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STUDY OF THE THERMAL AND ELECTRICAL SUPPLY OF THE L'ILLA PERDUDA NEIGHBOURHOOD (VALENCIA, SPAIN) USING PROTON EXCHANGE MEMBRANE FUEL CELLS

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Abstract

Decentralised energy generation has been identified as a promising strategy towards powering a sustainable future. It is well-established that centralised production at conventional power facilities is inefficient and results in the significant release of greenhouse gas emissions. This thesis presents an assessment of the techno-economic feasibility of using a Proton Exchange Membrane Fuel Cell (PEMFC) energy system to accommodate the thermal and electrical demand of the L'illa Perduda neighbourhood in Valencia, Spain. The PEMFC system, fed with natural gas, will generate both thermal and electrical energy through the process of cogeneration, or combined heat and power (CHP), to supplement existing energy supplies. Consumption data of the neighbourhood provided by the Cátedra de Transición Energética Urbana, a collaboration between the Universitat Politècnica de València and the Las Naves Foundation of the Valencia City Council, was analysed and an operating model of the energy system was constructed on *HOMER.*

Peak thermal and electrical demands of the neighbourhood were determined to be 11.98 MWh_{th} in February and 3.37 MWh_e in August, respectively. Based on demand variations throughout the year, to inform the techno-economic viability of the project, a number of optimisations were conducted to assess several energy system configurations. Based on 'best estimate' inputs, including a €2,000,000 / MW_e PEMFC capital cost and a €0.59 / m^3 natural gas price, the existing grid-electric and boiler infrastructure of the neighbourhood was deemed most economically viable. A net present cost (NPC) of €47,637,932 (over 25 years) and a levelised cost of energy (LCOE) of €0.150 / kWh was determined for the existing case. However, only a small increase in NPC (+4.2%) and LCOE (+8.0%) was observed for the implementation of a 1 MW_e grid-connected PEMFC-based CHP unit. In alignment with research which suggests that fuel cells are only recently becoming competitive with conventional systems, this result is comparable. Based on a sensitivity analysis of varying fuel cell and natural gas costs, natural gas cost reductions were identified to significantly improve the economics, with the 1 MW_e configuration becoming economically feasible at a cost of €0.48 / m^3. In addition, fuel cell capital cost reductions down to €1,400,000 were also determined to achieve this. On this basis, a full economic appraisal should be carried out prior to project commissioning.

Keywords: Fuel cell, Proton Exchange Membrane Fuel Cell, PEMFC, power generation, combined heat and power, CHP, *HOMER*

Resumen

La generación distribuida de energía es una estrategia prometedora para impulsar un futuro sostenible. La producción de energía centralizada en las instalaciones eléctricas convencionales es ineficiente y provoca un aumento de las emisiones de gases de efecto invernadero. Este proyecto presenta una evaluación técnico-económica de la viabilidad del uso de pilas de combustible de membrana de intercambio de protones (PEMFC) para suministrar energía térmica y eléctrica al barrio de L'illa Perduda en Valencia, España. El sistema PEMFC, alimentado con gas natural, generaría energía tanto térmica como eléctrica mediante cogeneración (CHP), y complementaría a la red de suministro local. Se analizaron los datos de consumo del barrio facilitados por la Cátedra de Transición Energética Urbana, en colaboración con la Universitat Politècnica de València y la Fundación Las Naves del Ayuntamiento de Valencia y se simuló un modelo de funcionamiento del sistema energético utilizando el software *HOMER*.

Se determinó que las demandas térmicas y eléctricas máximas del vecindario fueron de 11,98 MWhth en febrero y 3,37 MWhe en agosto, respectivamente. Sobre la base de las variaciones de la demanda a lo largo del año, para informar la viabilidad técnico-económica del proyecto, se llevaron a cabo una serie de optimizaciones para evaluar distintas configuraciones de sistemas de energía. En base a las mejores estimaciones utilizadas como inputs, incluidos el coste de los sistemas PEMFC (2.000.000 € / MWe), un precio del gas natural de 0,59 €/m3 y utilizando la red eléctrica existente como sistema de back up, el sistema se considera económicamente viable. Se determinó un valor actual neto (VAN) de 47.637.932 € (durante 25 años) y un coste levelizado de la energía (LCOE) de 0,150 € / kWh para el caso existente. Sin embargo, se observó un pequeño aumento en VAN (+ 4.2%) y LCOE (+ 8.0%) para la implementación de una unidad de cogeneración de 1 MWe basada en PEMFC conectada a la red. Los resultados obtenidos están en la misma línea de las investigaciones realizadas que sugieren que las pilas de combustible sólo empiezan a ser competitivas en comparación con los sistemas convencionales. En base al análisis de sensibilidad basado en diferentes costes de gas natural, se identificaron reducciones de costes de gas natural para mejorar significativamente la economía, y la configuración de 1 MWe permitiendo que el sistema sea económicamente viable a un coste de € 0,48 / m3. Además, para lograrlo, también requiere una reducción de los costes de capital de las pilas de combustible hasta € 1.400.000. En función de lo dicho, se debe realizar una evaluación económica completa antes de la puesta en marcha del proyecto.

Palabras clave: pila de combustible, pila de combustible de membrana de intercambio de protones, PEMFC, generación de energía, calor y energía, cogeneración, *HOMER*.

Resum

La generació distribuïda d'energia és una estratègia prometedora per a impulsar un futur sostenible. La producció d'energia centralitzada en les instal·lacions elèctriques convencionals és ineficient i provoca un augment de les emissions de gasos d'efecte d'hivernacle. Aquest projecte presenta una avaluació tecnicoeconòmica de la viabilitat de l'ús de piles de combustible de membrana d'intercanvi de protons (PEMFC) per a subministrar energia tèrmica i elèctrica al barri de L'illa Perduda a València, Espanya. El sistema PEMFC, alimentat amb gas natural, produiria energia tant tèrmica com elèctrica mitjançant cogeneració (CHP), i complementaria a la xarxa de subministrament local. Es van analitzar les dades de consum del barri facilitats per la Càtedra de Transició Energètica Urbana, en col·laboració amb la Universitat Politècnica de València i la Fundació Las Naves de l'Ajuntament de València i es va simular un model de funcionament del sistema energètic utilitzant el programari *HOMER*.

Es va determinar que les demandes tèrmiques i elèctriques màximes del veïnat van ser de 11,98 MWhth al febrer i 3,37 MWhe a l'agost, respectivament. Sobre la base de les variacions de la demanda al llarg de l'any, per a informar la viabilitat tecnicoeconòmica del projecte, es van dur a terme una sèrie d'optimitzacions per a avaluar diferents configuracions de sistemes d'energia. Sobre la base de les millors estimacions utilitzades com a inputs, inclosos el cost dels sistemes PEMFC (2.000.000 € / MWe), un preu del gas natural de 0,59 €/m³ i utilitzant la xarxa elèctrica existent com a sistema de backup, el sistema es considera econòmicament viable. Es va determinar un valor actual net (VAN) de 47.637.932 € (durant 25 anys) i un cost nivelitzat de l'energia (LCOE) de 0,150 € / kWh per al cas existent. No obstant això, es va observar un xicotet augment en VAN (+ 4.2%) i LCOE (+ 8.0%) per a la implementació d'una unitat de cogeneració d'1 MWe basada en PEMFC connectada a la xarxa. Els resultats obtinguts estan en la mateixa línia de les investigacions realitzades que suggereixen que les piles de combustible només comencen a ser competitives en comparació amb els sistemes convencionals. Sobre la base de l'anàlisi de sensibilitat basat en diferents costos de gas natural, es van identificar reduccions de costos de gas natural per a millorar significativament l'economia, i la configuració d'1 MWe permetent que el sistema siga econòmicament viable a un cost de € 0,48 / m³. A més, per a aconseguir-ho, també requereix una reducció dels costos de capital de les piles de combustible fins a € 1.400.000. En funció del que s'ha dit, s'ha de realitzar una avaluació econòmica completa abans de la posada en marxa del projecte.

Paraules clau: pila de combustible, pila de combustible de membrana d'intercanvi de protons, PEMFC, generació d'energia, calor i energia, cogeneració, *HOMER*.

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List of Abbreviations

Abbreviation	
AC	Alternating Current
ACS	Agua Caliente Sanitaria (Domestic Hot Water)
AFC	Alkaline Fuel Cell
BoL	Beginning of Life
BoP	Balance-of-Plant
CHP	Combined Heat and Power
CHP-FCP	Combined Heat and Power Fuel Cell Plant
CIS	Centro de Investigaciones Sociológicas (Sociological Research Centre)
CIBSE	Chartered Institution of Building Services Engineers
LCOE	Levelised Cost of Energy
CTE	Código Tecnico de la Edificación (Technical Building Code)
DC	Direct Current
DHW	Domestic Hot Water
DMFC	Direct Methanol Fuel Cell
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HOMER	*Hybrid Optimisation Model for Multiple Energy Resources*
HOR	Hydrogen Oxidation Reaction
IDAE	*Instituto para la Diversificación y Ahorro de la Energía*
HRR	Heat Recovery Ratio
kW	Kilowatt
kWh	Kilowatt Hour
MCFC	Molten Carbonate Fuel Cell
MW	Megawatt
NPC	Net Present Cost
O&M	Operation and Maintenance
ORR	Oxidation Reduction Reaction
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
SMR	Steam-methane Reforming
SOFC	Solid Oxide Fuel Cell
TEU Chair	*Cátedra de Transición Energética Urbana* (*Urban Energy Transition Chair*)
UPS	Uninterruptible Power Supply
UPV	*Universitat Politècnica de València (Polytechnic University of Valencia)*

DOCUMENT I: Memory

1 Introduction

The world needs energy. It is central to ensuring a better quality of life and underpins the socio-economic development of modern society. Yet with a rapidly growing global population and increasingly energy-intensive lifestyles, the world faces three major energy challenges – the security of energy supply, the maintenance of competitive energy prices and climate change [1]. The current global economy is heavily reliant on an energy system that is powered by conventional fossil fuel-driven technologies; however, natural resources are dwindling due to rising demand. In addition, the environmental impact associated with conventional power production methods is not going unnoticed thus there are increasing pressures to establish a much-improved global energy model. In recent times, the term 'energy transition' has become a very common headline topic and is used to describe the transformation of the global energy supply system to one that is more sustainable, whilst also reliable and affordable. In the near future it is envisioned that conventional energy supplies will continue to play an important role in the global energy mix; however, significant advancements in research and development of novel and more sustainable technologies are imperative for diversification and decarbonisation.

Recently, the development of fuel cell technology has gained momentum worldwide as a promising option on the pathway towards a low-carbon future. Due to their high efficiency, intrinsically clean operation and ability to be used in a wide range of applications, fuel cells are considered to be one of the key components for a 'hydrogen economy'. This is a concept which involves a transition towards the large-scale implementation of hydrogen infrastructure to support an economy in which hydrogen is used as a primary energy vector [2]. Pertaining to this concept, in the ideal case, fuel cells fed with pure hydrogen generated from renewables will eventually replace conventional power plants to generate electrical power; however, until then, the first generation of fuel cells will likely operate using the likes of natural gas or propane [3]. Despite this also involving the use of a finite fossil fuel, environmental benefits associated with the relatively clean nature of these fossil fuels in comparison to others can be realised and this can act as a transitory step towards the ultimate objective of the hydrogen economy. Furthermore, fuel cells can operate at much higher efficiencies in comparison with conventional power systems thus higher power demands can be met with lower amounts of fuel consumed – this further reduces the carbon footprint of fuel cell technology.

According to the Intergovernmental Panel on Climate Change (IPCC) '*Fifth Assessment Report' (AR5)*, the energy supply sector is the largest contributor to global anthropogenic greenhouse gas (GHG) emissions and accounted for approximately 35% of total emissions in 2010 [4]. Decarbonising electricity generation was also identified as being a key solution for the stabilisation of GHG concentrations at low levels and combined heat and power (CHP) technology is recognised to further enhance this. Cogeneration is the simultaneous production of electrical and useful thermal energy from a single primary energy source [5] and when incorporated within the design of fuel cell systems, efficiencies of more than 80% can be achieved [6]. This can be compared to efficiencies of up to 60% for fuel cell systems designed for distributed generation (electricity only) and up to 35% for conventional combustion power technologies [7]. Fuel cell-based CHP energy systems have thus recently emerged across parts of the international community for the use in stationary power generation applications for the domestic built environment.

1.1 Research Objectives

In alignment with the Paris Agreement to limit the increase in global average temperature to well below 2^{o}C (in reference to pre-industrial levels), the EU aims to be climate-neutral by 2050 [8]. To meet this objective, the EU has expressed an immediate need to fully transition to green, low-carbon technologies which requires full support from European countries at local government levels. As a result, Spain - amongst other Member States of the EU - has recently developed a national long-term strategy to achieve net-zero GHG emissions [9]. Outlined in the strategic report, a decarbonisation roadmap lays the foundations to meeting this objective in 2050 with interim targets in 2030 and 2040. The Spanish government has identified an ultimate goal of transitioning to a 100% renewable electricity system by 2050; however, short-term solutions that enhance energy efficiency are also an important focus.

The main research objective of the thesis is to assess the techno-economic feasibility of implementing a Proton Exchange Membrane Fuel Cell (PEMFC)-based energy system to supply the L'illa Perduda neighbourhood in Valencia, Spain. The PEMFC system, fed with natural gas, will supply both heat and power through the process of cogeneration. As it will be required to retrofit the CHP system in order to augment the existing heat and power generation infrastructure of the neighbourhood, the feasibility study will determine the technical and economic viability of the project thus better inform a potential future investment decision. The motivation of the study stems from the focus of the Institute of Energy Engineering of UPV and involved collaboration with the Urban Energy Transition Chair of Valencia; a public entity with the aim to develop a more sustainable energy model in the region. In addition, fuel cell and renewable hydrogen technology have been widely identified as key drivers to reduce GHG emissions and thus realise the green energy transition in Europe [10]. However, until robust hydrogen supply infrastructure is established, fuel cells fed with hydrogen generated from reformed natural gas – making use of existing natural gas infrastructure - will play an effective part in the integrated solution towards net-zero.

A summary of the key aims of the project are given below.

- Develop a greater understanding of fuel cell technology and their importance to enhance energy efficiency whilst also contribute to the minimisation of climate change impacts, in comparison to conventional energy production systems.
- Analyse the data provided by the Urban Energy Transition Chair to determine the typical 24-hour thermal and electrical load variations of the L’illa Perduda neighbourhood for a typical weekday and weekend day for each month in the year.
- Conduct research into the specifications of suitable commercial PEMFC models that can be implemented for the application based on the load variations.
- Develop an operating model of the energy system in parallel with the electricity grid on *HOMER (Hybrid Optimisation of Multiple Energy Resources)* to conduct a power balance and carry out optimisations to assess several different system configurations.
- Determine cost savings associated with surplus electricity (if any) sold to the grid and evaluate the techno-economic viability of the project.

2 Fuel Cell Fundamentals

2.1 Introduction to Fuel Cells

Dating back to 1839, a discovery made by Sir William Grove, a Welsh physicist and judge of Britain's High Court [11], is widely recognised as being the origin of the 'fuel cell'. With significant research and development ever since, contributing to the concept of a modern-day fuel cell, this initial discovery was described as being a 'gaseous voltaic battery'. This breakthrough was a result of an experiment involving the combination of hydrogen and oxygen, in contact with two platinum electrodes and in the presence of a sulphuric acid electrolyte, producing electricity and water. The electrolysis of water, the opposite process to that occurring in a fuel cell - that is, the use of electricity to split water into its component parts of hydrogen and oxygen - formed the basis of the experiment having been discovered earlier in the 19th Century [12].

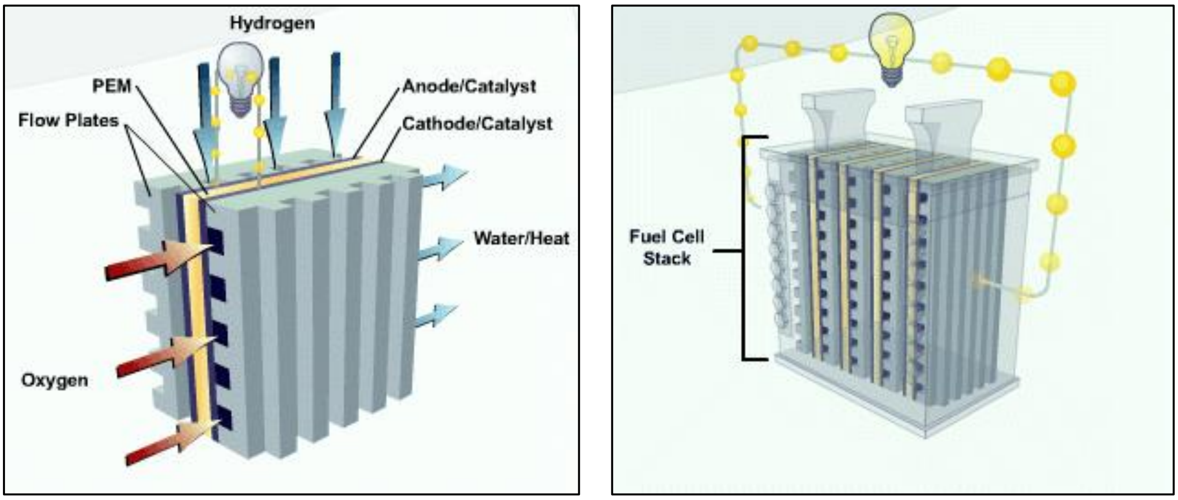
Similar to a standard battery, but with a continuous fuel supply that replenishes the system, a fuel cell is an electrochemical device that generates power through the conversion of chemical energy directly into electrical energy. The electrochemical reaction that takes place within fuel cells is a result of the combination of a fuel and an oxidiser - typically hydrogen and oxygen, respectively – in the presence of an electrolyte, resulting in the production of electricity, heat and water. Due to the benign nature of water, fuel cells are widely considered to be an intrinsically clean alternative to conventional fossil fuel-driven power production technologies. However, despite this environmental benefit and the early realisation of fuel cell technology, many critical technical barriers have hindered the development of fuel cells and only recently has it come close to full commercialisation and widespread adoption.

2.2 Basic Principle of Fuel Cells

A fuel cell, as illustrated in *Figure 1(a)*, consists of three key components: an anode (the negative electrode), a cathode (the positive electrode) and an electrolyte sandwiched between the two. The electrodes are porous and embedded with a catalyst that is uniformly affixed on a catalyst support material; the fuel is supplied to the anode where it is oxidised (loss of electrons), whereas the oxidiser is fed to the cathode where it is reduced (gain of electrons) [13]. For this to be achieved, both electrodes are electrically conductive and an external connection is established between them to allow for the transfer of electrons from the fuel to the oxidiser. This transfer of electrons resulting in the oxidation and reduction reactions can be considered as a 'redox' reaction.

To prevent the electrons being directly transferred from the fuel to the oxidiser, the electrolyte separates the two reaction areas. The electrolyte, insulating to electron conduction, is a substance - in the case below, a Proton Exchange Membrane (PEM) - that selectively allows ions to freely pass through it from one electrode to another. Electrolytes can take the form of a number of different substances and despite having the same basic operating principle, different fuel cell technologies exist which are named based on the type of electrolyte employed (as described in *Section 2.3*).

To increase the total voltage, and hence power, produced by a fuel cell system, they are scalable and modular in design such that individual fuel cells can be combined in series to form a fuel cell stack, as shown in *Figure 1(b)*. In this configuration, each individual fuel cell produces a voltage which summate collectively to produce the total voltage of the fuel cell stack. Similarly, individual fuel cells can be combined in parallel to produce a higher current.



(a) Single (PEM) fuel cell *(b) Fuel cell stack*

Figure 1 - Schematic of a single (PEM) fuel cell and fuel cell stack [14]

In addition to the components that make up the fuel cell stack, a number of ancillary components are also required to ensure smooth operation and regulate system conditions such as flow, temperature and pressure. The overall combination of all the individual subsystems, excluding the stack itself, is referred to as the 'Balance-of-Plant' (BoP). This can include, but is not limited to, start-up power sources, pumps, sensors, filters, heat exchangers, compressors, recirculation blowers or humidifiers [15]. A schematic of an air-cooled PEMFC system with a simple BoP arrangement is illustrated in *Figure 2*.

