the performance of the fuel cell during the warmest period of the year. During this period, the fuel cell is able to supply all the heating demand of the office; therefore it is not operating during all day. The size of the tank is selected in order to ensure that the fuel cell is switched on only once per day during some hours. The heat stored in the tank supplies the heating demand when the fuel cell is switched off making sure that the fuel cell is not switched on again during the same day.

Once the size of the tank is selected, simulations are carried out to obtain the outputs: operating hours of the fuel cell, fuel consumption, electricity generated, temperature inside the office and heat supplied to the office. These simulations have been repeated for the summer, winter and spring/autumn representative days and for the 250 m^2 and 500 m^2 office. Results show that the number of operating hours of the 250 m^2 office is lower than the operating hours of the 500 m^2 office. Therefore, the heat and electricity generated and fuel consumption is lower as well. For the 250 m^2 office the 93% of the heating demand is supplied by the CHP system and 7% by the back-up system. For the 500 m^2 office, 75% of the heating demand is supplied by the CHP system and 25% is supplied by the back-up. These results are reasonable as the capacity of the CHP system installed for both offices is the same and the heating demand for the 250 m^2 office is lower than the demand for the 500 m^2 office.

To validate the results obtained, they have been compared with the results obtained by an independent agency report. The CO_2 emissions calculated in this report are slightly higher than the ones calculated from ESP-r simulations. However, in ESP-r the fuel cell is always operating at rated power, performing with a higher efficiency. For this reason, the results are considered as correct.

Finally, annual results of CO_2 emissions and operating costs are calculated. When the proposed fuel cell CHP system is compared with a conventional natural gas boiler, the reduction of emissions is about 49% in the 250 m^2 office and 36% in the 500 m^2 office. From these results, it is possible to see that the impact on the emissions is higher when the percentage of heat supplied by the CHP system is higher. The operating cost analysis shows that, as the consumption of gas is increased, its cost is increased as well. However, if the electricity produced by the CHP system is used on-site, its cost can be deduced from the gas cost. In this case the cost of the operation of the system is reduced from £1,388 to £89 in the 250 m2 office and from £1,970 to £542 in the 500 m2. An economic analysis including the installation and maintenance cost of the fuel cell has to be made in order to calculate the total savings that can be achieved installing a fuel cell CHP system.

5 Analysis of fuel cell and renewable energy integrated systems

Even though it is not the main objective of this dissertation, it has been analysed the potential of an existing commercial software to simulate the integration of fuel cell CHP systems with renewable energies. The objective of this analysis is to determine the systems that can be simulated with this software and the results that can be obtained. For the simulations carried out, it has been designed a system with a logical size of components to obtain interesting results. There have been also described the limitations of the tool and the aspects that should be improved.

5.1 Homer energy simulations

The software selected to carry out these simulations is Homer Energy. It has been selected after analysing similar tools like Retscreen and Merit for its capability to simulate more complex systems. Homer Energy was originally developed at the National Renewable Energy Laboratory for the village power program. It can be used to design hybrid renewable microgrids either remote or attached to the general grid. The results obtained can be used to design systems and to evaluate their economic and technical feasibility for a large number of technologies.

5.1.1 Description of the model

The model simulated in Homer Energy represents a system that integrates renewable energy generation systems (Wind turbines and PV panels) and storage and utilization of hydrogen with a fuel cell. The components of the system are:

- 15 kW PV panel
- 3 kW wind turbine
- 20 kW electrolyser
- 1 kg hydrogen tank
- 5 kW fuel cell
- DC/AC inverter
- Back-up gas boiler

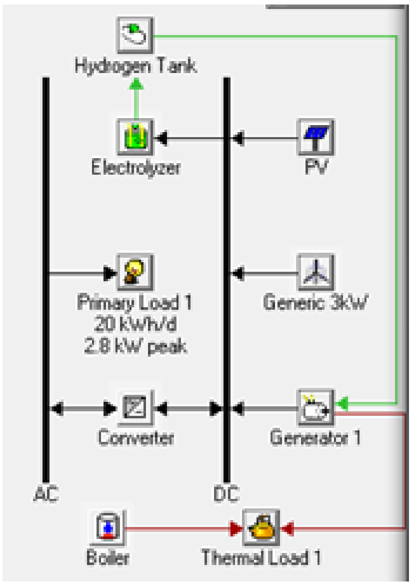


Figure 16: renewable-hydrogen system

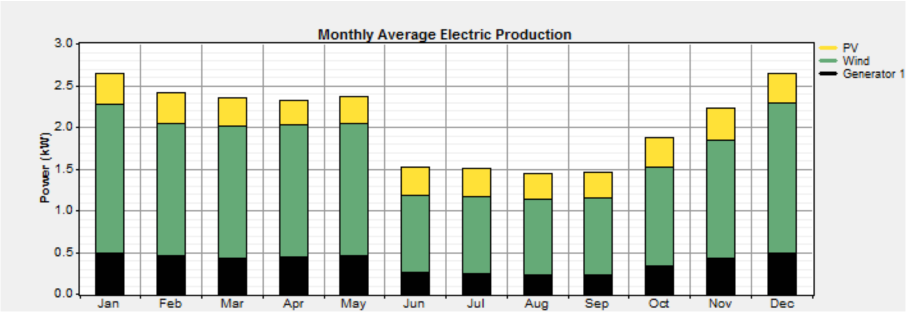
The system is supplying an electrical load with an average demand of a 20 kWh/day and a thermal load with an average demand of 50kWh/d. The electrolyser generates hydrogen from the renewable energy excess. This hydrogen is stored in the tank and used when there is no wind or sun available to supply the demand. The system is not connected to the grid, therefore all the electricity is supplied from renewable energy. There is a gas boiler to supply the heating demand of the system when the fuel cell is not operating.

Typical values for wind speed and sun radiations in the UK have been used for the model. Simulations have been carried out for a period of a year and some of the results have been analysed for the period of one week to analyse in more detail the performance of the system.

5.1.2 Results of the Homer Energy simulations

The results obtained from the Homer Energy simulations are detailed in this section.