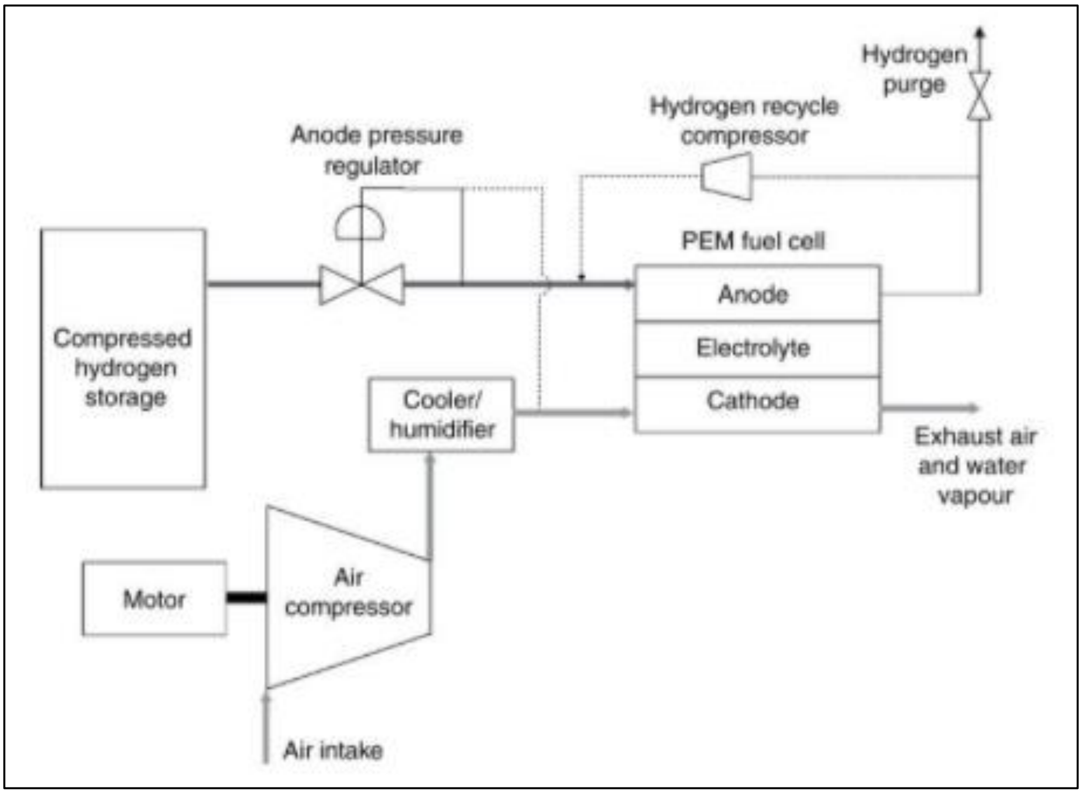


Figure 2 – Simplified schematic of a PEMFC system [16]

2.3 Comparison of Fuel Cell Technologies

Several fuel cell technologies exist, each named according to the type of electrolyte they use. The electrolyte essentially determines the characteristics of the fuel cell – specifically, the electro-chemical reactions that occur, and hence the type of migrating ion through the electrolyte; the temperature range of operation; and the type of fuel and catalysts required, amongst other factors [17]. As a result of the various potential operating configurations, each fuel cell has its own set of benefits thus presents development opportunities for certain applications. The main fuel cell technologies include [13]:

- Proton Exchange Membrane Fuel Cell (PEMFC)
- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)
- Direct Methanol Fuel Cell (DMFC)

The optimal operating temperature of these fuel cells range from room temperature to 1000 ^oC thus they can be classified according to two groups: low temperature, or first-generation fuel cells (PEMFC, AFC and PAFC); and high temperature, or second-generation fuel cells (MCFC and SOFC) [18]. In addition, the DMFC is a relatively new fuel cell technology with a fuel cell design based on that of the PEMFC but with a number of modifications to allow it to accommodate a liquid methanol feed; an inexpensive fuel with a high energy density [19]. The AFC is of historical importance as it was one of the first fuel cell technologies to be commercially developed in the 1960's for use in the Apollo-series missions [20]; however, since then the PEMFC has become by far the furthest developed and most commonly used fuel cell system.

A key advantage associated with low temperature fuel cells is that they achieve shorter start-up times which means that they can operate with high dynamic load changes associated with regular shutdown-start-up cycles. This results in less wear on system components and for this reason, low temperature fuel cells are generally beneficial for transportation and portable power applications [17]. On the contrary, high temperature fuel cells tend to be more favourable for applications that require fuel flexibility (due to a better tolerance to impurities as a result of the elevated operating temperature), higher grade heat exhaust (useful for CHP and steam turbine systems) and greater efficiency [21]. In addition, fuel cell stacks typically require a cooling system to maintain temperature homogeneity thus operating at a higher temperature allows for greater cooling efficiencies; this is due to a larger temperature difference between the stack and the cooling streams [22].

2.3.1 Fuel Cell Applications

The portfolio of fuel cell technologies is extremely diverse in terms of the variety of potential applications they can fulfil; in the earlier days, fuel cells were the primary source of electric power for NASA's Apollo spacecraft and now they are also used to power buildings, fuel cell electric vehicles (FCEVs), or even applications as small as mobile phones [23]. Their efficient operation coupled with their ability to produce clean power has recently allowed them to establish themselves on the podium alongside conventional batteries and combustion engines. The wide range of applications can be classified according to the more general categories of *Portable*, *Stationary* or *Transport*. Stationary applications are not required to relocate thus they do not have to meet requirements of being compact and having a quick start-up, as is the case in non-stationary (portable and transport) applications. A summary of the three application categories can be found in *Table 1*.

Table 1 - Summary of fuel cell application categories [24]

Application Type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including small auxiliary power units (APU)	Units that provide electricity (and sometimes heat) but are not designed to be moved	Units that provide propulsive power or range extension to a vehicle
Typical Power Range	1 W to 20 kW	0.5 kW to 2MW	1 kW to 300 kW
Typical Technology	PEMFC DMFC SOFC	PEMFC MCFC AFC SOFC PAFC	PEMFC (DMFC) (SOFC)
Examples	• Small 'movable' APUs (campervans, boats, lighting) • Military applications (portable soldier-borne power, skid-mounted generators) • Portable products (torches, battery chargers), small personal electronics (mp3 player, cameras)	• Large stationary prime power and combined heat and power (CHP) • Small stationary micro-CHP • Uninterruptible power supplies (UPS) • Larger 'permanent' APUs (e.g. trucks and ships)	• Materials handling vehicles • Fuel cell electric vehicles (FCEVs) • Trucks and buses • Rail vehicles • Autonomous vehicles (air, land or water)

2.3.2 Summary of Fuel Cell Technologies

A summary of the key characteristics of the main fuel cell technologies can be found in *Table 2*. Hydrogen used as a fuel can either be fed to the system directly as pure hydrogen, or it can be generated within the fuel cell system from hydrogen-rich fuels, such as natural gas, using a reformer.

Table 2 - Summary of fuel cell technologies (adapted from [25] using [26])

Fuel Cell Type	Common Electrolyte	Fuel(s)	Operating Temperature	Applications	Advantages	Challenges
Proton Exchange Membrane Fuel Cell (PEMFC)	Nafion™ (a perfluoro sulfonic acid polymer membrane)	Hydrogen	< 120 °C	• Backup power • Portable power • Distributed generation • Transportation • Speciality vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline Fuel Cell (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	Hydrogen	< 100 °C	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid Fuel Cell (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	Hydrogen	150 – 200 °C	• Distributed Generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulphur sensitivity
Molten Carbonate Fuel Cell (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	Hydrogen, carbon monoxide or methane	600 – 700 °C	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide Fuel Cell (SOFC)	Yttria stabilized zirconia (zirconium oxide doped with yttrium oxide)	Hydrogen, carbon monoxide or methane	500 – 1000 °C	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns
Direct Methanol Fuel Cell (DMFC)	Nafion™ (same as for a PEMFC but thicker in design)	Methanol	< 130 °C	• Military • Backup power • Transportation • Portable power	• Inexpensive fuel • Ease of storage and transportation of fuel • No fuel reformer required • Low temperature • Quick start-up	• Expensive catalysts • Methanol crossover • Slow electro-oxidation kinetics

2.4 Advantages of Fuel Cell Technology

Fuel cells offer several advantages in comparison to conventional power systems; they are a promising, sustainable solution to help drive decarbonisation of the global economy. As fuel cell technology continues to mature, they are becoming more prevalent across a number of sectors as their benefits are realised. The main advantages of fuel cells are described below.

- **Environmentally friendly.**
  They only emit water so there are no emissions, such as carbon dioxide, produced directly from the process. Fuel cell operation with pure hydrogen obtained from renewable energy is desirable, however systems utilising hydrogen obtained from natural gas reforming still only produce about half of the total greenhouse gas emissions of gasoline systems [27].

- **High operating efficiency.**
  They can generate electricity at efficiencies of up to 60% (and even higher in CHP applications), roughly two times that of typical conventional combustion technologies [25] (see *Annex 1* for comparison of theoretical efficiency limits for fuel cells and heat engines).

- **Quiet operation.**
  They make less noise during operation as they have fewer moving parts (this also reduces maintenance requirements). This is beneficial for various applications such as power generation in residential areas and transportation.

- **Modular design.**
  A single fuel cell can be expected to generate a bit less than 1V, however they are typically stacked to produce higher voltages [23]. The modularity of fuel cells allows for increased fault tolerance and flexibility in power output.

2.5 Fuel Cell Challenges

Despite the aforementioned benefits, fuel cells have not yet fully penetrated the energy market as they must first overcome a number of challenges that make them less favourable than traditional technologies. The capital costs of fuel cell systems are still too high thus high-volume production is required to allow fuel cell technology to become cost-competitive through economies of scale. Minimising cost and increasing durability of components are also vital to allow the benefits of fuel cells to be capitalised; the success of ongoing research must be achieved to identify and develop new, cost-effective materials that extend their service life. This is especially important for high temperature systems as more extreme operating environments can enhance the degradation of fuel cell stack components [28]. The development of certain applications may also face other issues such as meeting the weight and size specifications associated with non-stationary systems – system complexity and large volume requirements for fuel storage may prevent fuel cells from replacing batteries or combustion engines. Yet, as the pressures of energy shortage and climate change increase, fuel cells stand as a promising next-generation technology to provide energy security through the supply of clean and reliable power. It is thus important that high efforts of research and development are sustained to further develop fuel cell technology.

3 Proton Exchange Membrane Fuel Cell Technology

3.1 PEMFC Overview

The prominence of PEMFCs stem from their ability to start-up quickly, as a result of low temperature operation, and their high-power density – both the specific power ($W\ kg^{-1}$) and area-specific power density ($W\ cm^{-2}$) are considerably higher than for any other type of fuel cell [29]. Their development gained momentum in the 1990s, having been established as a promising fuel cell technology for rapid commercialisation due to their low cost and versatility for use in a wide number of markets [20]. Ever since, the momentum has been rising exponentially and PEMFCs now disproportionately outweigh the other fuel cell technologies in terms of both shipments and capacity, worldwide. An insight into the annual fuel cell shipments and installed capacity (MW) by fuel cell type from 2015 – 2019 is provided in *Figure 3* and *Figure 4*, respectively.

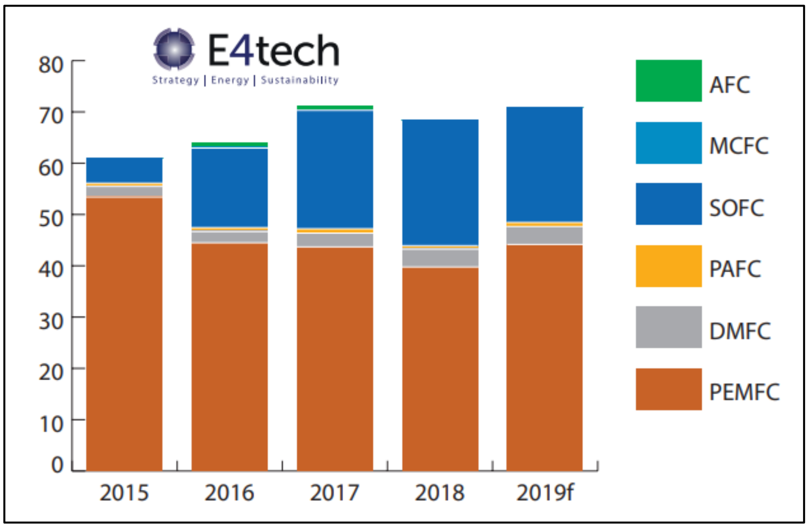


Figure 3 - Fuel cell shipments (1,000 units) by fuel cell type (2015 - 2019) [24]

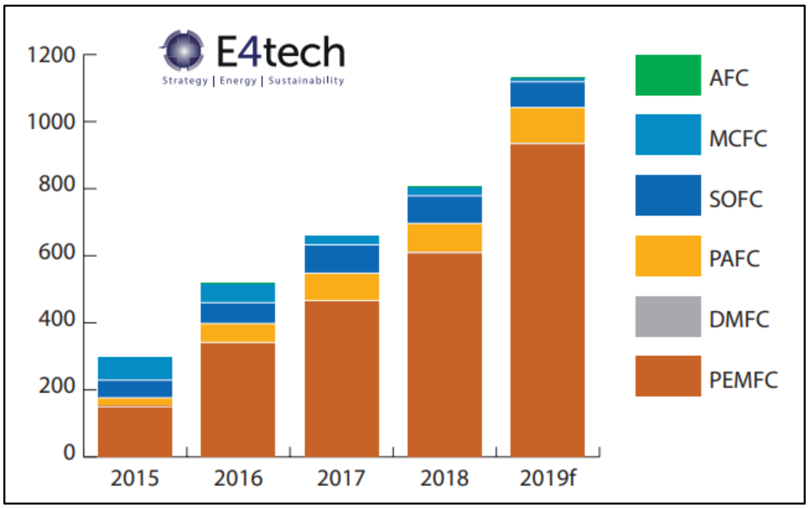


Figure 4 - Fuel cell installed capacity (MW) by fuel cell type (2015 - 2019) [24]

*2019f was E4tech's forecast for the full year of 2019, based on firm data from January to September.

3.2 Working Principle of PEMFCs

In the case of a PEMFC, hydrogen is fed to the anode where it is catalytically separated into individually bound hydrogen ions (or protons) as a result of the release of electrons. This is referred to as a 'hydrogen oxidation reaction' (HOR) and whilst the electrons are transferred to the cathode via the external circuit, thus generating the current output of the fuel cell, the newly formed protons permeate through the electrolyte. On arrival to the cathode, both the protons and electrons react with the entering oxygen stream to produce water and heat in what is referred to as an 'oxygen reduction reaction' (ORR) [13]. Therefore, the overall cell reaction consists of hydrogen being combined with oxygen, typically from ambient air, to produce water. The water, unreacted oxygen and waste heat is then expelled from the cathode, allowing for more oxygen molecules to react so long as there is a continuous supply of hydrogen and oxygen to the system. A schematic illustrating the working principle of a PEMFC is shown in *Figure 5*.

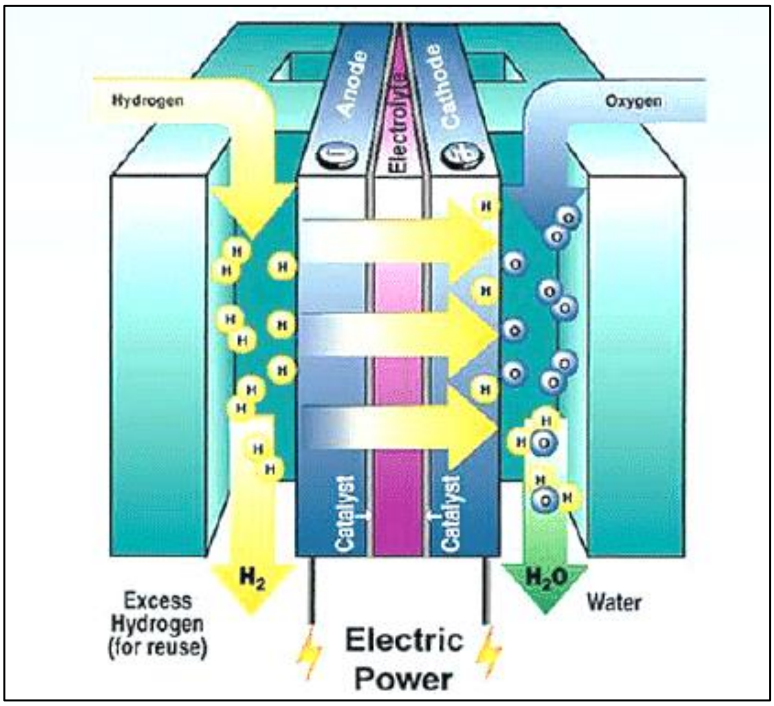


Figure 5 - Schematic of the working principle of a PEMFC [30]

The half-cell reactions and corresponding balanced overall cell reaction of a PEMFC are given below [31] (see *Annex 2* for the more detailed HOR and ORR reaction mechanisms).

Anode: $H_2 \rightleftharpoons 2H^+ + 2e^-$ (HOR) (1)

Cathode: $2H^+ + \frac{1}{2}O_2 + 2e^- \rightleftharpoons H_2O$ (ORR) (2)

Overall: $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$ (3)

3.3 Fuel Cell-based CHP Energy Systems for the Domestic Built Environment

In 2019, it was estimated that the built environment accounted for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU [32]. Furthermore, it is recognised amongst international experts that the most effective strategy for reducing GHG emissions consists of first, minimising energy losses through the efficient use of fossil fuels; second, implementing cost-effective renewable energy sources; and third, increasing the use of green fuels [33]. For decades, electricity provisioning has mainly consisted of a small number of large, centralised power generating plants to meet consumer demand across vast regions. However, due to the intermediate energy conversion steps and the long transmission and distribution lines associated with conventional power production methods, centralised energy generation incurs significant losses. Decentralisation and energy efficiency improvements of power systems supplying domestic buildings can thus significantly drive decarbonisation, whilst also improve energy security.

Combined heat and power fuel cell plant (CHP-FCP) systems offer an alternative and attractive method for stationary power generation due to their ability to produce both electricity and heat in a highly efficient, decentralised, quiet and sustainable way. In particular, PEMFCs and SOFCs have been identified to be the most promising fuel cell technologies for the application, although PEMFCs are considerably ahead in terms of commercial and technological maturity [34]. Other key CHP technologies include the conventional internal combustion engine and Stirling engine; however, fuel cells offer the advantage of having higher electrical efficiencies and thus lower heat-to-power ratios. This makes CHP-FCP systems better suited to residential building applications due to their potential to minimise 'heat dumping' – a process in which heat is wasted due to poor matching of CHP capacity to the heat and power loads of buildings during periods of low thermal demand [35]. Despite this, CHP-FCP technology is still in its infancy relative to conventional systems; it requires further advancements in order to reduce capital costs and become more widespread in the domestic built environment.

3.3.1 State-of-the-Art

Cogeneration systems can be categorised based on their rated capacity according to the following typical classifications: micro-CHP (< 5 kWe, or often < 2 kWe), mini- or small-scale CHP (5 to 500 kWe), medium- or mid-scale CHP (0.5 to 1 MW_e) and large-scale CHP (> 1 MW_e) [36]. Due to the modularity of fuel cells, they are extremely versatile in terms of achievable capacity and thus CHP-FCP systems can operate across a wide number of building applications. This ranges from micro-CHP for heat and power generation for individual homes to large-scale supply at a district level. Micro-CHP is more widespread; however, due to economies of scale and since fuel cells are more efficient as stack life is maximised, district supply is gaining popularity - the latter benefit is linked to the potential for more continuous operation associated with the integration of multiple buildings with different demand patterns [37]. Despite recent commercialisation, CHP-FCP systems now currently present the main focus of interest as the most promising technology for CHP. A comparison of the main heat and power generation technologies is illustrated in *Figure 6*.