In the following graph it can be seen the monthly generation of electricity by the wind turbines, the PV panels and the fuel cell:

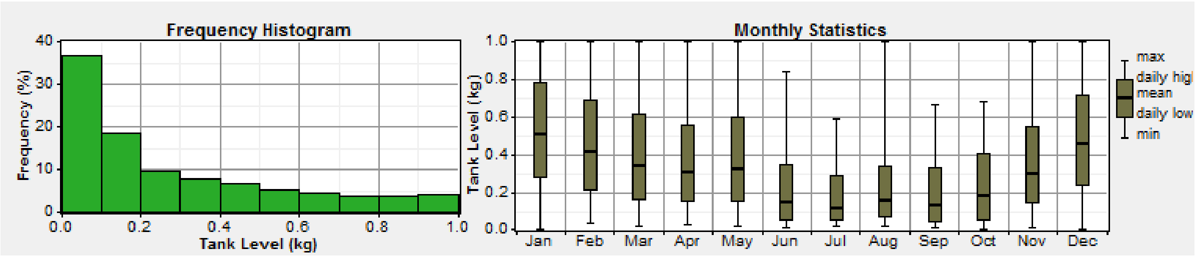


Graph 30: Monthly generation of electricty

During a year, the wind turbine is generating 11,000 kWh, the PV panel 3,000kWh and the fuel cell 3,300 kWh. Part of the electricity generated by the renewable source is used by the electrolyser to generate hydrogen (10,750 kWh), and part is used to supply directly the electrical load (3,250 kWh). The total load consumption is 6,200 kWh, therefore it is possible to see that that approximately 50% of the electricity is supplied by the wind and solar energy and the other 50 % is supplied by the fuel cell. The energy used by the electrolyser is 10,750 kWh and the generated by the fuel cell is 3,300 kWh, therefore the overall electrical efficiency of the electrolyser and the fuel cell is about 30%. There is some part of the electrical demand that cannot be supplied by the system and results in an unmet electric load of 1,100 kWh.

Thermal results of the simulations show that 30% of the thermal load is supplied by the fuel cell and 70% is supplied by the gas boiler.

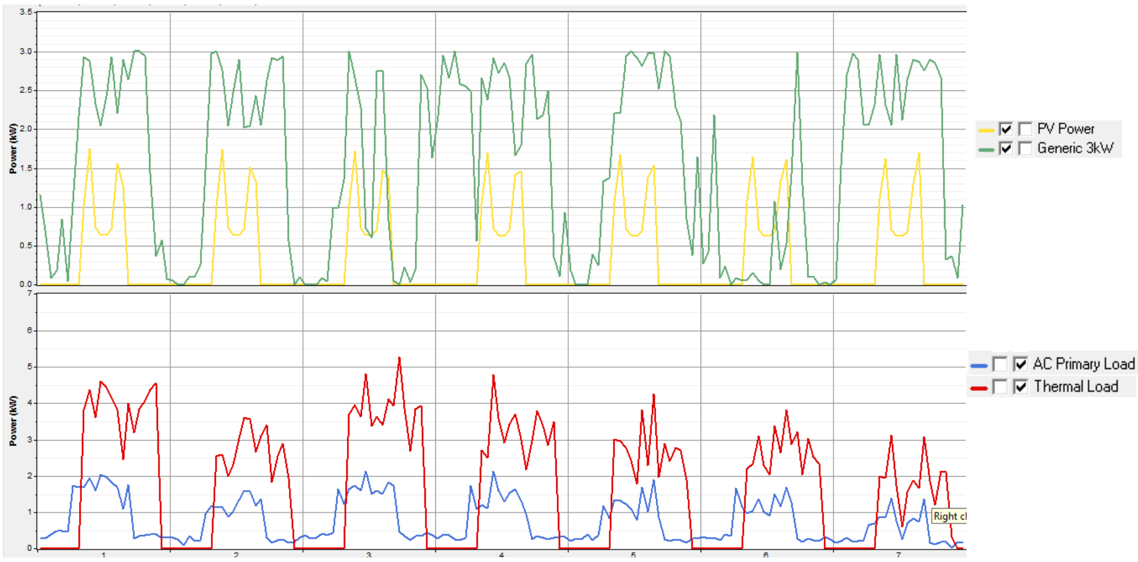
The performance of the hydrogen tank is also analysed in the simulations:



Graph 31: State of charge of the hydrogen tank

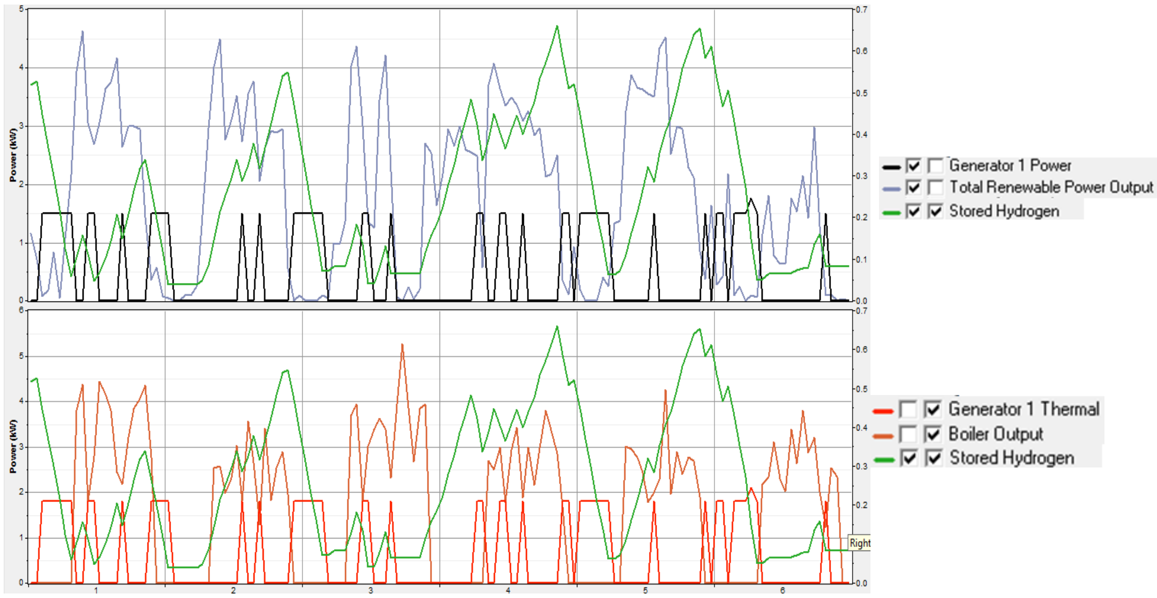
In the graph 31 is is possible to see that the tank is empty 38% of the time. This means that at these moments there is no hydrogen stored and if at the same time there is no renewable energy generation, the demad of the system cannot be supplied. It is possible to see as well that on some months there are moment when the tank is completely full. If there is excess of renewable energy at this moments, it can not be stored.

Some simulations have been carried out for a period of a week to see in more detail the performance of the system.



Graph 32: Renewable generation and heating and electric demand

Graph 32 shows the energy generated by the wind and the solar generation and the electrical and thermal loads of the system. It is possible to see that the solar generation is similar every day and the wind generation has more variation. Electric and thermal demands are similar every day but with some variations.



Graph 33: Renewable, fuel cell and back-up generation. State of charge of the hydrogen tank

The Superior part of the graph 33 shows the total energy generated by renewables, the energy generated by the fuel cell and the level of the storage tank. It is possible to see that the tank is charged when there is a lot of renewable energy generated and it is discharged when the renewable energy is low and the fuel cell is operating to supply the demand. The inferior part of the graph shows the thermal generation of the boiler and the fuel cell. In this model the fuel cell is controlled to follow the electrical demand therefore in some moments the generation of heat can be higher than the demand wasting part of the heat generated. When the fuel cell is operating it is possible to see that the energy generated by the boiler is reduced.

5.2 Conclusions of Homer Energy simulations

Results obtained in Homer Energy show that, using this software, it is possible to determine the total energy generated by renewables and the energy supplied by the fuel cell. Changing the size of the PV panes or the wind turbine, the scenario can be completely changed obtaining different matching percentages. The tool is useful to size the components and ensure that good results are obtained. Another interesting output is the overall efficiency of the system. From the results it is possible to see that the electrical efficiency of the electrolyser and fuel cell system is about 30%. This efficiency can be significantly improved if the heat generated by the fuel cell is used to supply a thermal demand. Results show that 30% of the thermal load is supplied by the fuel cell system. This means that the use of gas to supply the system is significantly reduced. The storage system can be also designed with the results obtained as the software provides a dynamic analysis of the level of charge of the tank.

Although Homer Energy can simulate a system integrating renewable energies and fuel cell CHP, it has some limitations. One of the big limitations is that it cannot be installed a hot water storage tank. One of the worse results obtained in the simulations is that only 30% of the thermal load is meet by the fuel cell. This is because when the generation of electricity from renewables is high enough to supply the electrical demand, the fuel cell is not operating. Therefore, all the heating has to be supplied by the back-up boiler. If a storage tank is installed in the system, the heat generated by the fuel cell can be stored to be used when the fuel cell is not operating. Another limitation of the tool is that the system is always controlled by the electrical demand. In some cases, it can be more efficient to operate the fuel cell according to the heating demand instead of the electrical demand. However, if a storage tank and an improved control system are added to the software the simulations will become more complex.

Summarizing, the results that can be obtained from Homer Energy are useful to design the system and to evaluate its performance. From the results it is possible to calculate environmental and economic impacts. However, the system has some limitations and some improvement should be made in order to simulate more complex systems.

6 Discussion and future work

This section describes the results obtained from each step undertaken in this dissertation in order to achieve the objectives originally defined. There are also described the limitations of the systems proposed and the future work detected.

Literature review of fuel cells revealed that, although the first fuel cell was developed in 1942, the technology remained in a research stage until the early 1990s. Since then, the efforts have been focused on increasing the life span and reducing the cost of fuel cells. Although interesting improvements have been achieved, the technology is still not competitive with conventional systems. Current applications of fuel cells include: transport, stationary and portable generation of energy. From these applications, the stationary power generation is the most used. Many companies are designing CHP systems with the intention to achieve competitive prices in the coming years. The application that is closer to the market is the micro-CHP (750 We) systems developed in Japan through the ene.farm scheme which has installed over 50,000 units and aims to be cost-competitive by 2015. The main benefit of the fuel cell CHP technology is that it has higher efficiency than conventional CHP systems, which leads to a reduction of the CO_2 emissions. Apart from this benefit, fuel cells have the potential to integrate with renewable energy systems in the future. Some research projects are designing systems to convert the excess renewable energy into hydrogen, store it into a hydrogen tank and use a fuel cell to generate energy from the hydrogen when no renewable energy is available. In the future, these systems have to be improved to be competitive with current technologies.

To analyse the performance of CHP systems there are some commercial tools that can be used and which have been analysed in this dissertation. The CHP Site Assessment tool provides a list of recommended conventional CHP systems for a proposed site. An interesting improvement for the future could be to incorporate fuel cell to its database of components and to identify the scenarios where a fuel can be more efficient than a conventional CHP system. Using SBEM, CO_2 emissions results and operating costs of the system can be obtained. The calculated results depend on the efficiencies of the CHP system and on the percentage of heating demand supplied by the CHP system. These values vary according to the system's design. Therefore, dynamic simulations are needed to analyse the performance of the system in detail and to design its components. In SBEM, a fuel cell CHP is configured like a conventional CHP system with higher efficiency. Therefore, it is not representing the reduction of pollutants such are NO_x, SO_2 and CO due to the utilization of fuel cells. An interesting improvement of SBEM would be to incorporate fuel cell components to represent their real environmental impact.

ESP-r has been used in this dissertation to analyse the performance of fuel cell CHP systems and to determine their environmental and economic impact. After analysing different available fuel cell models in the software, a one node model was selected for its capacity to simulate the most used type of fuel cell in the industry (PEM) and for the level of detail of its configuration and results. A methodology has been developed to size the hot water storage tank in order to ensure that the fuel cell is not switched on and off more than once during a day. This is done by analysing the operating hours of the fuel cell for different tank sizes. Simulations results showed that, with a 5 kW PEM fuel cell CHP system it is possible to supply 93% of the heating demand of a 250 m^2 office and 75% of the heating demand of a 500 m^2 office obtaining significant reductions in CO_2 emissions and operating costs. However, the model developed for this dissertation does not include a back-up system and the percentage of back-up used has to be calculated by comparing the heating demand of the zone with the heating supplied by the CHP system. As the back-up is not integrated in the system, some errors in the results have been detected in the simulations: in some cases the heat supplied by the CHP and the back-up is higher than the total heating demand. Future work detected would be to integrate the back-up system into the model in order to correct this error. The model proposed represents a 5 kW PEM fuel cell. However, recent investigations are developing other types and sizes of fuel cells CHP systems which are close to reaching a commercial stage. In the future, new components should be developed in ESP-r to represent these types of fuel cells.