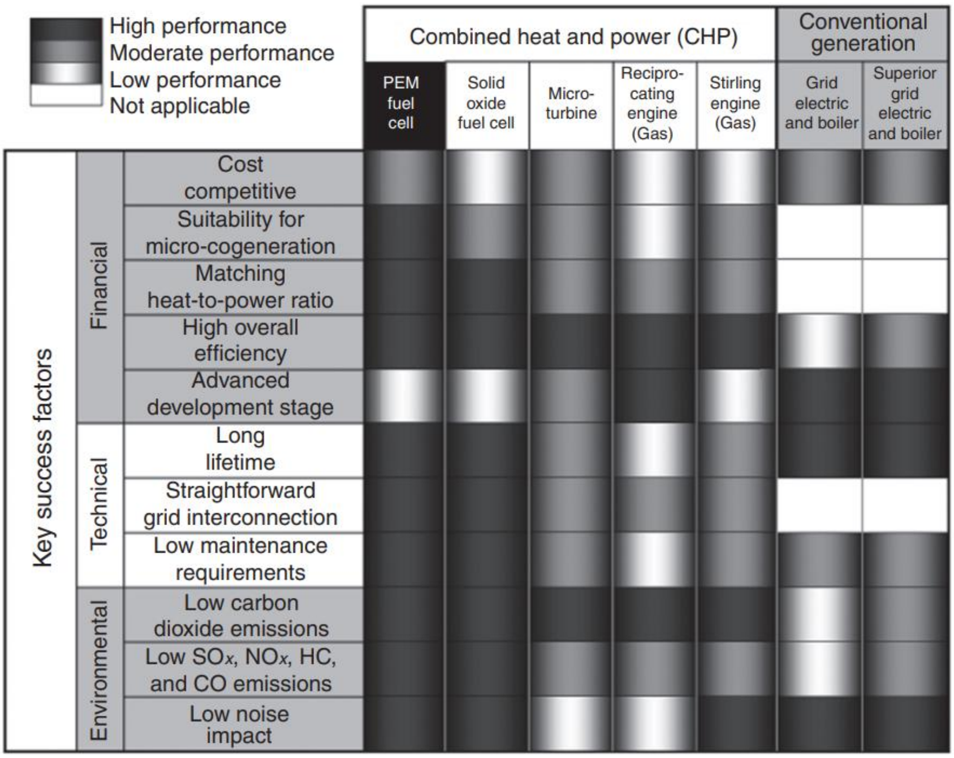


Figure 6 - Comparison of main heat and power generation technologies [38]

When comparing PEMFCs and SOFCs, it is thought amongst commercial developers that SOFCs will eventually be the superior fuel cell technology for domestic built environment applications. With further development, due to operation at elevated temperatures, SOFCs are projected to have lower capital costs associated with the use of cheaper catalysts and their ability to use natural gas directly with internal fuel reformation occurring at the anode [34]. However, PEMFCs are currently the most prominent fuel cell technology due to greater maturity - to put this into perspective, it is estimated that around 80% of micro-CHP applications employ PEMFCs, with the remainder mainly consisting of SOFCs [35]. Much of this stems from the large-scale EneFarm demonstration program in Japan which, with support from Japanese national subsidy programs, resulted in the largest deployment of micro-CHP systems for domestic buildings worldwide [39]. This positioned Asia at the forefront of the stationary power generation, and overall, fuel cell market (see *Annex 3* for the annual fuel cell shipments and installed capacity (MW) by region from 2015 – 2019) and has since influenced similar projects such as Europe's Ene.Field and PACE programs [24].

3.3.2 Design of PEMFC-based CHP Systems for District Supply

Fuel cell cogeneration at a district level is an effective way to optimise energy systems by integrating the mono-disciplines of electricity and heat. The infrastructure to deliver natural gas to communities is already well-established in developed countries thus retrofit of decentralised CHP-FCP technology to augment existing grid-electric and boiler systems is plausible. Natural gas from the central network can be fed into the fuel cell system to generate electrical power which can directly supply buildings or, at times of surplus production, be sold and exported via the electricity grid. Simultaneously, the heat generated from the electricity production process can be recovered and used within a district heating network to supply space heating and domestic hot water demands; though, absorption chillers can also be used for space cooling [40]. In the case of a PEMFC, the water removed from the cathode is often at a temperature of around 80^{o}C which is optimal for these heating applications [39]. In addition, despite lower electrical efficiency than SOFCs, PEMFCs can avoid continuous operation due to long start-up/shutdown times and also damage due to thermal cycling associated with high-temperature operation [41]. As a result, PEMFC systems require less maintenance and can be scheduled to be turned off at night when demands and grid sell-back rates are low [37].

An overall CHP-FCP system is comprised of four sub-systems, each with a function as described below [38].

- **Fuel processor.**
  The fuel processor reforms a hydrocarbon fuel, such as natural gas, into a hydrogen-rich stream via one of three processes: steam reforming (an endothermic reaction), partial oxidation (an exothermic reaction), or a combination of the two. Steam reforming of natural gas is currently the most common method due to having a much higher fuel processing efficiency and is governed by the reactions below [42].

  Steam-methane reforming (SMR): $$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \quad (4)$$

  Water-gas shift: $$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g) \quad (5)$$

- **Fuel cell stack.**
  The fuel cell stack produces direct current (DC) electricity via electrochemical reaction as previously described.

- **Power electronics.**
  As the fuel cell generates DC electricity, an inverter is typically required for conversion into an alternating current (AC) for compatibility with external electricity systems such as the grid.

- **Heat/water management system.**

  A heat/water management system is required to recover the waste heat generated at the cathode to supply heating demands. It is also vital for a PEMFC to avoid excessive temperatures to prevent drying out of the electrolyte membrane as this is detrimental to the operation of the system due to inhibition of proton conduction [43].

A schematic illustrating the sub-systems that constitute an overall CHP-FCP system is provided in *Figure 7*.

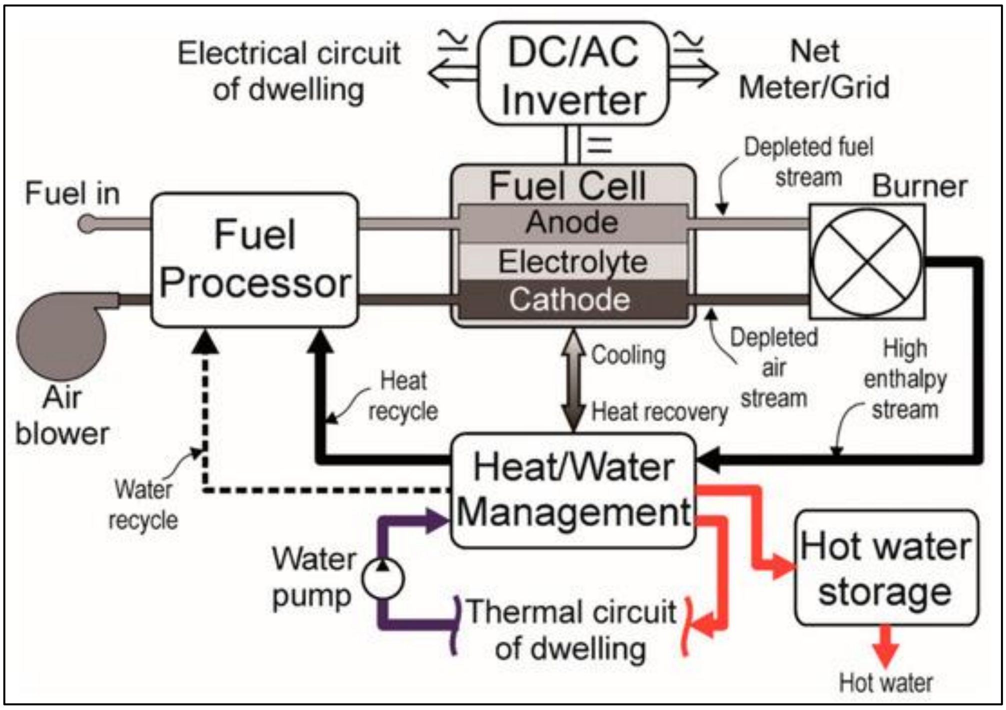


Figure 7 - Schematic of the main features of a fuel cell-based CHP system [35]

To maximise the benefit of the CHP system in parallel with the existing supply infrastructure, a control system should be implemented to ensure that heat and power is taken from the CHP system as the priority source. In doing so, CHP running hours are maximised and the grid and existing boilers can supplement the capacity to meet peak loads. Thermal energy storage, such as a hot water tank, to store the thermal output of the fuel cell at times of low thermal demand may also be beneficial [37].

4 Feasibility Study Methodology

4.1 Overview of Feasibility Study

The L'illa Perduda neighbourhood is located to the east of Valencia in the district of Algirós (see *Annex 4* for a description of the 19 districts in Valencia). It has a total area of 0.232 km^2; a population of 9,360 and a population density of 40,345 inhabitants per km^2 [44]. A map of the neighbourhood is provided in *Figure 8*. An additional plan of L'illa Perduda can be found in Plan 1 in *DOCUMENT V: Plans*.

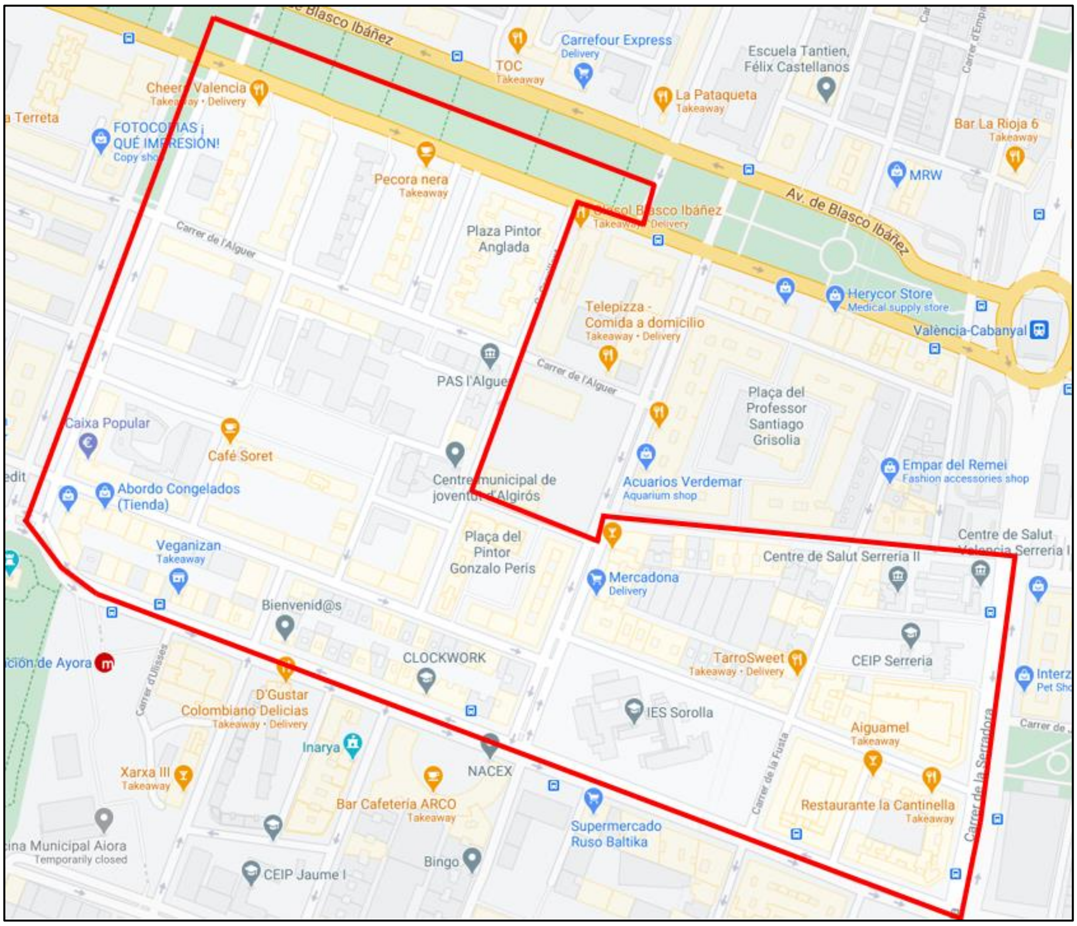


Figure 8 - Map of L'illa Perduda (outlined in red) taken from Google Maps [45]

With sustainability and energy efficiency improvements in mind, an assessment of the techno-economic feasibility of implementing a PEMFC-based CHP energy system in the neighbourhood was conducted. The feasibility study is a preliminary evaluation of the viability of installing the CHP-FCP system in parallel with existing energy supply infrastructure and is an essential phase prior to detailed design. It involved analysis of heat and power consumption data of the neighbourhood, provided by the TEU Chair, and subsequent construction and optimisation of an operating model to simulate possible energy system configurations.

4.2 Input Data

Detailed heat and power demand profiles are critical to accurately sizing a CHP system based on the unique requirements of a site. An accurate approach would be to construct hour-by-hour profiles over a whole year to fully represent both daily and seasonal variations in demand. This method, however, would consist of collecting demand data for a total of 8,760 consecutive hours and thus require extensive energy usage metering. Instead, the neighbourhood consumption data provided by the TEU Chair consisted of estimated annual thermal and electrical demand data which was manipulated into monthly demands. The thermal demand comprised contributions from space heating and domestic hot water (DHW), whereas the electrical demand consisted of air-conditioning (cooling), lighting, cooking and appliances. From the monthly data, 24-hour demand profiles for a typical weekday and weekend day in each month could then be determined which is deemed sufficient for modelling a prospective CHP system.

The data provided by the TEU Chair was compiled from the following two sources.

- ***Typology Approach for Building Stock Energy Assessment* (*TABULA)* project** [46] [47]**.**
  The purpose of the *TABULA* project, carried out by Intelligent Energy Europe (IEE) from 2009 to 2012, was to produce a harmonised database of energy usage for heating, cooling and DHW for different residential building classes in 13 European countries. The focus of the study was to collect energy usage data for a set of sample buildings to allow for energy classification assignment of respective buildings depending on their size, age and climate region, amongst other factors. This enabled standard references to be established to benefit further studies such as those for energy efficiency improvements.

- ***Analysis of the Energy Consumption in Spanish Households* (*SPAHOUSEC*) project** [48]**.**
  The *SPAHOUSEC* project is within the framework of the *Development of Detailed Statistics on Energy Consumption in Households* (*SECH*) project and was developed by the Institute for Energy Diversification and Savings (Instituto para la Diversificación y Ahorro de la Energía, or IDAE). The main focus of the project was to use an integrated, bottom-up approach to determine the consumption of the residential sector in Spain by combining various methods and data sources. This allowed for the lighting, cooking and appliance consumption contributions to be determined.

A detailed step-by-step methodology used to obtain the consumption of the neighbourhood for each month can be found in *Annex 5.*

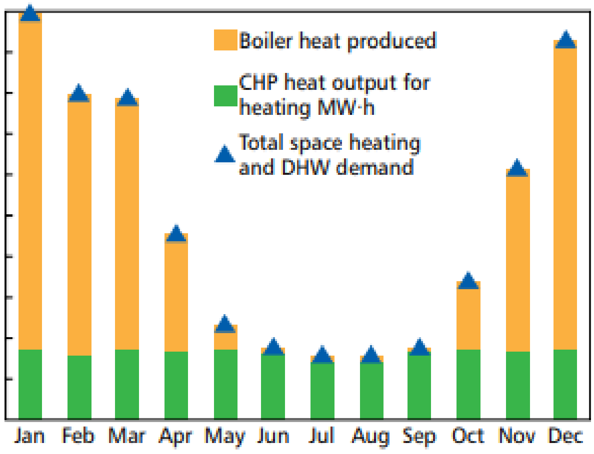
4.3 Use of Tools

The first stage of the study involved the use of *Excel* to transform the monthly neighbourhood consumption data into the 24-hour electrical and thermal energy demand profiles. This was achieved by considering typical occupancy patterns of a standard home (see *Annex 6* for the hourly percentage occupancy data used) and adjusting this to accommodate night hours whereby demand is expected to be reduced. To adjust the hourly percentage occupancy to an hourly percentage demand, data representing the average hours at which Spanish people are expected to be asleep, determined by the Spanish Sociological Research Centre (Centro de Investigaciones Sociológicas, CIS) [49], was used (see *Annex 7* for the CIS sleep data).

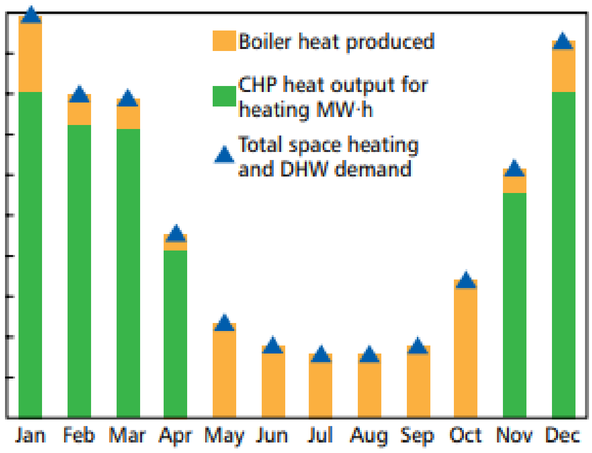
Once the daily demand profiles were determined, an operating model of the energy system was developed using the *HOMER Legacy v2.19* software. *HOMER* was originally developed at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and is a useful tool to evaluate designs for both off-grid and grid-connected power systems [50]. By selecting the appropriate components for the energy system - such as a *Generator* to model a fuel cell - and providing the model with demand, capacity, cost and resource inputs, energy balance calculations were simulated to assess technical and economic performance. Numerous optimisations were tested to analyse several feasible energy system configurations which were ranked by net present cost (NPC) over the project lifetime.

4.4 CHP Sizing Considerations

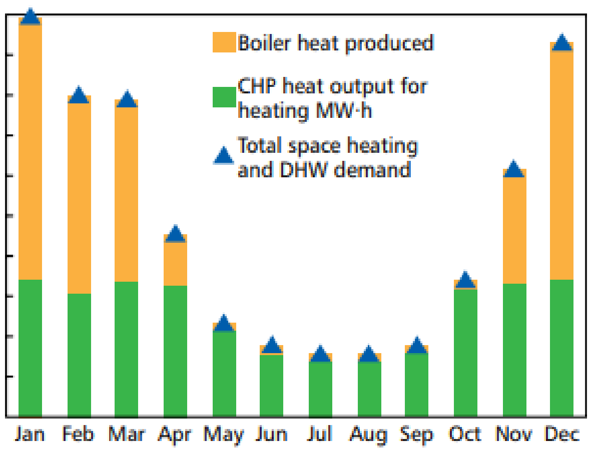
The Chartered Institution of Building Services Engineers (CIBSE), an international professional engineering association, have published a guidance document for the design and implementation of CHP systems for building applications [37]. The document describes methods of best practice for sizing and performing feasibility studies for prospective CHP installations, much of which influenced the methodology of the thesis. Using CHP can offer benefits of improved fuel efficiency and security of electricity supply, as well as reduced energy costs and environmental emissions [51]; however, sizing of CHP systems is a fine balancing act. For grid-connected installations, as surplus electricity can be sold, thermal demand is typically the limiting factor thus CHP systems for building applications are often sized based on heat demand. As building applications are characterised by significant daily and seasonal variations in demand, it is important that sizing is optimised to prevent under- or over-sizing. Undersized systems will provide a reduced supply and thus limit the above-mentioned benefits associated with CHP; however, running hours at full capacity will be maximised. On the other hand, oversized systems can result in excessive capital and energy costs and will lead to excessive heat dumping; therefore, it may be unfeasible to operate the CHP system during periods of low heat demand, such as in the summer. *Figure 9* provides a comparison of different CHP sizes for an arbitrary seasonal heat demand variation over a full year – it is generally optimal to size a CHP system to slightly above base heat load.