The investigation of the integration of fuel cells and renewable energy systems revealed that there are some research projects which are aiming to analyse the performance of systems which recover the excess of renewable energy generation systems and store it to supply a fuel cell when no wind or solar energy is available. Homer Energy software can be used to analyse the performance of these systems. Results show that converting the excess of electricity into hydrogen using an electrolyser and converting it back into electricity with a fuel cell has an efficiency of about 30%. This efficiency can be increased using the heat generated by the fuel cell when it is generating electricity to supply a heating demand. However, using Homer Energy it is not possible to install a hot water storage tank and therefore the heating back-up system is supplying a high percentage of the heating demand. A future improvement of the software would be to add this functionality to represent this more complex system. The control system of the software is operating the fuel cell according to the electrical demand. Another future development that has been identified would be to modify the control system to operate the fuel cell to supply either the heating or the electrical demand according to the most efficient option.

7 Conclusions

Fuel cells are still a non-mature technology aiming to reach the market in the coming years. One of the applications which has a high potential of becoming cost-competitive is the fuel cell CHP system for buildings. The 750 W PEM fuel cell CHP systems developed in Japan are expected to reach a competitive commercial stage by 2015. Commercial modelling tools currently available on the market cannot accurately represent fuel cells; therefore, academic tools have to be used for this purpose. It is possible, using the academic software ESP-r, to represent fuel cell CHP systems in order to: supply the heating demand of an office, size the system and evaluate the environmental and economic impacts. By creating a model in ESP-r, it has been possible to develop a methodology for selecting the best size of hot water storage tank and to obtain interesting results by carrying out simulations. Results obtained from ESP-r simulations show that significant reductions can be achieved by using a 5 kW PEM fuel cell CHP system to supply the demand of an office between 250 m^2 and 500m^2. CO_2 emissions and operating costs reductions are higher for the 250 m^2 office as the percentage of heating demand supplied by the CHP system is higher than for the 500 m^2 office. Another benefit of fuel cells is their potential integration with renewable energy systems. The unpredictable generation of renewable energy systems can be compensated by storing the excess of renewable energy as hydrogen and using it to supply a fuel cell. The commercial tool Homer Energy can simulate this system by representing its performance in order to design its components and to evaluate the environmental and economic impact.

In conclusion, the optimization of the performance of the fuel cells technology and its integration with renewable energy systems can play an important role in reducing our dependence on fossil fuels and in developing a more sustainable future.

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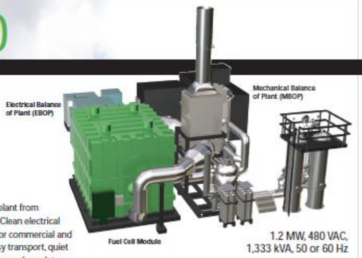
Appendix A: Specifications of a 1.2 MW DFC power plant

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

DFC1500

Key Features
- High Efficiency
- Low Environmental Impact
- Fuel Flexibility
- High Reliability
- Quiet Operation



1.2 MW, 480 VAC, 1,333 kVA, 50 or 60 Hz

Advantages
The DFC®1500™ stationary fuel cell power plant from FuelCell Energy provides high-quality, Ultra-Clean electrical power with 47% efficiency 24/7. Designed for commercial and industrial applications, the system offers easy transport, quiet and reliable operation, and easy site planning and regulatory approval. The DFC1500 is ideal for wastewater treatment plants, manufacturing, food and beverage processing, large hotels, hospitals, and universities.

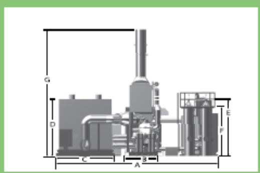
Performance

Power Output	
Power @ Plant Rating	1,200 kW
Standard Output AC Voltage	480 V
Standard Frequency	60 Hz
Optional Output AC Voltages	460, 440, 420, 400, 380 V
Optional Output Frequency	50 Hz
Efficiency	
LHV	47 +/- 2 %
Available Heat	
Exhaust Temperature	700 +/- 50 °F
Exhaust Flow	15,800 lb/h
Allowable Backpressure	5 iwc
Heat Energy Available for Recovery (to 250°F)	1,900,000 Btu/h
(to 120°F)	3,197,000 Btu/h

Fuel Consumption	
Natural gas (at 930 Btu/ft³)	156 scfm
Heat rate, LHV	7,260 Btu/kWh
Water Consumption	
Average	3.5 gpm
Peak during WTS backflush	15 gpm
Water Discharge	
Average	1.7 gpm
Peak during WTS backflush	15 gpm
Pollutant Emissions	
NOx	0.01 lb/MWh
SOx	0.0001 lb/MWh
PM10	0.00002 lb/MWh
Greenhouse Gas Emissions	
CO_2	980 lb/MWh
CO_2 (with waste heat recovery)	520-680 lb/MWh

DFC1500

Specifications



Dimensions

Front View

A	Overall Width	40.0 ft
B	Width of Process Skid	8.5 ft
C	Width of Module	12.6 ft
D	Height of Module	13.7 ft
E	Height of EBOP	11.3 ft
F	Elevation of Desulfurizer Platform	10.0 ft
G	Height of Exhaust Stack (Required on units with no heat recovery)	30.0 ft

Side View

H	Overall Length	55.8 ft
I	Height of Water Treatment Skid	13.0 ft
J	Height of Discharge Vent	18.3 ft

Noise Level

Standard	72 dB(A) at 10 feet
Optional	65 dB(A) at 10 feet

Weights

Water Treatment Skid	15,000 lb
Main Process Skid	40,000 lb
Desulfurization	15,000 lb
Electrical Balance of Plant (Total weight of 3 pieces)	63,000 lb
Fuel Cell Module	115,000 lb

Experience & Capabilities
With more than 35 years of experience, FuelCell Energy is recognized as a world leader in the development, manufacture, and commercialization of fuel cells for stationary electric power generation. The result of years of research and the investment of more than $530 million, our patented, carbonate Direct FuelCell products have generated more than 200 million kilowatt hours of electrical energy to date at more than 50 locations worldwide.

FuelCell Energy's fleet of Direct FuelCell power plants are certified to or comply with a variety of commercial and industrial standards: ANSI/CSA America FC-1, UL 1741, CARB 2007, OSHA 29 CFR Part 1910, IEEE 1547, NFPA 70, NFPA 853, and California Rule 21.