(a) CHP size too small



(b) CHP size too large



(c) CHP size that may be optimum

Figure 9 - Comparison of CHP sizes for a seasonal heat demand variation over a full year [37]

4.5 Summary of Feasibility Study Methodology

A summary of a typical approach to conduct a full feasibility study for a prospective CHP system is illustrated in *Figure 10.* It is important to note that due to limited data availability, such as sophisticated site and vendor cost data, the full method was not achievable. However, a preliminary techno-economic feasibility study (as indicated by the grey-highlighted boxes) was completed for the purpose of the thesis.

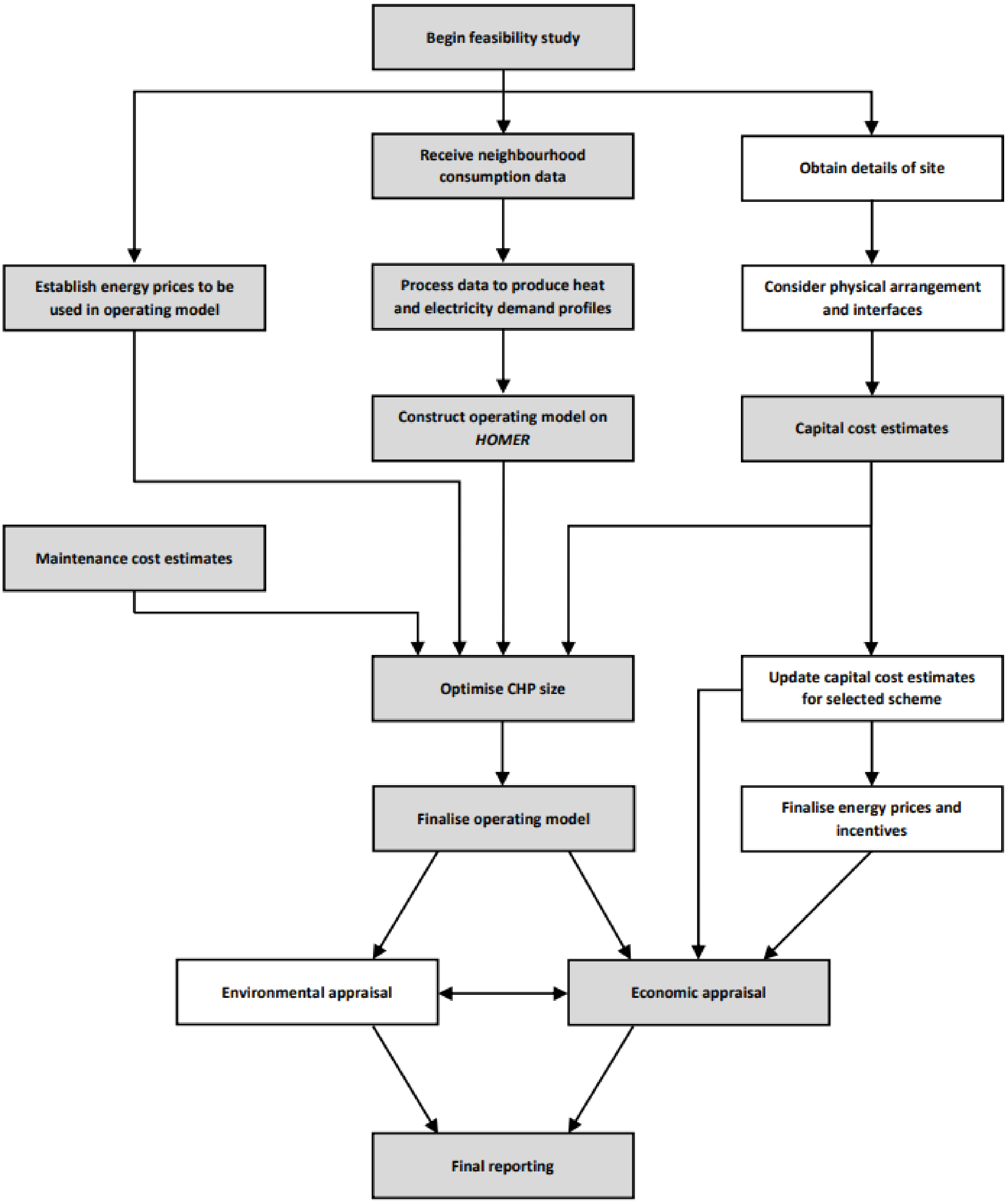


Figure 10 - Flowchart illustrating CHP feasibility study methodology (adapted from [37])

5 Design of the Energy System

5.1 Summary of Demand Variations

An understanding of the seasonal variation in demand is essential for optimal CHP sizing. As opposed to conventional electricity and heating systems which are designed to accommodate peak demands (which leads to variable part-load operation to achieve continuous capacity and demand matching [37]), it is typically beneficial for CHP installations to operate at full capacity over longer running hours. This is the reason that CHP is often sized to supply a load somewhat above base heat load, resulting in greater CHP utilisation and hence operational savings. In addition, initial capital spending can be reduced and, as heat demands are often overestimated and can decrease over a project lifetime due to energy efficiency improvements, potential CHP redundancy can be avoided [37]. To estimate the CHP capacity required to supply the neighbourhood, the peak hourly thermal and electrical demands for each month were determined; this is presented in *Figure 11*.

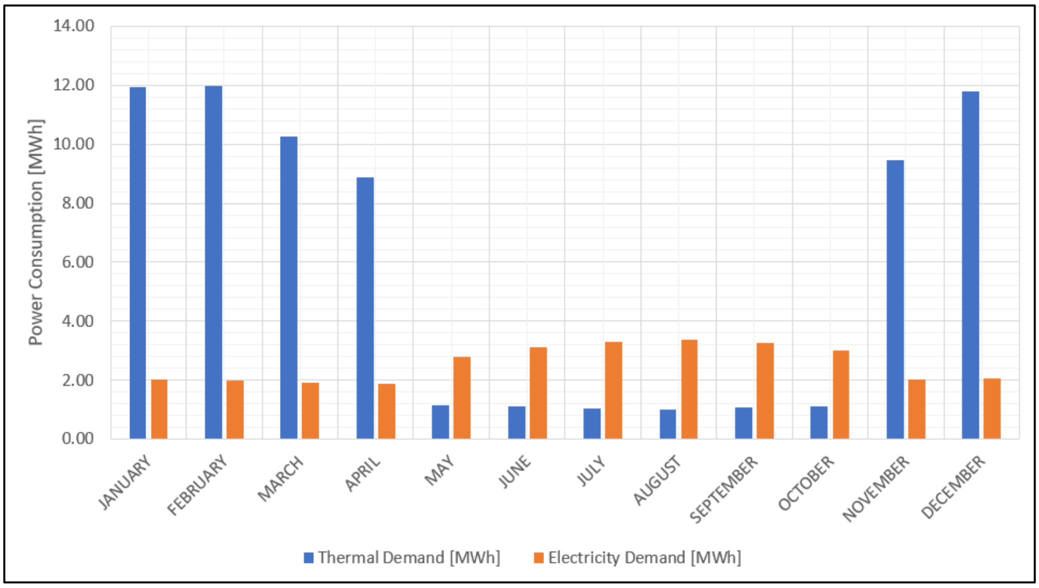


Figure 11 - Peak hourly thermal and electrical demands of L'illa Perduda for each month

A seasonal variation is observed, more significantly in thermal demand, with peak thermal and electrical demands determined to be 11.98 MWh_{th} in February and 3.37 MWh_{e} in August, respectively. In addition, the heat-to-power ratio, which provides an indication of the proportion of heat and power required to be generated to supply the neighbourhood, ranged from 6.02 and 0.30 between these months. To visualise the variation in demand on a 24-hour basis, hour-by-hour demand curves for a typical weekday and weekend day in February and August are provided in *Figure 12* and *Figure 13*, respectively. Both daily demands follow a similar pattern, with a low demand in the early hours of the morning which rises as occupants begin to wake up. During the day, there are fluctuations in demand which peaks in the mid-afternoon at around 3pm.

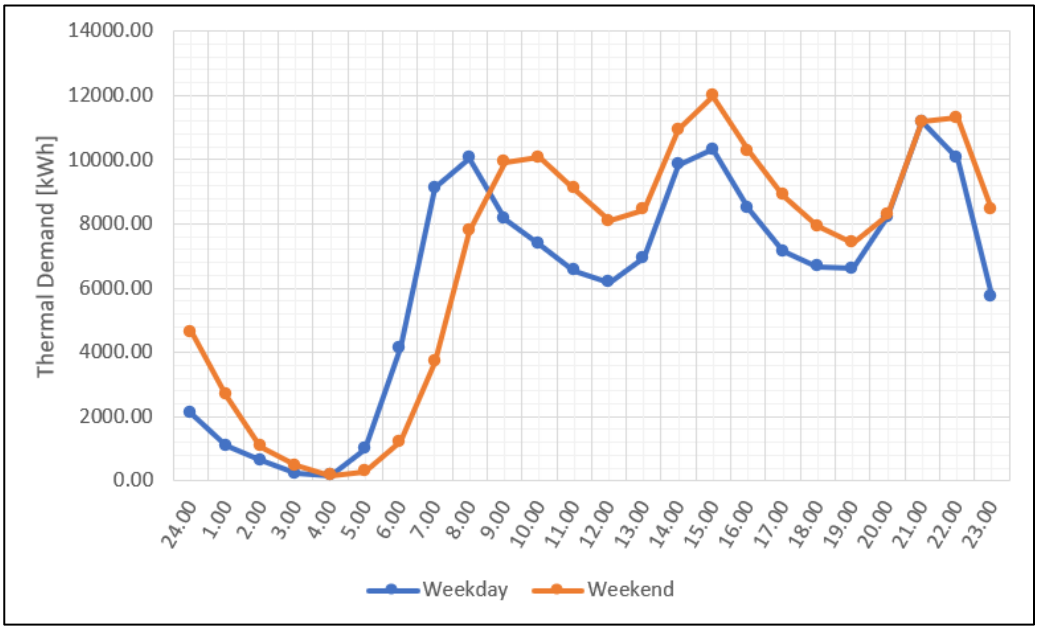


Figure 12 - Daily thermal demand curves for a typical weekday and weekend day in February

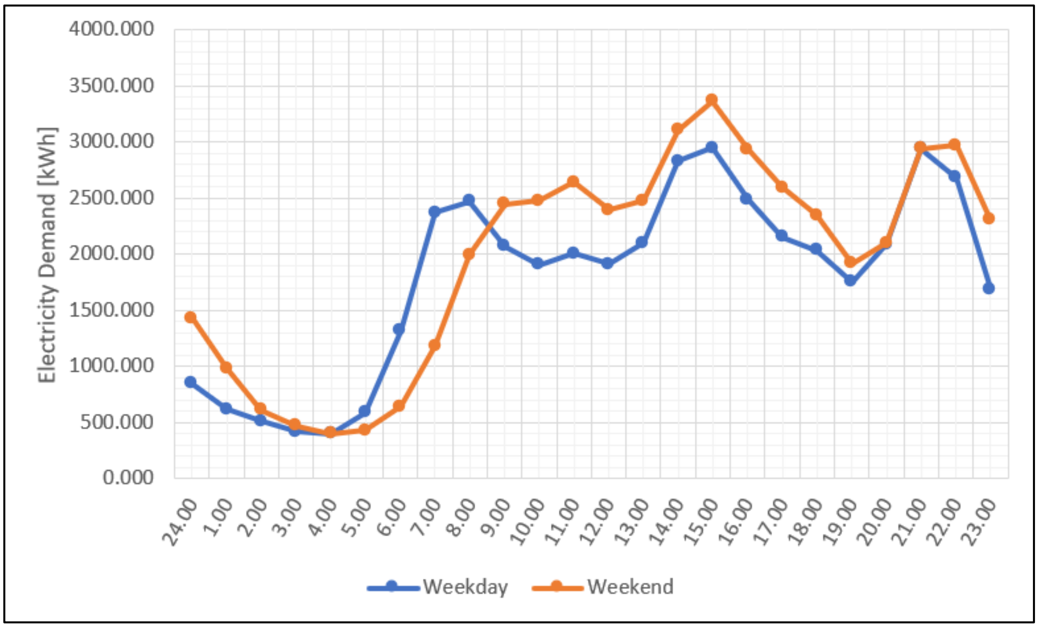


Figure 13 - Daily electrical demand curves for a typical weekday and weekend day in August

5.2 Evaluation of Suitable Commercial PEMFC Models

Research was conducted into several fuel cell suppliers to understand the variety of commercial PEMFC-based CHP models currently available on the market. The majority of suppliers were found to offer products with significantly smaller capacities than that required for the neighbourhood, ranging in values from around 0.01 to 500 kWe, with only a few in the MW range. To gain an understanding of the maximum available capacity, currently, the largest PEMFC power plant developed is 2 MW_e [52]; however, this size was not found to be sold commercially. Based on the MW requirement of the neighbourhood, the most suitable PEMFC-based CHP systems available were determined to be the 1.5

MW_e Gensure High Power Fuel Cell Generator by *Plug Power* [53] and the 1 MW_e PemGen CHP-FCPS-1000 by *Nedstack* [54]. It is important to note that both products require a pure hydrogen feed so an external reformer would have to be considered in the design of the system. The main specifications of the above-mentioned products are as follows (see *Annex 8 and Annex 9* for full specification sheets).

- ***Plug Power* - 1.5 MW_e Gensure High Power Fuel Cell Generator** [53]
  - Minimum Electrical Output Power (Cont.) = 0.15 MW_e
  - Maximum Electrical Output Power (Cont.) = 1.5 MW_e
  - Electrical Efficiency > 45%
  - Output Heat Load (max) = 2.25 MW_{th}
- ***Nedstack* – 1 MWe PemGen CHP-FCPS-1000** [54]
  - Nominal Power = 1 MW_e
  - Peak Power (BoL) = 1.252 MW_e
  - Recoverable Heat > 0.8 MW_{th}
  - Stack Refurbishment = 24k – 30k running hours

These systems can be purchased on a configure-to-order basis and be installed to integrate seamlessly with the existing supply infrastructure of the neighbourhood. To gain an understanding of the space and transport requirements, the 1 MWe PemGen CHP-FCPS-1000 model has the dimensions 12.19m x 2.44m x 2.90m (Length x Width x Height) and weighs 29,000 kg [54]. The overall system, including the fuel cell modules and BoP, is housed in a self-contained unit as illustrated in *Figure 14*.

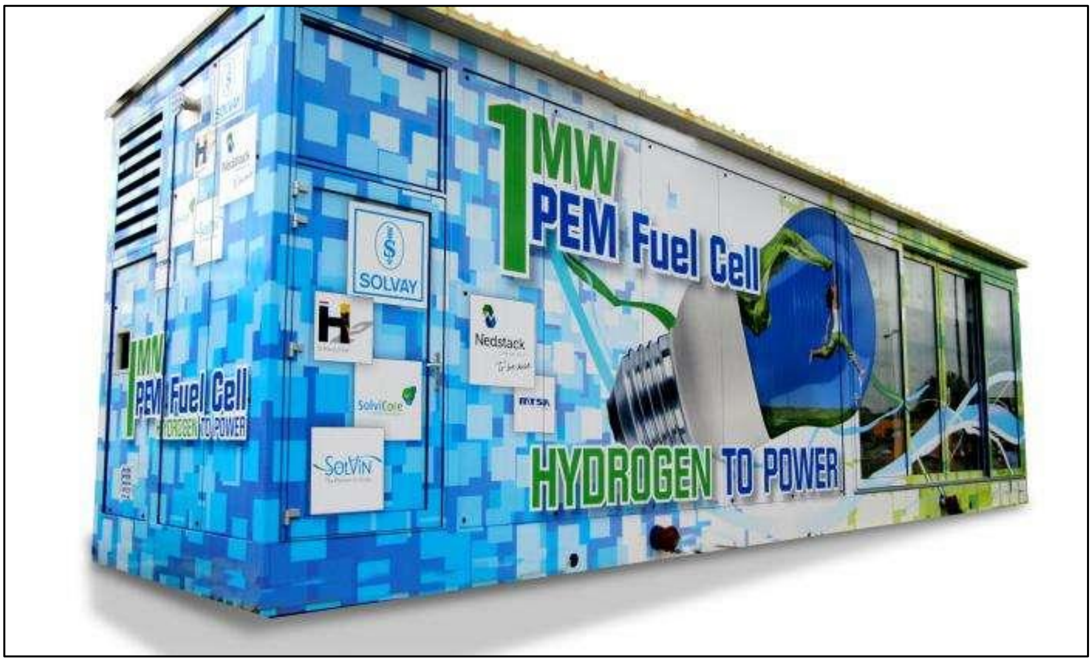


Figure 14 - Photograph of 1 MWe PemGen CHP-FCPS-1000 Model (Nedstack) [54]

5.3 HOMER Operating Model Construction

5.3.1 Component Selection

To construct the operating model, the appropriate components required for the design of the energy system in parallel with the electricity grid were selected. Input of the daily thermal and electrical demand data was also included within the model to set the load requirements of the neighbourhood (see *Annex 10* for the thermal and electrical load user input prompts). The annual average thermal and electrical loads required, as calculated on *HOMER*, were determined to be 75 MWh_{th}/d and 35 MWh_e/d, respectively. A schematic of the overall system is presented in *Figure 15*.

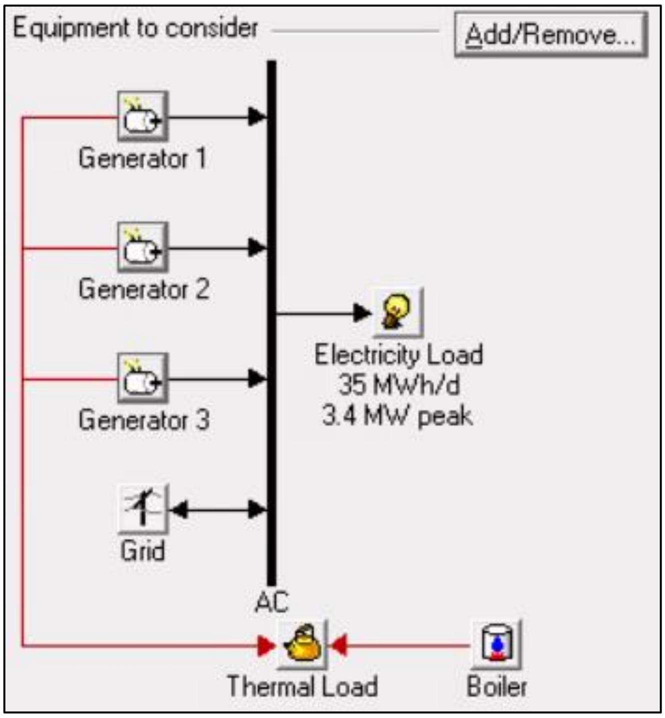


Figure 15 - HOMER grid-connected CHP-FCP power system operating model

Three *Generator* components were included within the operating model as this allowed for an assessment of whether or not more than one fuel cell is optimal for the application. According to CIBSE recommendations, implementing more than one CHP unit enables better load following and two different sized units offer the greatest flexibility [37]. Due to the low output heat capacity of a single unit relative to the peak thermal load of the neighbourhood, multiple units would also accommodate a greater demand and allow for better maintenance scheduling – they can provide a higher capacity in the winter months when heat demand is high, and then maintenance can be scheduled during summer months when demand is low. A data map (DMap) representing one year of time series data of the thermal and electrical load is provided in *Figure 16* and *Figure 17,* respectively (see *Annex 11* for average 24-hour thermal and electrical load profiles for each month). The DMaps allow for visualisation of the monthly (x-axis) and daily (y-axis) variations in demand as discussed in *Section 5.1*.

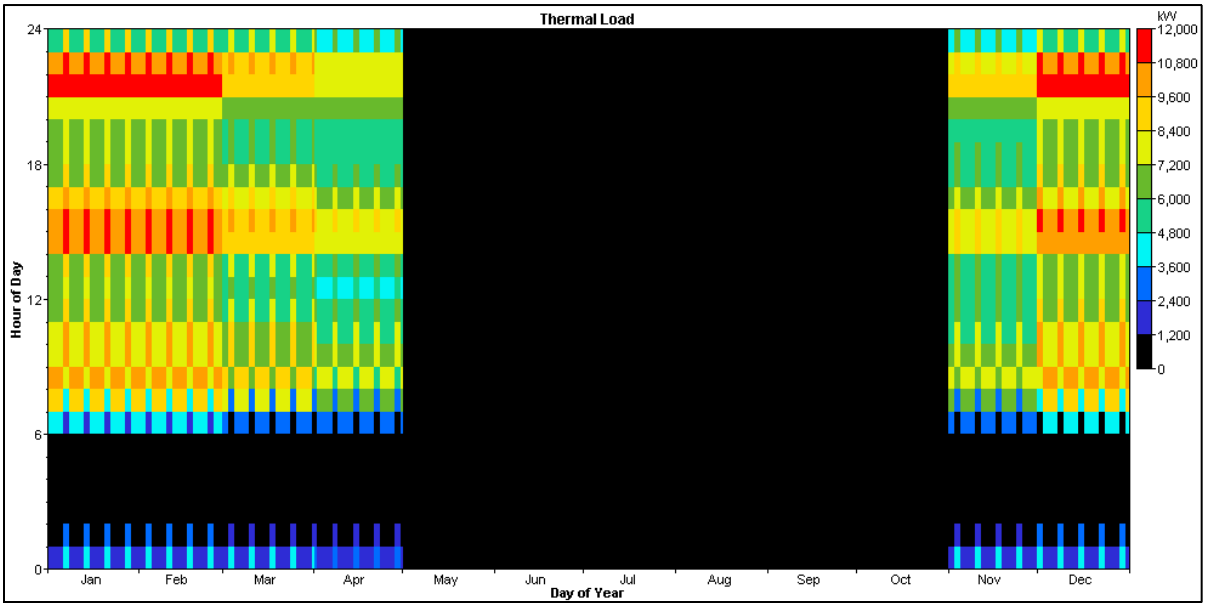


Figure 16 - Thermal demand DMap as generated on HOMER

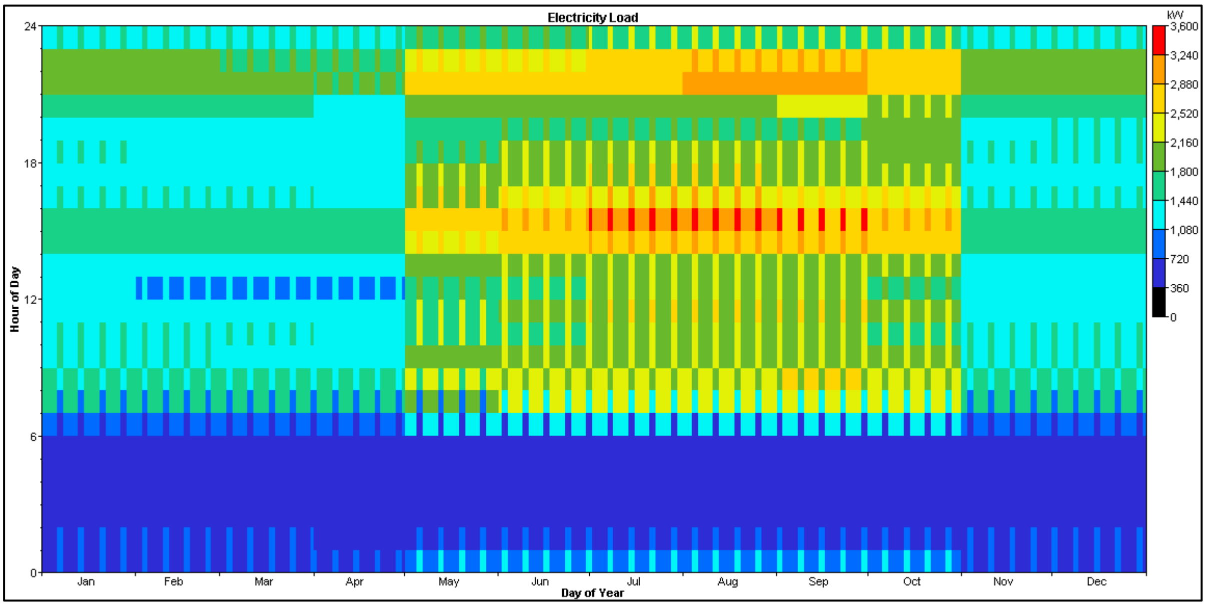


Figure 17 - Electrical demand DMap as generated on HOMER

5.3.2 Generator Inputs

By including the 0 MWe, 1 MWe and 1.5 MWe capacities into the 'Sizes to consider' input of the generators, it was possible for the simulation to determine the optimum configuration in relation to the commercial models researched. In order to simulate a cogeneration system, it was required to set the heat recovery ratio (HRR) of the generators to a non-zero value; however, it was discovered that *HOMER* could not explicitly model a system where an external reformer supplies a fuel cell with hydrogen [50]. Therefore, a sensitivity analysis was carried out to assess the HRR of the *Generator* components (ranging from 40% - 80%) that produced a fuel efficiency curve that represented the electrical and thermal output of the fuel cell and the natural gas fuel input to the reformer, based on the commercial specifications. A HRR of 75% was found to produce an output that most closely matched the specifications.

In terms of cost input, there is a lack of standard industry cost data of fuel cell-based CHP systems in literature; this is especially true for large-scale systems. Based on a paper which reviewed the cost of domestic fuel cell micro-CHP systems in 2015, a cost of $3000 – 5000 (around €2500 – 4200) for 1 – 2 kW_e systems was considered to be a reasonable cost target for 2020 [55]. In the same paper, it was also mentioned that a more ambitious cost target of $1000 (around €840) / kW_e by 2020 was set by the U.S. Department of Energy. By considering the more realistic figure of €2500 / kW_e and accounting for economies of scale, a capital cost assumption of €2,000,000 / MW_e was made for the initial simulation. In addition, as not all components of the CHP-FCP system will require replacement at the end of its lifetime, a replacement cost of 80% of the initial capital cost was assumed. The cost of operation and maintenance (O&M) was also taken to be $0.007 (€0.00589) / kWh [40].

To maximise operational savings, the generator schedules were set such that the systems would operate continuously year-round with downtime planned for summer months. According to CIBSE recommendations, planned and unplanned downtime should not exceed 400 hours each in an average year without a major overhaul [37]. In order to produce a conservative result, downtime for Generators 1, 2 and 3 were scheduled for the whole months of June, July and August, respectively. This would result in a total downtime of slightly above 700 hours for each generator and as an example, the generator schedule for Generator 1 is illustrated in *Figure 18*.

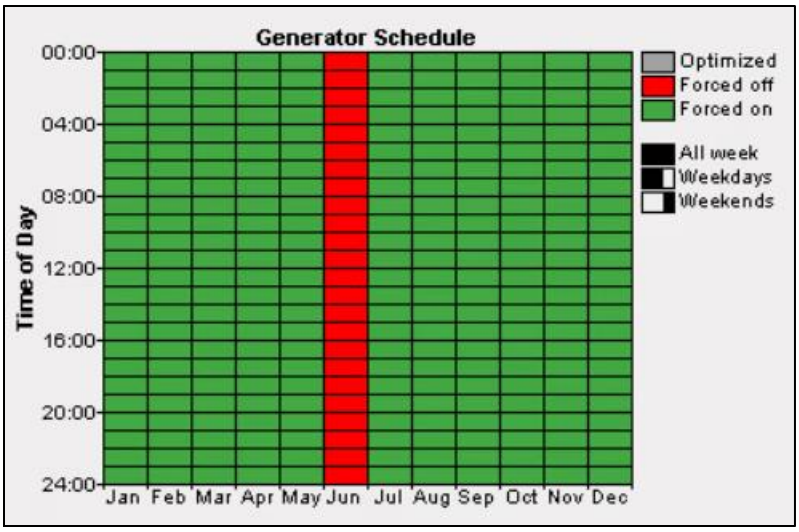


Figure 18 – Downtime schedule for Generator 1 on HOMER

Screenshots of the *Generator* user input prompts are provided in *Annex 12*. Please note that the $ unit for currency in *HOMER* is arbitrary and was used to represent euro values.

5.3.3 Grid Inputs

According to the recent Spanish Royal Decree-law 15/2018, Spain is now incentivising the decentralisation of electricity generation through promotion of self-consumption [56]. This involves compensating consumers for injecting surplus power back into the grid. To conduct a comparative study of the prospective grid-connected CHP-FCP configurations with the existing grid and boiler systems of the neighbourhood, cost inputs to account for electricity purchased from and sold to the grid was required. These inputs are described below.

- **Power cost.**
  The power cost, defined as the cost of buying power from the grid, was taken from data provided by Red Eléctrica de España, the operator of the Spanish electricity system. An average value from January 1 to December 31 2019 was taken from the operator's ESIOS website; this was calculated to be €110.40 / MWh (see *Annex 13* for the trend in power cost over the year) [57]. Data from 2019 was chosen as more recent values were not considered representative due to the current impacts of the COVID-19 pandemic.

- **Sellback price.**
  The sellback price, defined as the price of compensation for consumers who feed surplus power into the grid, was also taken from the ESIOS website over the same time period. Under the self-consumption model in Spain, this is also referred to as the 'Voluntary Price for Small Consumers' (Precio Voluntario para Pequeños Consumidores, or PVPC) and an average value of €45.09 / MWh was determined (also see *Annex 13* for the trend in PVPC) [57].

- **Demand cost.**
  The demand cost, defined as the monthly fee charged by the electricity system operator based on the monthly peak demand, was taken from the *2021 Regulated Energy Price Report* produced by IDAE [58]. A value of €38.04 / kW / year was taken and converted into a monthly rate of €3.17 / kW / month.

An electricity tax of 5.11% and VAT of 21% was added to all of the above-mentioned costs [59]. As is the case for the majority of residential consumers, a single grid rate was considered for the simulation; a summary of the grid inputs can be found in *Figure 19*. In addition to these inputs, the maximum grid demand and maximum power sale (the maximum capacity that can be drawn from or sold to the grid in each one-hour time step, respectively) were set to large values (99,999 kW) to avoid restriction of grid power purchase/sale.

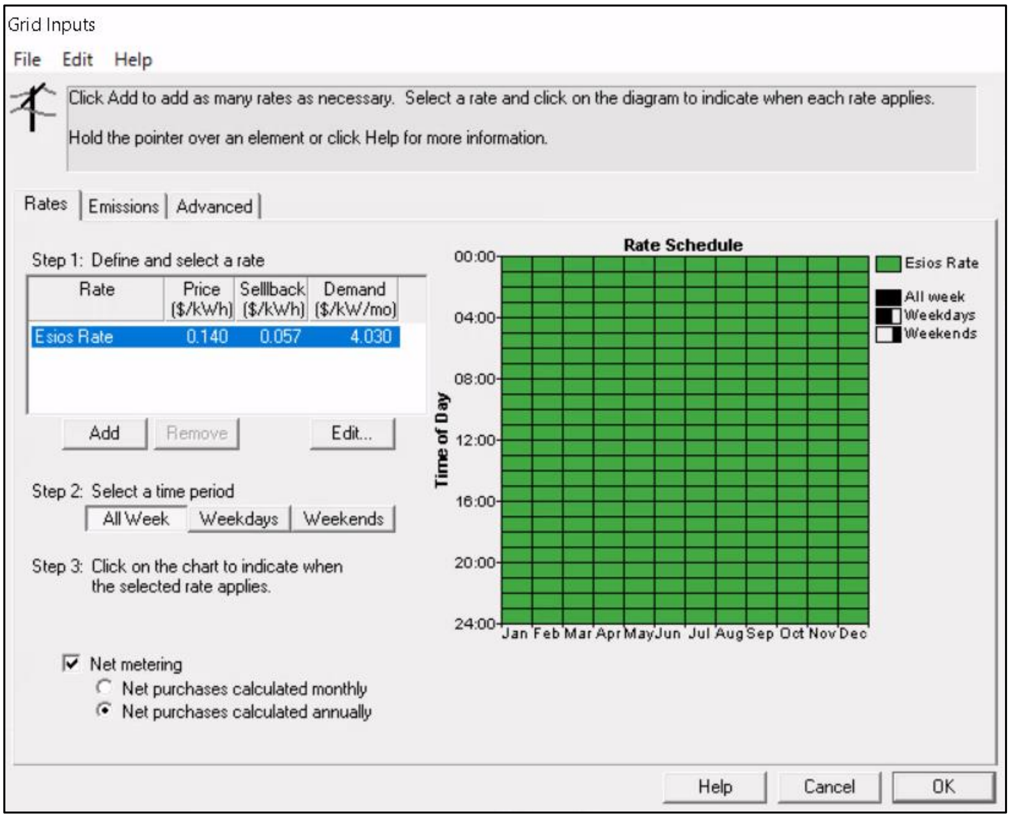


Figure 19 - HOMER grid input prompt

5.3.4 Cost of Natural Gas

The cost of natural gas in Spain varies depending on negotiation between a gas supplier and customer; the ability for a consumer to freely choose and make agreements with a natural gas supplier offers competitive prices. Rates consist of a fixed cost and a variable (consumption) cost which sum together to set a price per kilowatt hour, which in Spain ranges from €0.036 – 0.060 / kWh [58]. The fixed tariff depends on the volume of natural gas required, with potential savings for increased volumes due to economies of scale. For input into the *HOMER* simulation, however, a cost per m^3 was required which was calculated based on the natural gas fuel properties as described in *Figure 20*. Following conversion, the range in natural gas costs was determined to be €0.356 – 0.593 / m^3. To produce a conservative result, €0.59 / m^3 was selected for the initial simulation.

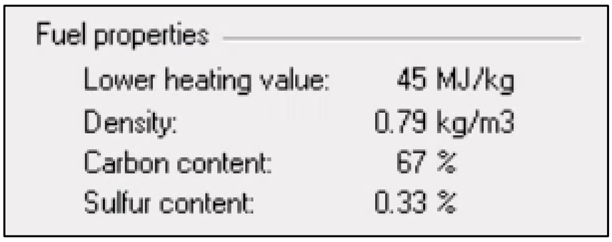


Figure 20 - HOMER natural gas fuel properties

6 Conclusions

This document presented a comprehensive literature review of fuel cells and, in particular, an in-depth discussion of PEMFC technology, with a focus on its application in the domestic built environment. Research suggests that fuel cell technology offers several advantages over conventional systems - due to their clean, efficient and versatile nature - and that PEMFCs are a key focus of interest for widespread implementation in the CHP market. The ability to produce electricity and heat using highly efficient decentralised units can offer the benefits of energy security, flexibility and reduced emissions. However, further research and development is still required to fully commercialise fuel cells as, although the concept of a fuel cell was first discovered in 1839, many technical barriers have hindered its maturity.

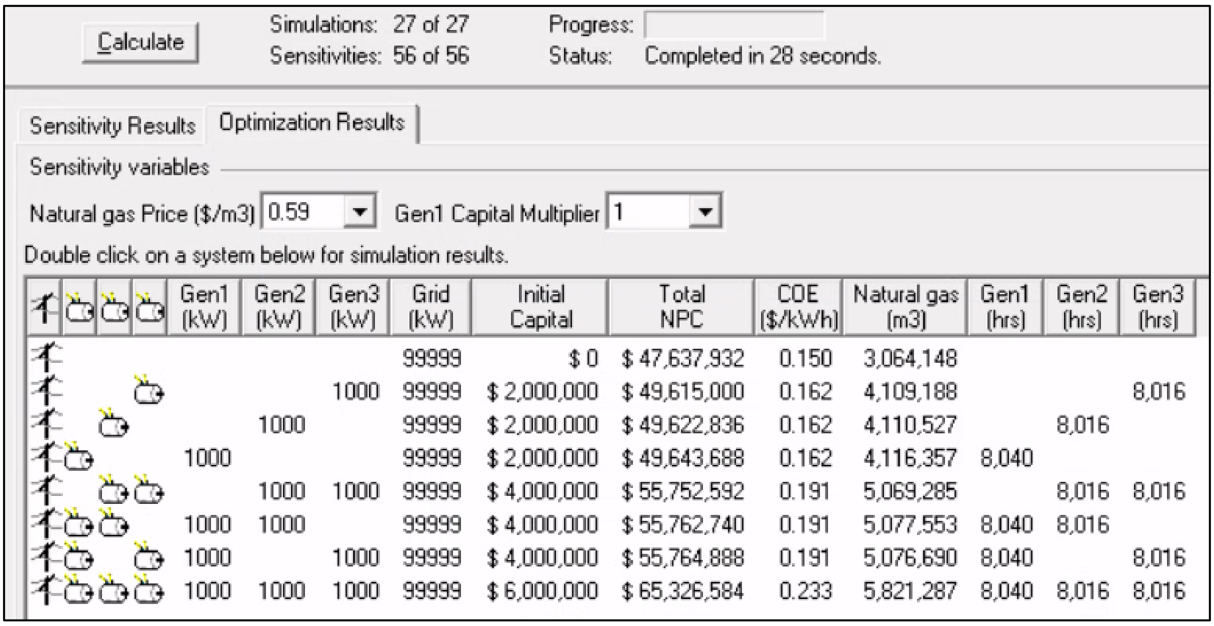
An operating model was constructed on *HOMER* to simulate the supply of the neighbourhood using grid-connected PEMFC cogeneration systems, based on the specifications of commercial models. There was limited information of commercial PEMFC systems that provide a MW capacity in literature; however, a 1 MW_e system by Nedstack and a 1.5 MW_e system by Plug Power were identified to be potentially suitable for the application. As an initial 'best estimate', a capital cost assumption of €2,000,000 / MW_e and a natural gas cost of €0.59 / m^3 was used as the basis of the simulation. These values, however, were chosen to produce a conservative result due to uncertainty in true fuel cell and natural gas costs. By contacting suppliers, a full economic appraisal should be carried out prior to project commissioning to determine the techno-economic viability of the project more accurately.

DOCUMENT II: Techno-economic Analysis

7 Techno-economic Analysis

7.1 Techno-economic Overview of Simulated CHP-FCP Systems

Based on the inputs of the simulation, all feasible system configurations were determined and displayed in tabular format ranked according to NPC, as shown in *Figure 21*. The NPC of each simulation – defined as the present value of all the costs of installing and operating the system minus the present value of all the revenues earned over the project lifecycle [50] - was calculated over a 25-year project lifetime and an annual discount rate of 6%.



Gen1 (kW)	Gen2 (kW)	Gen3 (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Natural gas (m3)	Gen1 (hrs)	Gen2 (hrs)	Gen3 (hrs)
			99999	$ 0	$ 47,637,932	0.150	3,064,148			
		1000	99999	$ 2,000,000	$ 49,615,000	0.162	4,109,188			8,016
	1000		99999	$ 2,000,000	$ 49,622,836	0.162	4,110,527		8,016	
1000			99999	$ 2,000,000	$ 49,643,688	0.162	4,116,357	8,040		
	1000	1000	99999	$ 4,000,000	$ 55,752,592	0.191	5,069,285		8,016	8,016
1000	1000		99999	$ 4,000,000	$ 55,762,740	0.191	5,077,553	8,040	8,016	
1000		1000	99999	$ 4,000,000	$ 55,764,888	0.191	5,076,690	8,040		8,016
1000	1000	1000	99999	$ 6,000,000	$ 65,326,584	0.233	5,821,287	8,040	8,016	8,016

Figure 21 - Feasible energy system configurations simulated on HOMER

The number and type of components for each simulation are indicated by columns 1 - 4, followed by the respective capacities of each component in columns 5 – 8. For example, the second most optimal configuration simulated (row 2) consists of grid-connection with one 1 MWe CHP-FCP system (*Generator 3)*. In addition to NPC, the levelised cost of energy (LCOE) was another economic indicator provided for each optimised result, defined as the average cost per kWh (€/kWh) of useful electrical energy produced [50]. Based on the inputs of the simulation, the existing grid-electric and boiler infrastructure (row 1) was determined to be the most economical option to supply the neighbourhood despite no additional capital spend. However, as an example, the results of the most optimal configuration that incorporates the use of a fuel cell (row 2) are summarised in the following sub-sections. Details of the operation of the fuel cell generator can be found in *Annex 14.*

7.1.1 Production and Consumption of Thermal and Electrical Energy

As can be observed in *Figure 22*, the configuration is heavily reliant on the existing boiler system to serve the thermal load; annually, 75% of the load is met by boilers whilst only 25% is met by the CHP-FCP system. By considering the relatively low thermal output of the 1 MW_e CHP-FCP system (> 0.8 MW_{th} for Nedstack's PemGen CHP-FCPS-1000 model as described in *Section 5.2*) in comparison to the monthly average neighbourhood load, this result is as expected. During the summer months, however, the CHP-FCP system is able to serve the majority of the thermal load, with the exception of August when maintenance is scheduled.