FuelCell Energy, Inc.
3 Great Pasture Road
Danbury, CT 06813-1305
203 825-6000
www.fuelcellenergy.com

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Appendix B: X and Y values for Quality Index calculations

Table GN10-1 QI Formulae for Various Sizes and Types of existing CHP Scheme (will be applied by the CHPQA programme from 1st January 2014).

Size Of Scheme (CHP_{TPC})	QI Definition
CONVENTIONAL FOSSIL FUELS SCHEMES	
Natural gas (inc. Reciprocating Engines)	
$\leq 1 MW_e$	$QI = 249 \times \eta_{power} + 115 \times \eta_{heat}$
>1 to $\leq 10 MW_e$	$QI = 195 \times \eta_{power} + 115 \times \eta_{heat}$
>10 to $\leq 25 MW_e$	$QI = 191 \times \eta_{power} + 115 \times \eta_{heat}$
>25 to $\leq 50 MW_e$	$QI = 186 \times \eta_{power} + 115 \times \eta_{heat}$
>50 to $\leq 100 MW_e$	$QI = 179 \times \eta_{power} + 115 \times \eta_{heat}$
>100 to $\leq 200 MW_e$	$QI = 176 \times \eta_{power} + 115 \times \eta_{heat}$
>200 to $\leq 500 MW_e$	$QI = 173 \times \eta_{power} + 115 \times \eta_{heat}$
$>500 MW_e$	$QI = 172 \times \eta_{power} + 115 \times \eta_{heat}$
Oil	
≤1MWe	$QI = 249 \times \eta_{power} + 115 \times \eta_{heat}$
>1 to ≤25MWe	$QI = 191 \times \eta_{power} + 115 \times \eta_{heat}$
>25MWe	$QI = 176 \times \eta_{power} + 115 \times \eta_{heat}$
Coal	
≤1MWe	$QI = 249 \times \eta_{power} + 115 \times \eta_{heat}$
>1 to ≤25MWe	$QI = 191 \times \eta_{power} + 115 \times \eta_{heat}$
>25MWe	$QI = 176 \times \eta_{power} + 115 \times \eta_{heat}$
SPECIAL CASES	
FUEL CELL SCHEMES	$QI = 180 \times \eta_{power} + 120 \times \eta_{heat}$

Appendix C: Site Assessment Tool Results

CHP Site Assessment Tool

Result Summary

Building Name : Dissertation Test
User Name: : Arnau Girona
Today's Date: : 18 August 2014
Building Sector: : Offices
Building Floor Area (m2) : 15,000
Building Region: : W Scotland

Technically Feasible : YES
Cost Effective : YES

	Units	Option 1	Option 2	Option 3	Option 4	Option 5
Technology		Reciprocating Engine	Reciprocating Engine	Reciprocating Engine	Reciprocating Engine	Reciprocating Engine
CHP Capacity	kWe	500	150	175	200	100
Electricity Generated	MWh / yr	1,354	463	457	471	396
Useful heat Recovered	MWh / yr	690	704	710	733	596
CHP Fuel consumption	MWh / yr	3,889	1,443	1,474	1,518	1,319
Primary Energy Savings	MWh / yr	595	715	675	698	516
CHP Capital Costs	£	£491,000	£176,000	£201,000	£225,000	£125,000
Annual Cost Savings	£ / Yr	£140,000	£78,000	£77,000	£79,000	£66,000
NPV	£	£700,000	£488,000	£453,000	£449,000	£438,000
Payback Period	Yrs	3.5	2.3	2.6	2.8	1.9
CO2 Saving against all fossil fuels	TCO2 / Yr	321	214	205	211	168
	%	25 %	17 %	16 %	17 %	13 %
CO2 Saving against all fuels including renewables and nuclear	TCO2 / Yr	109	141	133	137	106
	%	10 %	14 %	13 %	13 %	10 %
CO2 Saving against modern CCGT	TCO2 / Yr	35	116	109	112	84
	%	4 %	12 %	11 %	12 %	9 %

Note: For entries shown in red and marked as not viable in the table above, this is due to them having a negative NPV at the discount rate you selected and they are therefore not cost effective on this basis. However the payback period should also be considered.

Month	Elec Demand (kWh)	Total Heat (kWh)
Jan-15	121000	171000
Feb-15	109000	155000
Mar-15	121000	115000
Apr-15	118000	112000
May-15	119000	113000
Jun-15	118000	56600
Jul-15	123000	58600
Aug-15	119000	57400
Sep-15	118000	112000
Oct-15	121000	115000
Nov-15	116000	111000
Dec-15	123000	174000

Appendix D: SBEM calculations

SBEM Specification Information

Scottish Building Regulations 2010 Section 6 Guidance
Carbon Dioxide Emissions, U-Values, Air Permeability, and HVAC

Project name

Accreditation test 1

Date: Tue Aug 19 19:14:52 2014

Administrative information

Building Details

Address: 123 Chesterton Avenue, Portsmouth, PO1 3GF

Certification tool

Calculation engine: SBEM

Calculation engine version: v4.1.e.5

Interface to calculation engine: iSBEM

Interface to calculation engine version: v4.1.e

Compliance check version: v4.1.e.5

Owner Details

Name: Joe Bloggs Ltd.

Telephone number: 023 9123 456

Address: 124 Chesterton Avenue, Portsmouth, PO1 3GF

Agent details

Name: My name

Telephone number: My phone number

Address: My address, My city, NW1 1AA

1- Predicted CO2 emission from proposed building

1.1	Calculated CO2 emission rate from notional building	66.8 KgCO2/m2.annum
1.2	Improvement factor	0.41
1.3	LZC benchmark	0.15
1.4	Target CO2 Emission Rate (TER)	33.6 KgCO2/m2.annum
1.5	Building CO2 Emission Rate (BER)	58 KgCO2/m2.annum
1.6	Are emissions from building less than or equal to the target?	BER > TER NO

2- The performance of the building fabric and the building services systems

2.1 How do the U-values compare with Section 6 guidance?

The building does not follow guidance in Scottish Building Regulations 2010

Element	$U_{a-Limit}$	U_{a-Calc}	$U_{i-Limit}$	U_{i-Calc}	Surface where this maximum value occurs*
Wall	0.27	0.35	0.7	0.35	Office/s
Floor	0.22	0.25	0.7	0.25	Office/f
Roof	0.2	0.25	0.35	0.25	Office/c
Windows**, roof windows, and rooflights	2	2	3.3	2	Office/s/g
Personnel doors	2	-	3.3	-	"No external personnel doors"
Vehicle access & similar large doors	1.5	-	1.5	-	"No external vehicle access doors"

$U_{a-Limit}$ = Limiting area-weighted average U-values [W/(m2K)]
U_{a-Calc} = Calculated area-weighted average U-values [W/(m2K)]
$U_{i-Limit}$ = Limiting individual element U-values [W/(m2K)]
U_{i-Calc} = Calculated individual element U-values [W/(m2K)]

* There might be more than one surface exceeding the limiting standards.
** Display windows and similar glazing are not required to meet the standard given in this table.

2.2 Air permeability

Air Permeability	This building's value
m3/(h.m2) at 50 Pa	10

Page 1 of 4

2.b Building services

The building services parameters listed below are expected to be checked by the BCO against guidance.
No automatic checking is performed by the tool.

Whole building lighting automatic monitoring & targeting with alarms for out-of-range values	NO
Whole building electric power factor achieved by power factor correction	>0.95

1- Office

Heating seasonal efficiency	Cooling nominal efficiency	Specific fan power [W/(l/s)]
0.89	3.12	1.8
Automatic monitoring & targeting with alarms for out-of-range values for this HVAC system		NO

1- HWS

Heating seasonal efficiency	Hot water storage loss factor [kWh/litre per day]
0.75	-

"No zones in project where local mechanical ventilation or exhaust is applicable"

Technical Data Sheet (Actual vs. Notional Building)

Building Global Parameters

	Actual	Notional
Area [m²]	402.6	402.6
External area [m²]	1058.3	1058.3
Weather	GLA	GLA
Infiltration [m³/hm²@ 50Pa]	10	10
Average conductance [W/K]	411.86	469.61
Average U-value [W/m²K]	0.39	0.44
Alpha value* [%]	18.34	3.51

* Percentage of the building's average heat transfer coefficient which is due to thermal bridging

Building Use

% Area	Building Type
	Retail/Financial and Professional services
	Restaurants and Cafes/Drinking Est./Takeaways
100	**Offices and Workshop businesses**
	General Industrial and Special Industrial Groups
	Storage or Distribution
	Hotels
	Residential Inst.: Hospitals and Care Homes
	Residential Inst.: Residential schools
	Residential Inst.: Universities and colleges
	Secure Residential Inst.
	Residential spaces
	Non-residential Inst.: Community/Day Centre
	Non-residential Inst.: Libraries, Museums, and Galleries
	Non-residential Inst.: Education
	Non-residential Inst.: Primary Health Care Building
	Non-residential Inst.: Crown and County Courts
	General Assembly and Leisure, Night Clubs and Theatres
	Others: Passenger terminals
	Others: Emergency services
	Others: Miscellaneous 24hr activities
	Others: Car Parks 24 hrs
	Others - Stand alone utility block

Energy Consumption by End Use [kWh/m²]

	Actual	Notional
Heating	67.12	61.31
Cooling	18.04	27.52
Auxiliary	41.34	30.11
Lighting	45.54	45.54
Hot water	3.82	6.53
Equipment*	42.19	42.19
TOTAL**	**175.86**	**171.01**

* Energy used by equipment does not count towards the total for calculating emissions.
** Total is net of any electrical energy displaced by CHP generators, if applicable.

Energy Production by Technology [kWh/m²]

	Actual	Notional
Photovoltaic systems	10.64	0
Wind turbines	8.41	0
CHP generators	0	0
Solar thermal systems	0	0

Energy & CO_2 Emissions Summary

	Actual	Indicative Target
Heating + cooling demand [MJ/m²]	311.06	184.61
Primary energy* [kWh/m²]	378.05	186.33
Total emissions [kg/m²]	58	33.6

* Primary energy is net of any electrical energy displaced by CHP generators, if applicable.

HVAC Systems Performance

System Type		Heat dem MJ/m2	Cool dem MJ/m2	Heat con kWh/m2	Cool con kWh/m2	Aux con kWh/m2	Heat SSEEF	Cool SSEER	Heat gen SEFF	Cool gen SEER
[ST] Fan coil systems, [HS] LTHW boiler, [HFT] Natural Gas, [CFT] Electricity										
	Actual	189.9	121.1	67.1	18	41.3	0.79	1.87	0.89	2.5
	Notional	183.2	165.4	61.3	27.5	30.1	0.83	1.67	---	---

Key to terms

Heat dem [MJ/m2] = Heating energy demand
Cool dem [MJ/m2] = Cooling energy demand
Heat con [kWh/m2] = Heating energy consumption
Cool con [kWh/m2] = Cooling energy consumption
Aux con [kWh/m2] = Auxiliary energy consumption
Heat SSEFF = Heating system seasonal efficiency
Cool SSEER = Cooling system seasonal energy efficiency ratio
Heat gen SSEFF = Heating generator seasonal efficiency
Cool gen SSEER = Cooling generator seasonal energy efficiency ratio
ST = System type
HS = Heat source
HFT = Heating fuel type
CFT = Cooling fuel type

SBEM Specification Information

Scottish Building Regulations 2010 Section 6 Guidance
Carbon Dioxide Emissions, U-Values, Air Permeability, and HVAC

Project name

Accreditation test 1

Date: Tue Aug 19 19:21:56 2014

Administrative information

Building Details

Address: 123 Chesterton Avenue, Portsmouth, PO1 3GF

Certification tool

Calculation engine: SBEM

Calculation engine version: v4.1.e.5

Interface to calculation engine: ISBEM

Interface to calculation engine version: v4.1.e

Compliance check version: v4.1.e.5

Owner Details

Name: Joe Bloggs Ltd.