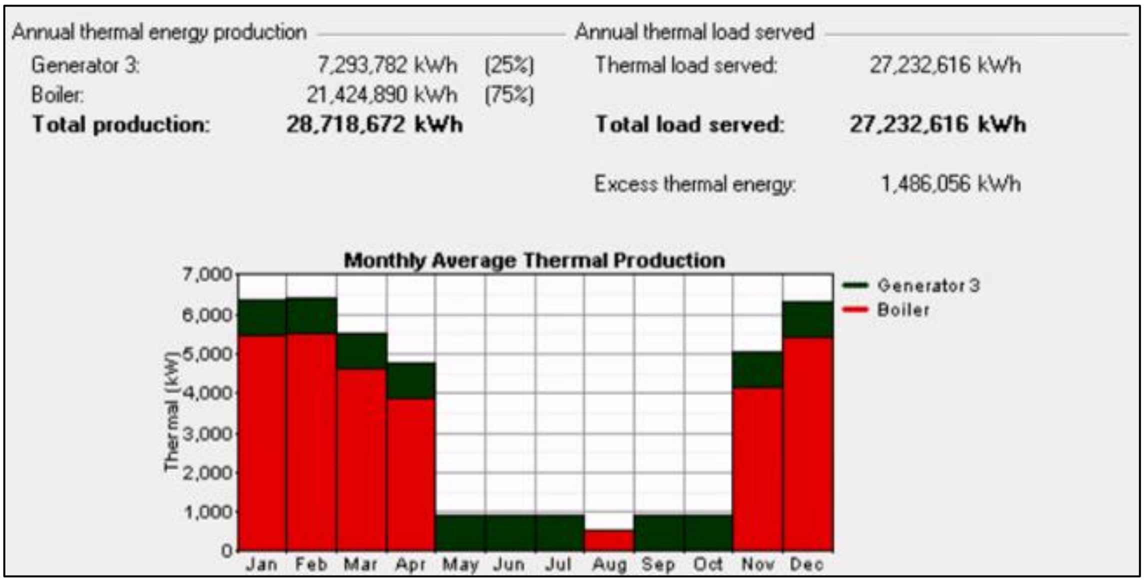


Figure 22 - HOMER results for the production and consumption of thermal energy

A similar result can be observed in *Figure 23* for the production and consumption of electricity; though, the CHP-FCP system is found to contribute a greater capacity (55%) than the grid (45%).

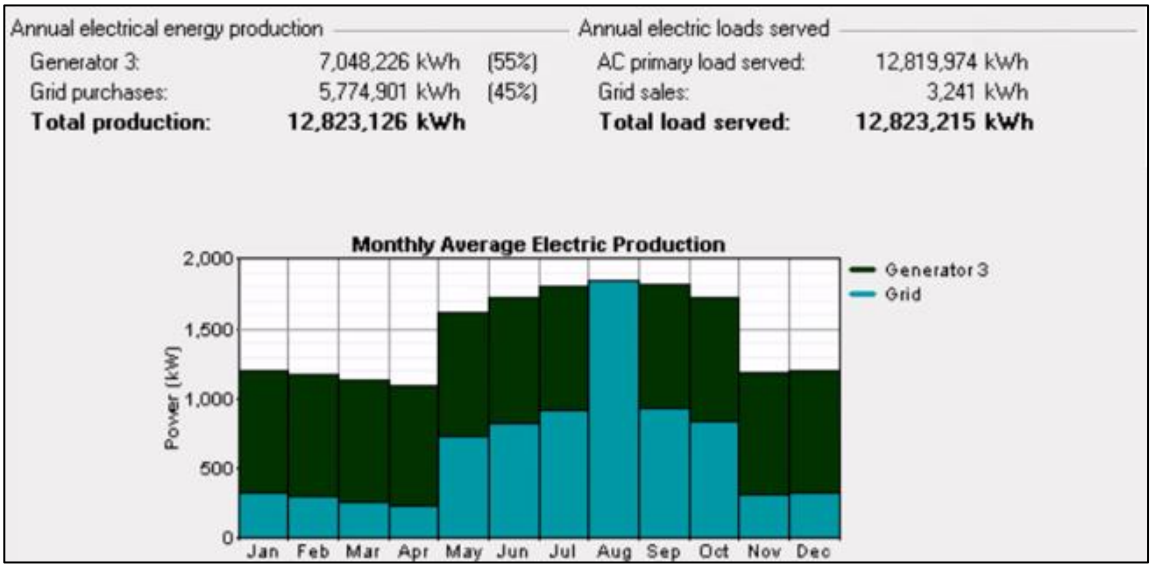


Figure 23 - HOMER results for the production and consumption of electricity

7.1.2 Grid Purchases and Sales

The monthly grid purchases and sales are summarised in *Table 3*. As shown in column 3, a negligible amount of surplus electricity is generated due to the relatively low electrical output of the CHP-FCP system in comparison to the electrical load of the neighbourhood. This suggests that little revenue to reduce the NPC is generated when implementing this configuration. The peak grid demand for each month is also provided, as well as the charges based on the grid inputs as described in *Section 5.3.3.*

Table 3 - HOMER results for grid purchases and sales (grid-connected fuel cell system)

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	240,395	437	239,958	1,040	0	4,191
Feb	200,185	435	199,749	991	0	3,992
Mar	198,177	543	197,634	923	0	3,719
Apr	167,643	582	167,062	861	0	3,470
May	545,912	161	545,751	1,804	0	7,268
Jun	598,158	97	598,061	2,118	0	8,537
Jul	684,182	44	684,137	2,310	0	9,310
Aug	1,369,696	0	1,369,696	3,367	0	13,567
Sep	671,347	18	671,330	2,248	0	9,058
Oct	624,360	63	624,298	2,012	0	8,108
Nov	227,265	443	226,822	1,018	0	4,103
Dec	247,580	419	247,161	1,060	0	4,272
Annual	5,774,901	3,241	5,771,659	3,367	808,032	79,596

To provide a comparison, the grid results for the most optimal configuration, which involves the grid providing the full capacity required to serve the electrical load, is provided in *Table 4*.

Table 4 - HOMER results for grid purchases and sales (grid only system)

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	889,463	0	889,463	2,040	0	8,221
Feb	785,261	0	785,261	1,991	0	8,022
Mar	843,616	0	843,616	1,923	0	7,749
Apr	790,492	0	790,492	1,861	0	7,500
May	1,204,576	0	1,204,576	2,804	0	11,298
Jun	1,237,742	0	1,237,742	3,118	0	12,567
Jul	1,346,943	0	1,346,943	3,310	0	13,340
Aug	1,369,696	0	1,369,696	3,367	0	13,567
Sep	1,313,807	0	1,313,807	3,248	0	13,088
Oct	1,286,333	0	1,286,333	3,012	0	12,138
Nov	854,836	0	854,836	2,018	0	8,133
Dec	897,132	0	897,132	2,060	0	8,302
Annual	12,819,898	0	12,819,898	3,367	1,794,786	123,926

7.2 Sensitivity Analyses

A number of sensitivity analyses were conducted to assess the effect of changing the natural gas and fuel cell costs on the NPC and LCOE, as shown in *Figure 24* and *Figure 25.* As previously described, the initial 'best estimate' simulation consisted of fuel cell capital and replacement costs of €2,000,000 / MW_e and €1,600,000 / MW_e (80% of the capital cost), respectively. A sensitivity link of these costs was made - meaning that if the capital cost was reduced by a certain percentage, then the replacement cost would reduce by the same amount - and several sensitivity values were assessed over a multiplier range of 0.4 – 1.0. This range was chosen to assess the change in economics when considering fuel cell cost reductions in alignment with the ~€840 / kW_e capital cost target set by the U.S. Department of Energy, as described in *Section 5.3.2.* In addition, the cost of natural gas was varied from €0.36 – 0.59 / m^3 to assess the effect in economics according to the different natural gas prices in Spain.

In both cases, the relative steepness of the two curves suggests that the NPC and LCOE are more sensitive to the price of natural gas in comparison to fuel cell costs. By first analysing the sensitivity in natural gas cost (as indicated by the blue line in each figure), at a constant fuel cell capital and replacement cost multiplier of 1.0, the NPC and LCOE both reduce at a constant gradient until a natural gas cost reduction from €0.59 / m^3 to €0.48 / m^3 is achieved. This is representative of cost savings for the most optimal (existing grid-electric and boiler system) configuration. After this point, the steepness of the curve increases (more evidently in *Figure 25*) and remains at a constant gradient from €0.48 / m^3 to €0.40 / m^3 as the one 1 MWe CHP-FCP system, as described previously, becomes most economically favourable. Beyond this point, the curve steepens again which is representative of a grid-connected configuration with a single 1.5 MW_e CHP-FCP system being optimal.

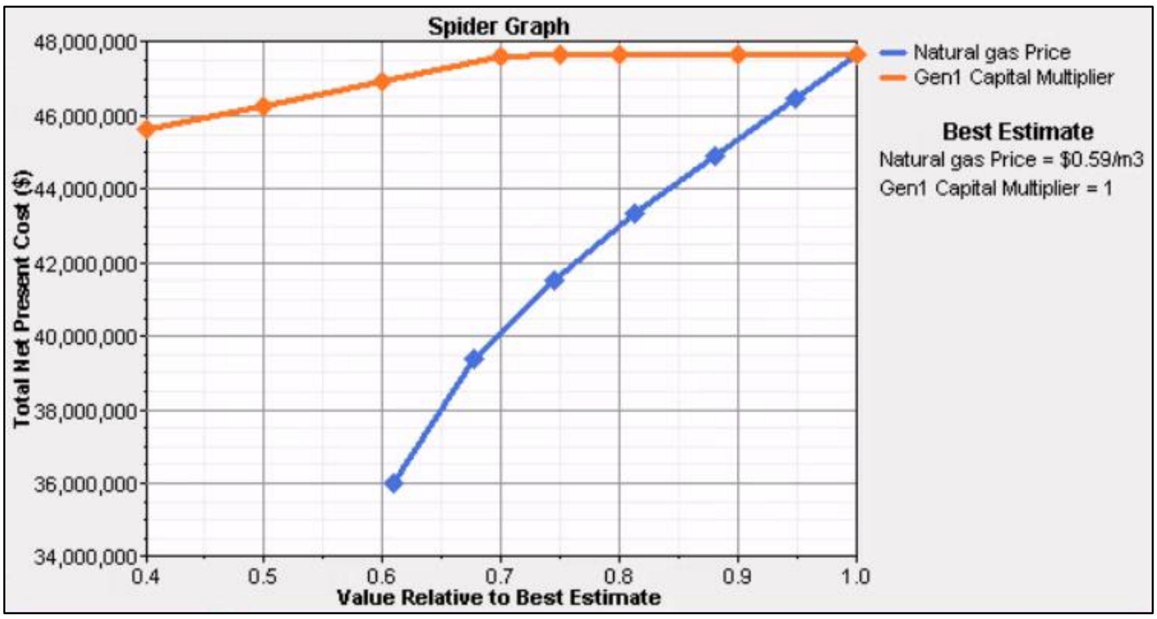


Figure 24 - Spider graph showing the effect of changing natural gas and fuel cell costs on NPC

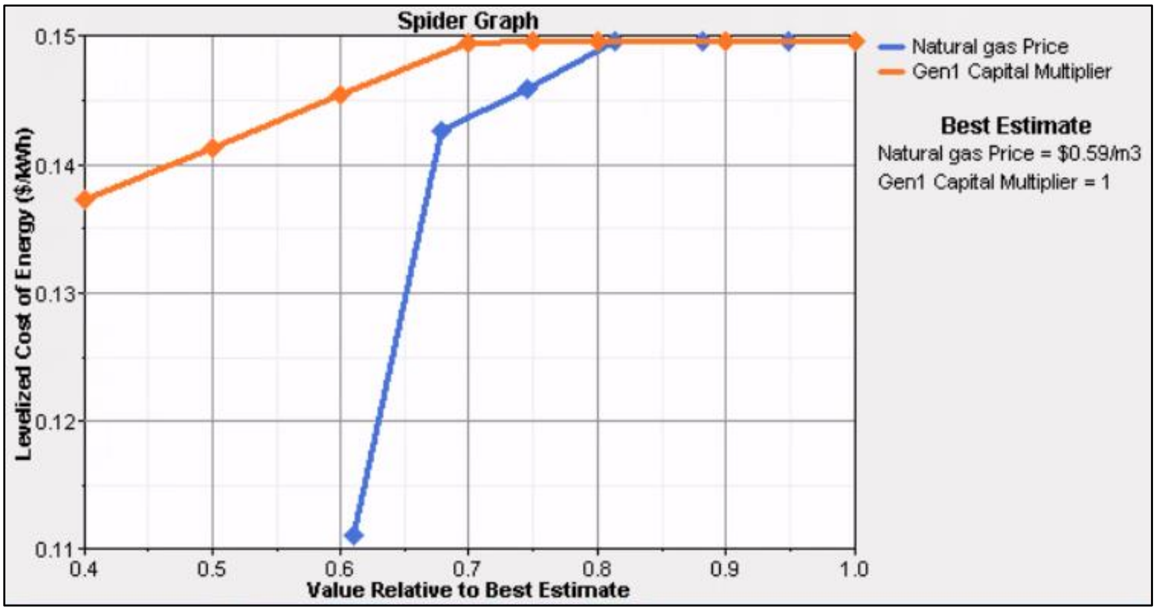


Figure 25 - Spider graph showing the effect of changing natural gas and fuel cell costs on LCOE

In terms of the sensitivity in fuel cell cost (as indicated by the orange line in each figure), there is only one transition with regards to a change in optimal configuration. As can be observed by the plateau in both NPC and LCOE over the multiplier range from 1.0 to 0.7 (cost reductions down to €1,400,000 / MW_e capital and €1,120,000 / MW_e replacement), at a natural gas cost of €0.59 / m^3, the single 1 MW_e CHP-FCP configuration will only become economically favourable when this cost reduction is achieved. This can be observed in *Figure 26;* further cost reductions reduce the NPC and LCOE for each system without affecting the ordering of the most optimal configurations.

Calculate | Simulations: 27 of 27 | Sensitivities: 56 of 56 | Progress: | Status: Completed in 28 seconds.

Sensitivity Results | Optimization Results

Sensitivity variables

Natural gas Price ($/m3) 0.59 | Gen1 Capital Multiplier 0.7

Double click on a system below for simulation results.

Gen1 (kW)	Gen2 (kW)	Gen3 (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Natural gas (m3)	Gen1 (hrs)	Gen2 (hrs)	Gen3 (hrs)
		1000	99999	$ 1,400,000	$ 47,613,300	0.149	4,109,188			8,016
	1000		99999	$ 1,400,000	$ 47,621,132	0.150	4,110,527		8,016	
1000			99999	$ 1,400,000	$ 47,637,048	0.150	4,116,357	8,040		
			99999	$ 0	$ 47,637,932	0.150	3,064,148			
	1000	1000	99999	$ 2,800,000	$ 51,749,184	0.168	5,069,285		8,016	8,016
1000	1000		99999	$ 2,800,000	$ 51,754,400	0.168	5,077,553	8,040	8,016	
1000		1000	99999	$ 2,800,000	$ 51,756,544	0.168	5,076,690	8,040		8,016
1000	1000	1000	99999	$ 4,200,000	$ 59,316,540	0.200	5,821,287	8,040	8,016	8,016

Figure 26 - Feasible system configurations (capital/replacement cost reduction multiplier of 0.7)

A summary of the sensitivity analysis results, illustrating the most optimal system configurations over a range of natural gas and fuel cell costs, is provided in *Figure 27*. The diamonds in the graph represent the 56 different sensitivity cases simulated and the colour of each diamond indicates the optimal system configuration for each. To provide examples, a summary of the results for a number of sensitivity cases (labelled A – F in *Figure 27*) is also provided in *Table 5.*

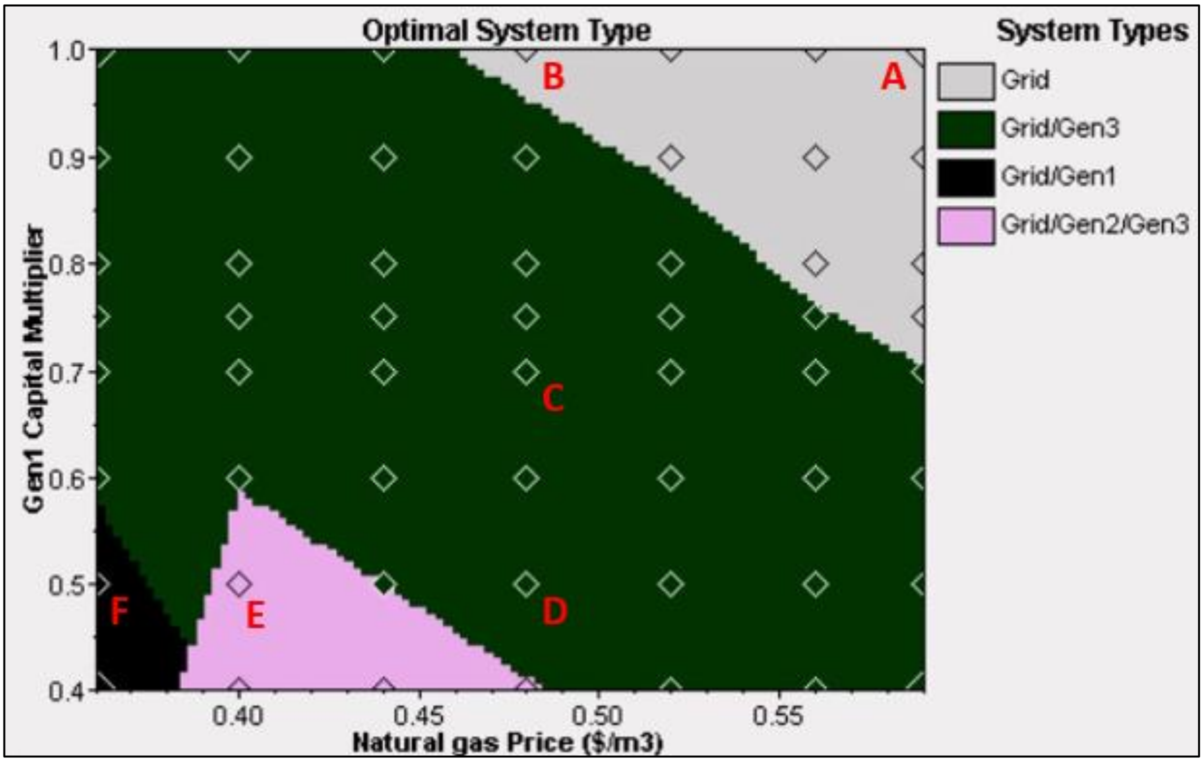


Figure 27 - Graph of optimal system configurations based on sensitivity results

Table 5 - Summary of optimal system configurations for example sensitivity cases A - F

Sensitivity Case	Fuel Cell Cost [€ / MW_e] (Multiplier)	Natural Gas Price [€ / m^3]	Optimal System Type	Initial Capital [€]	Total NPC [€]	COE [€ / kWh]
A	2,000,000 (1.0)	0.59	Grid	0	47,637,932	0.150
B	2,000,000 (1.0)	0.48	Grid	0	43,329,220	0.150
C	1,400,000 (0.7)	0.48	Grid / Gen3 (1 MW_e)	1,400,000	41,618,588	0.137
D	1,000,000 (0.5)	0.48	Grid / Gen3 (1.5 MW_e)	1,500,000	40,045,340	0.121
E	1,000,000 (0.5)	0.40	Grid / Gen2 (1 MW_e) / Gen3 (1MW_e)	2,000,000	34,915,888	0.097
F	1,000,000 (0.5)	0.36	Grid / Gen1 (1.5 MW_e)	1,500,000	30,978,432	0.086

8 Discussion

HOMER was used to analyse the techno-economic performance of prospective PEMFC-based CHP systems to augment the existing grid-electric and boiler supply of the L'illa Perduda neighbourhood. Based on the inputs of the simulation, only a small difference in NPC (calculated over a 25-year project lifetime) and LCOE was determined when considering a 1 MW_e grid-connected CHP-FCP system in comparison to the existing infrastructure of the neighbourhood. As can be seen in *Figure 21*, the NPC of the existing infrastructure and 1 MW_e CHP-FCP configurations were determined to be €47,637,932 and €49,615,000, respectively, which represents a 4.2% increase. In addition, the LCOE was found to increase by 8.0% from €0.150 / kWh to €0.162 / kWh. In alignment with research which suggests that fuel cells are only recently becoming competitive with conventional systems, this result is comparable.