Telephone number: 023 9123 456

Address: 124 Chesterton Avenue, Portsmouth, PO1 3GF

Agent details

Name: My name

Telephone number: My phone number

Address: My address, My city, NW1 1AA

1- Predicted CO2 emission from proposed building

1.1	Calculated CO2 emission rate from notional building	66.8 KgCO2/m2.annum
1.2	Improvement factor	0.41
1.3	LZC benchmark	0.15
1.4	Target CO2 Emission Rate (TER)	33.6 KgCO2/m2.annum
1.5	Building CO2 Emission Rate (BER)	54.8 KgCO2/m2.annum
1.6	Are emissions from building less than or equal to the target?	BER > TER NO

2- The performance of the building fabric and the building services systems

2.1 How do the U-values compare with Section 6 guidance?

The building does not follow guidance in Scottish Building Regulations 2010

Element	$U_{a\text{-}Limit}$	$U_{a\text{-}Calc}$	$U_{i\text{-}Limit}$	$U_{i\text{-}Calc}$	Surface where this maximum value occurs*
Wall	0.27	0.35	0.7	0.35	Office/s
Floor	0.22	0.25	0.7	0.25	Office/f
Roof	0.2	0.25	0.35	0.25	Office/c
Windows**, roof windows, and rooflights	2	2	3.3	2	Office/s/g
Personnel doors	2	-	3.3	-	"No external personnel doors"
Vehicle access & similar large doors	1.5	-	1.5	-	"No external vehicle access doors"

$U_{a\text{-}Limit}$ = Limiting area-weighted average U-values [W/(m2K)]
$U_{a\text{-}Calc}$ = Calculated area-weighted average U-values [W/(m2K)]
$U_{i\text{-}Limit}$ = Limiting individual element U-values [W/(m2K)]
$U_{i\text{-}Calc}$ = Calculated individual element U-values [W/(m2K)]

* There might be more than one surface exceeding the limiting standards.
** Display windows and similar glazing are not required to meet the standard given in this table.

2.2 Air permeability

Air Permeability	This building's value
m3/(h.m2) at 50 Pa	10

2.b Building services

The building services parameters listed below are expected to be checked by the BCO against guidance.
No automatic checking is performed by the tool.

Whole building lighting automatic monitoring & targeting with alarms for out-of-range values	NO
Whole building electric power factor achieved by power factor correction	>0.95

1- Office

Heating seasonal efficiency	Cooling nominal efficiency	Specific fan power [W/(l/s)]	
0.89	3.12	1.8	
Automatic monitoring & targeting with alarms for out-of-range values for this HVAC system			NO

1- HWS

Heating seasonal efficiency	Hot water storage loss factor [kWh/litre per day]
0.75	-

"No zones in project where local mechanical ventilation or exhaust is applicable"

Technical Data Sheet (Actual vs. Notional Building)

Building Global Parameters

	Actual	Notional
Area [m²]	402.6	402.6
External area [m²]	1058.3	1058.3
Weather	GLA	GLA
Infiltration [m³/hm² @ 50Pa]	10	10
Average conductance [W/K]	411.86	469.61
Average U-value [W/m²K]	0.39	0.44
Alpha value* [%]	18.34	3.51

* Percentage of the building's average heat transfer coefficient which is due to thermal bridging

Building Use

% Area	Building Type
	Retail/Financial and Professional services
	Restaurants and Cafes/Drinking Est./Takeaways
100	**Offices and Workshop businesses**
	General Industrial and Special Industrial Groups
	Storage or Distribution
	Hotels
	Residential Inst.: Hospitals and Care Homes
	Residential Inst.: Residential schools
	Residential Inst.: Universities and colleges
	Secure Residential Inst.
	Residential spaces
	Non-residential Inst.: Community/Day Centre
	Non-residential Inst.: Libraries, Museums, and Galleries
	Non-residential Inst.: Education
	Non-residential Inst.: Primary Health Care Building
	Non-residential Inst.: Crown and County Courts
	General Assembly and Leisure, Night Clubs and Theatres
	Others: Passenger terminals
	Others: Emergency services
	Others: Miscellaneous 24hr activities
	Others: Car Parks 24 hrs
	Others - Stand alone utility block

Energy Consumption by End Use [kWh/m²]

	Actual	Notional
Heating	112.45	61.31
Cooling	18.04	27.52
Auxiliary	41.34	30.11
Lighting	45.54	45.54
Hot water	3.82	6.53
Equipment*	42.19	42.19
TOTAL**	**198.12**	**171.01**

* Energy used by equipment does not count towards the total for calculating emissions.
** Total is net of any electrical energy displaced by CHP generators, if applicable.

Energy Production by Technology [kWh/m²]

	Actual	Notional
Photovoltaic systems	10.64	0
Wind turbines	8.41	0
CHP generators	23.08	0
Solar thermal systems	0	0

Energy & CO_2 Emissions Summary

	Actual	Indicative Target
Heating + cooling demand [MJ/m²]	311.06	184.61
Primary energy* [kWh/m²]	356.91	186.33
Total emissions [kg/m²]	54.8	33.6

* Primary energy is net of any electrical energy displaced by CHP generators, if applicable.

HVAC Systems Performance

System Type		Heat dem MJ/m2	Cool dem MJ/m2	Heat con kWh/m2	Cool con kWh/m2	Aux con kWh/m2	Heat SSEEF	Cool SSEER	Heat gen SEFF	Cool gen SEER
[ST] Fan coil systems, [HS] LTHW boiler, [HFT] Natural Gas, [CFT] Electricity										
	Actual	57	121.1	20.1	18	41.3	0.79	1.87	0.89	2.5
	Notional	183.2	165.4	61.3	27.5	30.1	0.83	1.67	---	---

Key to terms

Heat dem [MJ/m2]	= Heating energy demand
Cool dem [MJ/m2]	= Cooling energy demand
Heat con [kWh/m2]	= Heating energy consumption
Cool con [kWh/m2]	= Cooling energy consumption
Aux con [kWh/m2]	= Auxiliary energy consumption
Heat SSEFF	= Heating system seasonal efficiency
Cool SSEER	= Cooling system seasonal energy efficiency ratio
Heat gen SSEFF	= Heating generator seasonal efficiency
Cool gen SSEER	= Cooling generator seasonal energy efficiency ratio
ST	= System type
HS	= Heat source
HFT	= Heating fuel type
CFT	= Cooling fuel type

SBEM Specification Information

Scottish Building Regulations 2010 Section 6 Guidance
Carbon Dioxide Emissions, U-Values, Air Permeability, and HVAC

Project name

Accreditation test 1

Date: Tue Aug 19 19:23:52 2014

Administrative information

Building Details

Address: 123 Chesterton Avenue, Portsmouth, PO1 3GF

Certification tool

Calculation engine: SBEM

Calculation engine version: v4.1.e.5

Interface to calculation engine: iSBEM

Interface to calculation engine version: v4.1.e

Compliance check version: v4.1.e.5

Owner Details

Name: Joe Bloggs Ltd.