The analysis was based on conservative estimates of key parameters, such as fuel cell and natural gas prices, so an assessment based on true costs may suggest that the project is feasible. To improve the robustness of the study, a sensitivity analysis was conducted to evaluate the impact of the results across a range of uncertainty in the above-mentioned parameters. As shown in *Figure 24* and *Figure 25*, the cost of natural gas was identified to have a more significant impact on both the NPC and LCOE, with the 1 MW_e CHP-FCP becoming economically feasible at a natural gas cost of €0.48 / m^3 in comparison to the €0.59 / m^3 'best estimate' (assuming a €2,000,000 / MW_e fuel cell cost). Therefore, price agreements with natural gas suppliers prior to project commissioning should greatly influence investment decisions. Fuel cell cost reductions also improve the economics; however, as the cost of CHP-FCP systems are largely pre-determined by suppliers based on current competitive climates, a large industry effort will be required to offer better prices. A sensitivity analysis of varying CHP-FCP generator lifetimes and O&M costs can also benefit further studies.

The results of the sensitivity analysis indicate that, even with cost reductions, the most optimal configurations involving a CHP-FCP system mainly consist of a single unit. As can be seen in *Figure 22*, however, due to the relatively higher demand of the neighbourhood, a single unit can only provide a limited thermal capacity. By considering CIBSE recommendations of sizing CHP systems based on heat demand, as detailed in *Section 4.4,* this highlights a limitation of *HOMER;* the simulation evaluates the configurations with the best economics with a priority of serving the electrical load over the thermal load. Therefore, despite specifying the option to utilise multiple CHP-FCP units which could offer greater thermal capacities, due to an inability to set these desired generator controls, the simulation results favour configurations in which grid utilisation is maximised. As a result, negligible surplus electricity is generated as indicated in *Table 3*.

To improve the study, an assessment of the implementation of multiple units can be conducted by restricting the maximum grid demand such that the priority of the CHP-FCP systems is increased. This, however, would not be fully representative of the desired system but it could provide a comparative study of the estimated costs when utilising more than one unit. In addition to the benefits of greater load-following and maintenance flexibility, the strategic positioning of multiple units in different locations of the neighbourhood can optimise energy distribution. Although, this would require an in-depth analysis of the compatibility of installing the prospective CHP-FCP systems with the existing heat and power infrastructure of the neighbourhood. Future changes in demand should also be considered, especially the possibility of reductions, as changing occupancy patterns and building thermal efficiency improvements over the project lifetime can impact the techno-economics.

9 Conclusions

The main objective of the thesis was to provide a techno-economic analysis of implementing a natural gas-fed, PEMFC-based energy system to augment the supply of energy to the L'illa Perduda neighbourhood in Valencia, Spain. By conducting an analysis of the thermal and electrical demand of the neighbourhood, daily and seasonal variations in demand were identified characteristic of a range of factors such as varying occupancy patterns and outdoor temperatures. Peak thermal and electrical demands were determined to be 11.98 MWh_{th} in February and 3.37 MWh_{e} in August, respectively.

It can be concluded that, based on the initial inputs to the *HOMER* simulation, the existing infrastructure was deemed most economically feasible in terms of NPC and LCOE; however, the implementation of a 1 MW_{e} CHP-FCP system was not far off. Despite an additional €2,000,000 capital investment for the 1 MW_{e} system, only a small increase in NPC and LCOE was observed at 4.2% and 8.0%, respectively. Based on sensitivity analysis results, however, reductions in fuel cell costs and, more significantly, the cost of natural gas can impact the economics and make the implementation of CHP-FCP feasible.

Given the uncertainty of CHP-FCP costs, it is recommended that a full economic appraisal is conducted by contacting suppliers and receiving accurate cost data to fully evaluate the viability of the project. Further details regarding specific site arrangements and potential subsidies and incentives will also benefit the study. In addition, a comparative study into the environmental impact of the existing infrastructure and the prospective CHP-FCP system should be conducted as environmental savings may outweigh the slightly extra costs and make the project 'viable'.

DOCUMENT III: Budget

10 Budget

10.1 General Expenses

In addition to the costs discussed in *DOCUMENT II: Techno-economic Analysis*, general expenses associated with the work carried out to complete the project include an hourly rate of pay and the cost of the *HOMER* license.

The hourly rate can be defined as the payment associated over the project lifecycle, from the initial research stage through to final documentation of the TFM. By assuming a wage of €25 per hour and that 300 hours have been dedicated to the work carried out, a total cost of €7,500 was calculated.

The cost of the *HOMER* license depends on the type of package purchased from the *HOMER Energy* website with monthly and annual subscriptions available under the *Standard*, *Academic* or *Student* packages [60]. A summary of the software pricing is given in *Table 6*.

Table 6 - HOMER software license pricing plans [60]

	Description	Monthly	Annual
Standard	General-use commercial licenses that apply to most users.	\$65 / mo	\$42 / mo
Academic	For permanent faculty and staff, research use only.	\$33 / mo	\$21 / mo
Student	For research, classroom, or thesis work.	\$10 / mo	\$6 / mo

Despite a student subscription available, given that the software license was provided through remote access by UPV, and assuming that the university has an annual subscription, the academic rate of \$21 per month was considered. This was converted to €17.43 per month by considering a 1 US Dollar to 0.83 Euro conversion and thus a total licensing cost over the 3-month project timeframe was calculated to be €52.29.

A summary of the general expenses can be found in *Table 7*.

Table 7 - Total General Expenses

	Cost
Total Wage Payment	€7,500.00
Total Licensing Cost	€52.29
Total General Expenses	€7552.29

DOCUMENT IV: General Technical Considerations

11 General Technical Considerations

11.1 Site Location

A number of technical considerations will be required from the detailed design stage of the project through to final installation and commissioning; a fundamental aspect being site location. The location of the CHP unit in the neighbourhood can have a significant effect on heat distribution to end-users and thus it must be optimised to maintain high overall system efficiency. As indicated in *Plan 2* in *DOCUMENT V: Plans*, the boundaries surrounding L'illa Perduda form a complex geometry and the neighbourhood comprises a relatively high-density building environment. Due to the crowded nature of the neighbourhood, and hence lack of free construction space, a suitable location to install the CHP unit was not obvious; therefore, it is recommended that a full site assessment is carried out by liaising with local urban planners. In addition, it is also important that a full assessment of the existing infrastructure and associated piping arrangements is carried out to ensure retrofit capability of the new CHP system and distribution network. Intuitively, as indicated by the red shaded area in *Plan 2,* a central location is likely to be optimal if a single CHP unit is chosen in order to minimise heat losses. *Plan* 3 and *Plan 4* have been included to provide a clearer visualisation of the size of the CHP unit relative to the neighbourhood topography; the exact location, as indicated by the red circle, was chosen as an example.

11.2 Heat and Electrical Systems

In terms of heat supply, integration of the CHP unit with the heating circuits of individual buildings in the neighbourhood is required. Installation of a heat network – consisting of pre-insulated distribution pipework to deliver heat to the buildings – will enable the CHP-FCP energy system to provide thermal capacity and thus supplement individual boilers. Typically, when retrofitting CHP to pre-existing heating infrastructure, the CHP unit is installed in series with the boilers to minimise impact on the boiler circuit upon connection [37]. As discussed previously, it may also be beneficial to incorporate a thermal store into the system to enable temporary heat storage and allow higher peaks in demand to be served. Heat losses and pumping requirements would also have to be considered.

As grid-connection requirements vary, communication with the distribution network operator (DNO) is required to connect the CHP unit to the electrical grid; additional power conditioning equipment and metering and instrumentation devices may be required depending on these requirements [37]. In addition, purchase and export agreements will be necessary for operation.

A schematic representing the basic configuration of the existing grid-electric and boiler infrastructure retrofitted with a CHP unit is illustrated in *Figure 28*.

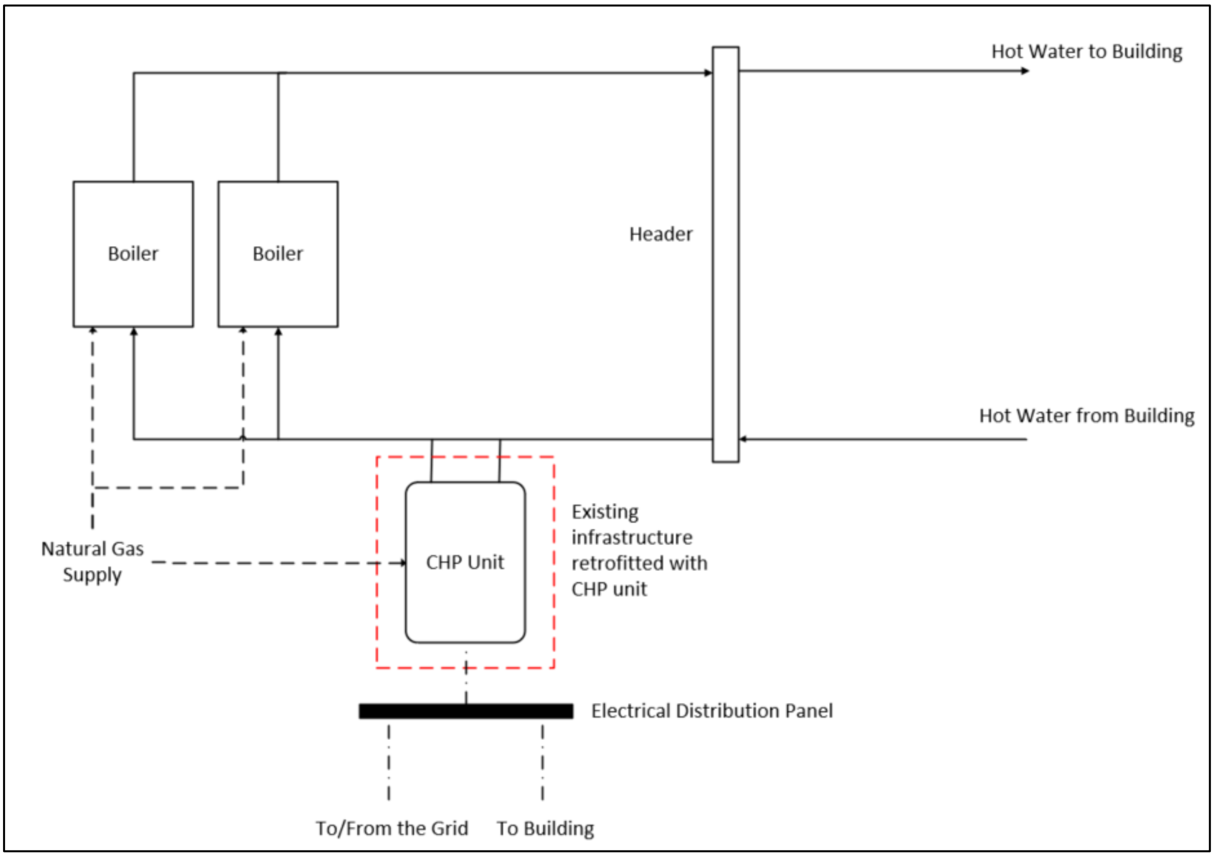
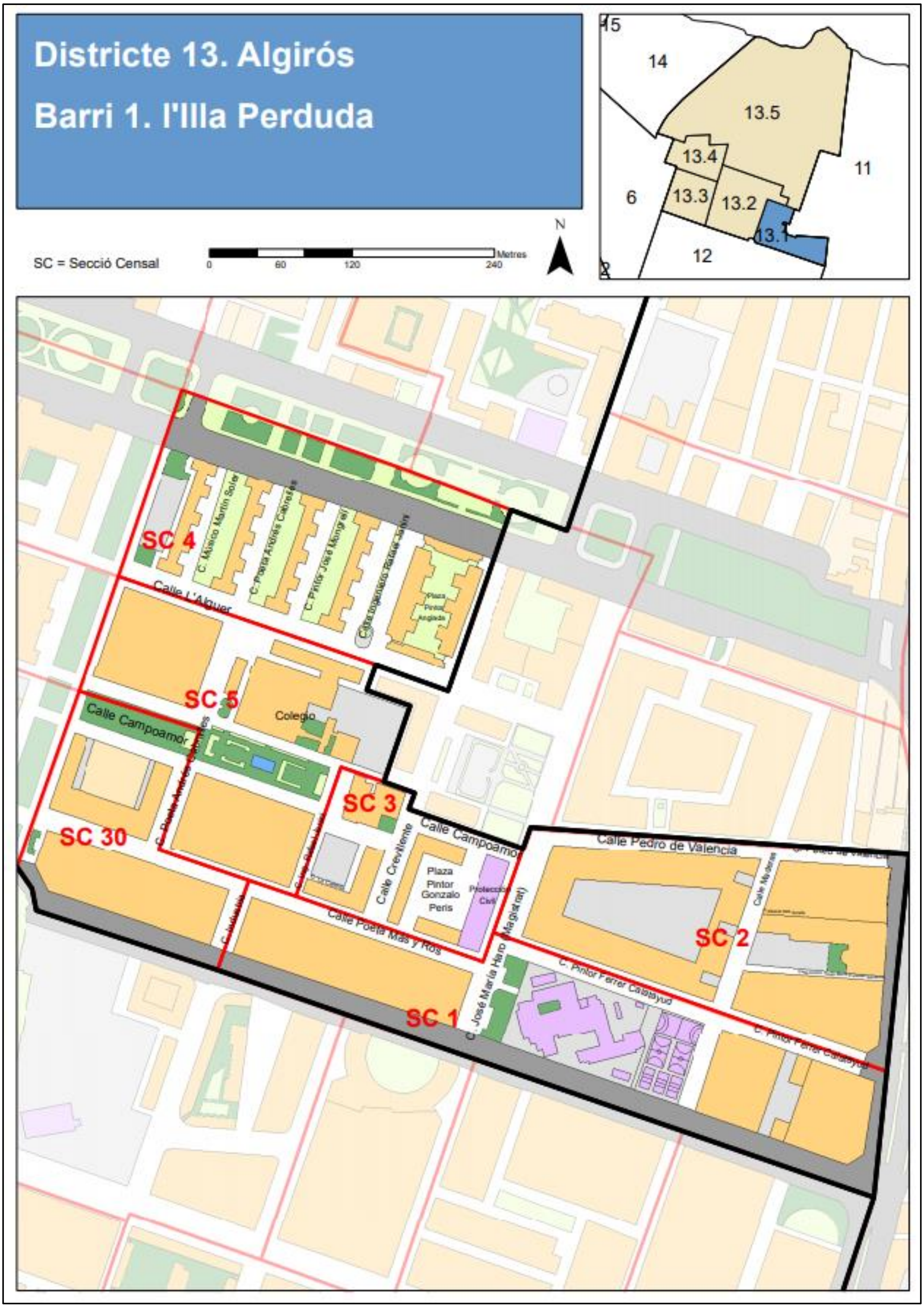


Figure 28 - Basic Schematic of CHP Integration with Existing Infrastructure

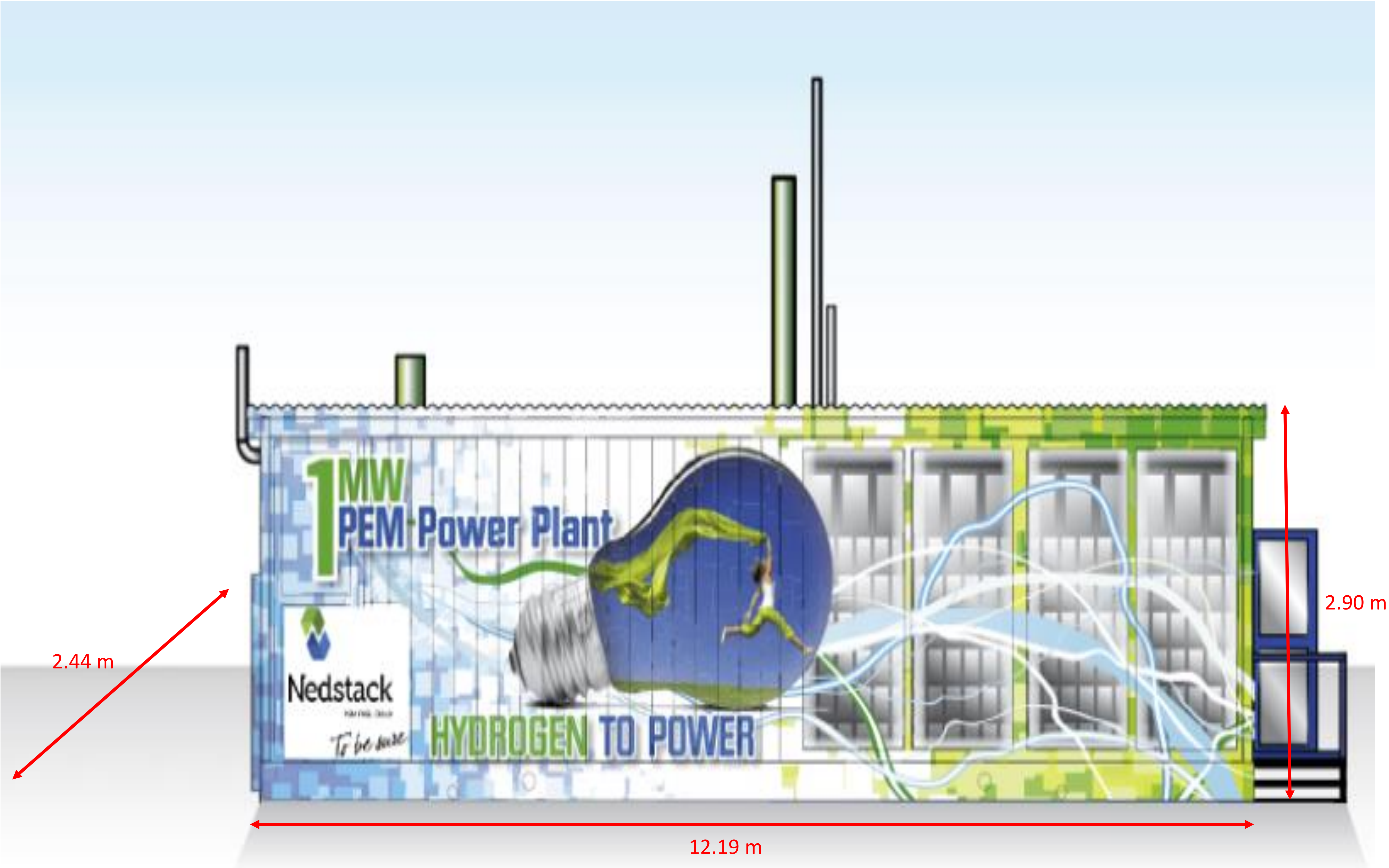
DOCUMENT V: Plans



Plan 1 - Plan of L'illa Perduda taken from Valencia City Council website [61]