Telephone number: 023 9123 456

Address: 124 Chesterton Avenue, Portsmouth, PO1 3GF

Agent details

Name: My name

Telephone number: My phone number

Address: My address, My city, NW1 1AA

1- Predicted CO2 emission from proposed building

1.1	Calculated CO2 emission rate from notional building	66.8 KgCO2/m2.annum
1.2	Improvement factor	0.41
1.3	LZC benchmark	0.15
1.4	Target CO2 Emission Rate (TER)	33.6 KgCO2/m2.annum
1.5	Building CO2 Emission Rate (BER)	48.9 KgCO2/m2.annum
1.6	Are emissions from building less than or equal to the target?	BER > TER NO

2- The performance of the building fabric and the building services systems

2.1 How do the U-values compare with Section 6 guidance?

The building does not follow guidance in Scottish Building Regulations 2010

Element	$U_{a-Limit}$	U_{a-Calc}	$U_{i-Limit}$	U_{i-Calc}	Surface where this maximum value occurs*
Wall	0.27	0.35	0.7	0.35	Office/s
Floor	0.22	0.25	0.7	0.25	Office/f
Roof	0.2	0.25	0.35	0.25	Office/c
Windows**, roof windows, and rooflights	2	2	3.3	2	Office/s/g
Personnel doors	2	-	3.3	-	"No external personnel doors"
Vehicle access & similar large doors	1.5	-	1.5	-	"No external vehicle access doors"

$U_{a-Limit}$ = Limiting area-weighted average U-values [W/(m2K)]
U_{a-Calc} = Calculated area-weighted average U-values [W/(m2K)]
$U_{i-Limit}$ = Limiting individual element U-values [W/(m2K)]
U_{i-Calc} = Calculated individual element U-values [W/(m2K)]

* There might be more than one surface exceeding the limiting standards.
** Display windows and similar glazing are not required to meet the standard given in this table.

2.2 Air permeability

Air Permeability	This building's value
m3/(h.m2) at 50 Pa	10

2.b Building services

The building services parameters listed below are expected to be checked by the BCO against guidance.
No automatic checking is performed by the tool.

Whole building lighting automatic monitoring & targeting with alarms for out-of-range values	NO
Whole building electric power factor achieved by power factor correction	>0.95

1- Office

Heating seasonal efficiency	Cooling nominal efficiency	Specific fan power [W/(l/s)]
0.89	3.12	1.8
Automatic monitoring & targeting with alarms for out-of-range values for this HVAC system		NO

1- HWS

Heating seasonal efficiency	Hot water storage loss factor [kWh/litre per day]
0.75	-

"No zones in project where local mechanical ventilation or exhaust is applicable"

Technical Data Sheet (Actual vs. Notional Building)

Building Global Parameters

	Actual	Notional
Area [m²]	402.6	402.6
External area [m²]	1058.3	1058.3
Weather	GLA	GLA
Infiltration [m³/hm²@ 50Pa]	10	10
Average conductance [W/K]	411.86	469.61
Average U-value [W/m²K]	0.39	0.44
Alpha value* [%]	18.34	3.51

* Percentage of the building's average heat transfer coefficient which is due to thermal bridging

Building Use

% Area	Building Type
	Retail/Financial and Professional services
	Restaurants and Cafes/Drinking Est./Takeaways
100	**Offices and Workshop businesses**
	General Industrial and Special Industrial Groups
	Storage or Distribution
	Hotels
	Residential Inst.: Hospitals and Care Homes
	Residential Inst.: Residential schools
	Residential Inst.: Universities and colleges
	Secure Residential Inst.
	Residential spaces
	Non-residential Inst.: Community/Day Centre
	Non-residential Inst.: Libraries, Museums, and Galleries
	Non-residential Inst.: Education
	Non-residential Inst.: Primary Health Care Building
	Non-residential Inst.: Crown and County Courts
	General Assembly and Leisure, Night Clubs and Theatres
	Others: Passenger terminals
	Others: Emergency services
	Others: Miscellaneous 24hr activities
	Others: Car Parks 24 hrs
	Others - Stand alone utility block

Energy Consumption by End Use [kWh/m²]

	Actual	Notional
Heating	93.99	61.31
Cooling	18.04	27.52
Auxiliary	41.34	30.11
Lighting	45.54	45.54
Hot water	3.82	6.53
Equipment*	42.19	42.19
TOTAL**	**175.41**	**171.01**

* Energy used by equipment does not count towards the total for calculating emissions.
** Total is net of any electrical energy displaced by CHP generators, if applicable.

Energy Production by Technology [kWh/m²]

	Actual	Notional
Photovoltaic systems	10.64	0
Wind turbines	8.41	0
CHP generators	27.33	0
Solar thermal systems	0	0

Energy & CO_2 Emissions Summary

	Actual	Indicative Target
Heating + cooling demand [MJ/m²]	311.06	184.61
Primary energy* [kWh/m²]	325.67	186.33
Total emissions [kg/m²]	48.9	33.6

* Primary energy is net of any electrical energy displaced by CHP generators, if applicable.

HVAC Systems Performance

System Type		Heat dem MJ/m2	Cool dem MJ/m2	Heat con kWh/m2	Cool con kWh/m2	Aux con kWh/m2	Heat SSEEF	Cool SSEER	Heat gen SEFF	Cool gen SEER
[ST] Fan coil systems, [HS] LTHW boiler, [HFT] Natural Gas, [CFT] Electricity										
	Actual	57	121.1	20.1	18	41.3	0.79	1.87	0.89	2.5
	Notional	183.2	165.4	61.3	27.5	30.1	0.83	1.67	---	---

Key to terms

Heat dem [MJ/m2]	= Heating energy demand
Cool dem [MJ/m2]	= Cooling energy demand
Heat con [kWh/m2]	= Heating energy consumption
Cool con [kWh/m2]	= Cooling energy consumption
Aux con [kWh/m2]	= Auxiliary energy consumption
Heat SSEFF	= Heating system seasonal efficiency
Cool SSEER	= Cooling system seasonal energy efficiency ratio
Heat gen SSEFF	= Heating generator seasonal efficiency
Cool gen SSEER	= Cooling generator seasonal energy efficiency ratio
ST	= System type
HS	= Heat source
HFT	= Heating fuel type
CFT	= Cooling fuel type