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL UNIVERSITAT POLITÈCNICA DE VALÈNCIA ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA	Proyecto: *Study of the Thermal and Electrical Supply of the L'illa Perduda Neighbourhood (Valencia, Spain) using Proton Exchange Membrane Fuel Cells*	Plano: Proposed Location (45)	Fecha: May 2021	Nº Plano: 2
		Autor: Adam Kemshell	Escala:	

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL	Proyecto:	Plano:	Fecha:	Nº Plano:
UNIVERSITAT POLITÈCNICA DE VALÈNCIA — ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA	*Study of the Thermal and Electrical Supply of the L'illa Perduda Neighbourhood (Valencia, Spain) using Proton Exchange Membrane Fuel Cells*	Site Scale Example	May 2021	3
		Autor: Adam Kemshell	Escala:	



TRABAJO FIN DE MÁSTER EN INGENIERIA INDUSTRIAL UNIVERSITAT POLITÈCNICA DE VALÈNCIA ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA	Proyecto: *Study of the Thermal and Electrical Supply of the L'illa Perduda Neighbourhood (Valencia, Spain) using Proton Exchange Membrane Fuel Cells*	Plano: Potential Commercial Self-contained PEMFC-CHP Unit (Nedstack) [58] Autor: Adam Kemshell	Fecha: May 2021 Escala:	Nº Plano: 4

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Annexes

Annex 1 – Comparison of Theoretical Efficiency Limits for Fuel Cells and Heat Engines

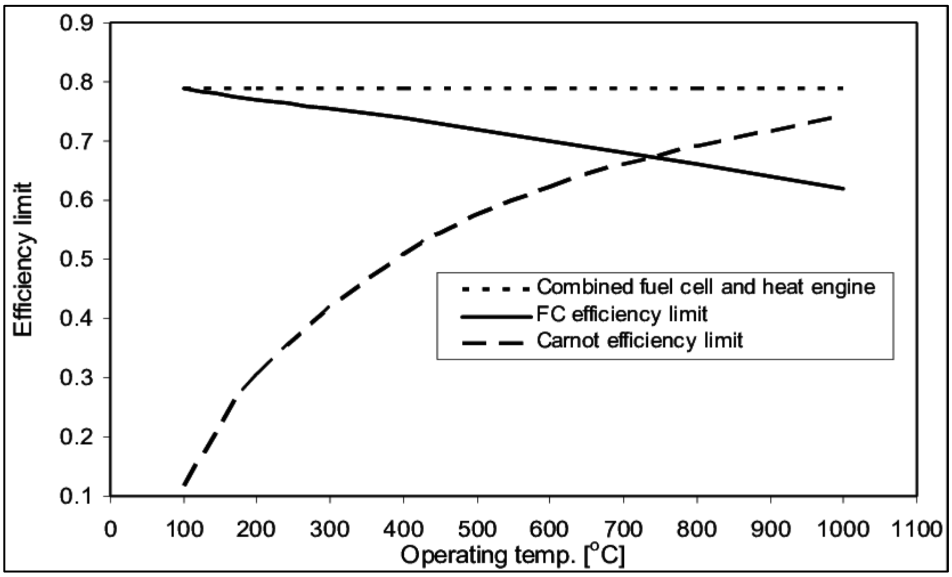
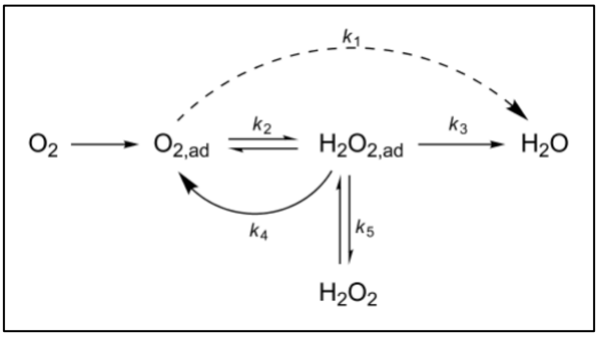


Figure 29 - Comparison of theoretical efficiency limits for fuel cells and heat engines [62]

Annex 2 – HOR and ORR Reaction Mechanisms

1. Mass transport of H_2 to the electrode:
   $H_{2(bulk)} \rightarrow H_{2(surface)}$
2. Adsorption of H_2 to surface:
   $H_{2(surface)} + M \rightarrow M \cdots H_2$
3. Separation of H_2 molecule to individually bound hydrogen atoms:
   $M \cdots H_2 + M \rightarrow 2M \cdots H$
4. Transfer of electrons from H to form H^+:
   $2 \times \left[M \cdots H \rightarrow (M + e^-) + H^+_{surface}\right]$
5. Mass transfer of H^+ away from the electrode:
   $2 \times \left[H^+_{surface} \rightarrow H^+_{bulk\ electrolyte}\right]$



*(a) HOR reaction mechanism at anode** *(b) ORR reaction mechanism at cathode***

Figure 30 - HOR and ORR reaction mechanisms [63]

* M denotes the metal electrode surface.
**If the reaction follows the multi-step pathway, hydrogen peroxide (H_2O_2) may be produced which can damage the electrolyte.

Annex 3 – Fuel Cell Shipments and Installed Capacity (MW) by Region

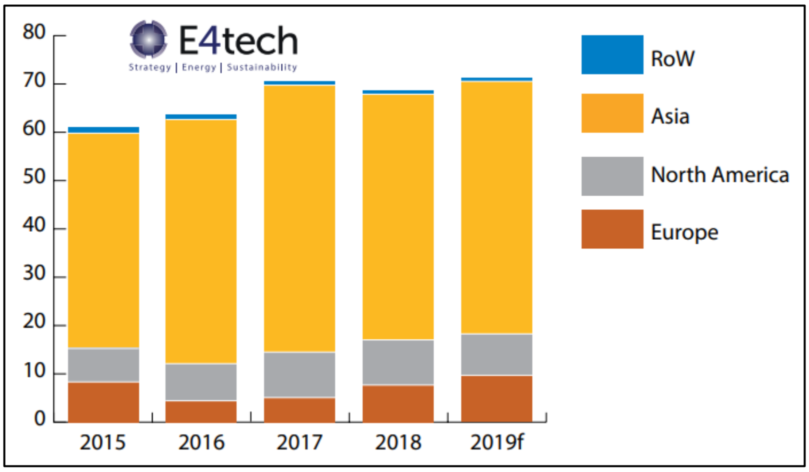


Figure 31 - Fuel cell shipments (1,000 units) by region of adoption (2015 - 2019) [24]

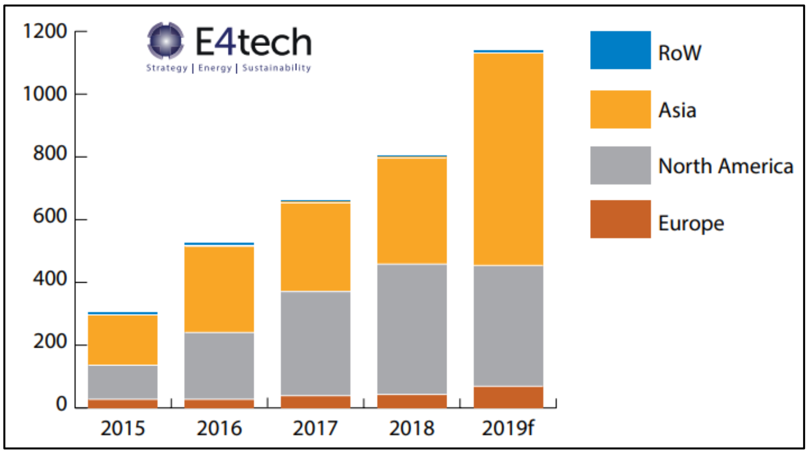


Figure 32 - Fuel cell installed capacity (MW) by region of adoption (2015 - 2019) [24]

*2019f was E4tech's forecast for the full year of 2019, based on firm data from January to September.

Annex 4 - Description of the 19 Districts in Valencia

Valencia is the third largest city in *Spain* with a population of around 800,000 inhabitants [64]. The city comprises of 19 districts, as illustrated in *Figure 33*, each composed of three or four neighbourhoods.

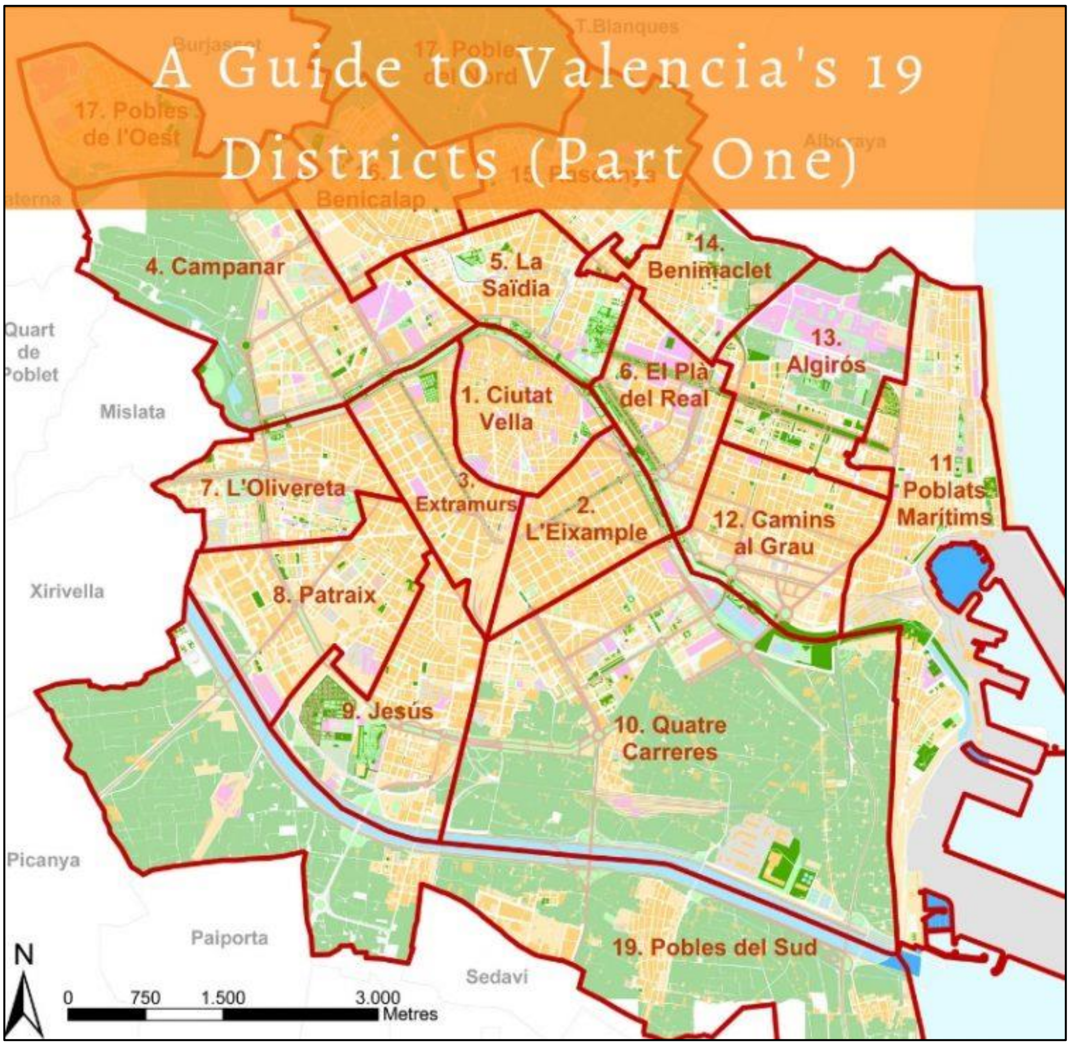


Figure 33 - Map of the 19 districts in Valencia [65]

Annex 5 - Energy Demand Input Data

The following data was provided by the *TEU Chair* to form the basis of the study.

ENERGY REQUIREMENTS IN L'ILLA PERDUDA

INPUT DATA

Two different sources of information have been used to calculate the energy demand required by the homes in the neighbourhood. First, the annual heating, cooling and DHW demands have been established from "TABULA". TABULA was a European project whose objective was to relate the type of building, characterized by its size and year of construction, with its corresponding energy consumption in order to propose energy efficiency improvements.

The parameters on which the project focuses are:

The period of construction of the building:

- G1: Up to the year 1900
- G2: 1901-1937
- G3: 1937-1959
- G4: 1960-1979
- G5: 1980-2006
- G6: 2007-2020

Building size:

- SFH (Single Family House)
- TH (Terraced House)
- MFH (Multi Family House)
- AB (Apartment Block)

Each classification was made according to the location, which in all cases corresponds to the Mediterranean climate given the location of the neighbourhood.

	BUILDINGS	HOUSEHOLDS
AB-G4	121	2927
AB-G5	17	1208
MHF-G4	4	59
SUM	**142**	**4194**

The other source of information from which the rest of the energy demands were obtained was the IDAE, specifically from the SECH-SPAHOUSEC project, which analyses the energy consumption of the residential sector in Spain.

ANNUAL DEMANDS

First, the following variants of the heating, cooling and DHW demands were obtained:

		AB-G4 (kWh/m²yr)	AB-G5 (kWh/m²yr)	MFH-G4 (kWh/m²yr)
UNRENOVATED BUILDING	**Heating**	67	16,7	44,3
	Cooling	4,8	10,7	16,5
	DHW	12,5	12,5	12,5
RENOVATED COMMON BUILDING	**Heating**	12,9	9,5	10,9
	Cooling	6	10,6	12,7
	DHW	12,5	12,5	12,5
ADVANCED RENOVATED BUILDING	**Heating**	12,9	8,6	5,5
	Cooling	0	10,6	4,3
	DHW	5	0	0

To carry out the energy study, the typical state of the building without renovation was considered in all cases since *L'illa Perduda* is a humble neighbourhood in which there has been no investment in improvements.

To know the rest of the energy demands, as mentioned above, they were established based on the consumption collected by the IDAE from the SECH-SPAHOUSEC project. The annual energy demands obtained in the same energy unit are summarized below:

	AB-G4	AB-G5	MFH-G4
HEATING (kWh/m²)	67	16,7	44,3
COOLING (kWh/m²)	4,8	10,7	16,5
DHW (kWh/m²)	12,5	12,5	12,5
COOKING (kWh/household)	436,5		
LIGHTING (kWh/household)	348,2		
APPLIANCES (kWh/household)	1568,95		

Once the annual energy demands per area or per household were known, each annual demand for the total neighbourhood could be calculated:

DEMANDA TOTAL (kWh/yr)	
HEATING	21701695
COOLING	2950057
DHW	5377988
COOKING	1830846
LIGHTING	1460236
APPLIANCES	6580204

MONTHLY DEMANDS

Both heating and cooling demands depend on the average outdoor temperature in the city of Valencia:

	$T_{outdoor_{ave}}$ (ºC)
JANUARY	11,2
FEBRUARY	11,1
MARCH	13,4
APRIL	15,3
MAY	18,2
JUNE	21,8
JULY	24,6
AUGUST	24,9
SEPTEMBER	22,8
OCTOBER	18,9
NOVEMBER	14,5
DECEMBER	11,9

So, the following conclusions were made:

- Heating is used in January, February, March, April, November and December
- Cooling is used from May to October

From the annual demands, the daily demands could be determined:

	AB-G4	AB-G5	MFH-G4
Heating (kWh/m²day)	0,37	0,09	0,24
Cooling (kWh/m²day)	0,03	0,06	0,09

(The annual demand was divided by the number of days in the corresponding months).

Once the daily demands were known, the monthly demands could be calculated. The first step was to calculate the heating demand. Taking into account the number of days in each month, the following monthly demand per area was obtained:

	AB-G4 (kWh/m²)	AB-G5 (kWh/m²)	MFH-G4 (kWh/m²)
JANUARY	11,48	2,86	7,59
FEBRUARY	10,36	2,58	6,85
MARCH	11,48	2,86	7,59
APRIL	11,10	2,77	7,34
NOVEMBER	11,10	2,77	7,34
DECEMBER	11,48	2,86	7,59

But these demands do not take into account the outside temperature; the lower the monthly average temperature, the higher the heating demand. Therefore, in order to know the demand that occurs in each month, the general average temperature of the cold months was calculated. The heating consumption of each month was then increased or decreased according to the difference between this calculated average temperature and the average outdoor temperature of the month. As a result:

	T (ºC)	ΔT (%)	AB-G4 (kWh/m²)	AB-G5 (kWh/m²)	MFH-G4 (kWh/m²)
JANUARY	11,2	13,18	12,99	3,24	8,59
FEBRUARY	11,1	13,95	11,82	2,95	7,81
MARCH	13,4	-3,88	11,04	2,75	7,30
APRIL	15,3	-18,60	9,05	2,25	5,98
NOVEMBER	14,5	12,40	9,74	2,43	6,44
DECEMBER	11,9	7,75	12,37	3,08	8,18
AVERAGE	**12,9**		0,37	0,09	0,24

The cooling demand for each month was calculated in the same way.

	AB-G4 (kWh/m²)	AB-G5 (kWh/m²)	MFH-G4 (kWh/m²)
MAY	0,81	1,80	2,78
JUNE	0,78	1,74	2,69
JULY	0,81	1,80	2,78
AUGUST	0,81	1,80	2,78
SEPTEMBER	0,78	1,74	2,69
OCTOBER	0,81	1,80	2,78

	T (ºC)	ΔT (%)	AB-G4 (kWh/m²)	AB-G5 (kWh/m²)	MFH-G4 (kWh/m²)
MAY	18,2	-16,77	0,67	1,50	2,31
JUNE	21,8	-0,30	0,78	1,74	2,68
JULY	24,6	12,50	0,91	2,03	3,13
AUGUST	24,9	13,87	0,92	2,05	3,17
SEPTEMBER	22,8	4,27	0,82	1,82	2,81
OCTOBER	18,9	-13,57	0,70	1,56	2,40
AVERAGE	**21,86**		**0,03**	**0,06**	**0,09**

On the other hand, the demand for DHW varies throughout the year depending on the temperature of the mains water. The energy required is proportional to the daily demand and to the difference in temperature between consumption and grid. The CTE establishes in Section HS4 of its Basic Health Document that the DHW supply temperature at the consumption points must be between 50 and 65ºC, so a consumption temperature of 60ºC was considered.

The annual DHW demand for all building types in the neighbourhood is 12.5 kWh/m2 so the average daily demand is 0.0342 kWh/m2.

	T_{RED} (ºC)	T_{ACS}-T_{RED} (ºC)	kWh/m²
JANUARY	10	50	1,17
FEBRUARY	11	49	1,04
MARCH	12	48	1,12
APRIL	13	47	1,06
MAY	15	45	1,05
JUNE	17	43	0,97
JULY	19	41	0,96
AUGUST	20	40	0,94
SEPTEMBER	18	42	0,95
OCTOBER	16	44	1,03
NOVEMBER	13	47	1,06
DECEMBER	11	49	1,15
AVERAGE	**14,61**	**45,395**	**0,0342**

Finally, the lighting demand changes throughout the year depending on the hours of sunshine:

	SUNRISE	SUNSET	SUNSHINE	NIGHT
JANUARY	8:20	18:01	9,68	14,32
FEBRUARY	7:54	18:37	10,72	13,28
MARCH	7:12	19:09	11,95	12,05
APRIL	7:24	20:40	13,27	10,73
MAY	6:47	21:09	14,37	9,63
JUNE	6:34	21:31	14,95	9,05
JULY	6:47	21:28	14,68	9,32
AUGUST	7:14	20:57	13,72	10,28
SEPTEMBER	7:43	20:09	12,43	11,57
OCTOBER	8:12	19:22	11,17	12,83
NOVEMBER	7:46	17:46	10,00	14,00
DECEMBER	8:15	17:39	9,40	14,60

The annual lighting demand, as mentioned above, is 348.2 kWh/household which is equivalent to an average daily demand of 0.954 kWh/household. The average monthly demands are summarised below according to the days of each month:

	kWh/household
JANUARY	29,571
FEBRUARY	26,709
MARCH	29,571
APRIL	28,617
MAY	29,571
JUNE	28,617
JULY	29,571
AUGUST	29,571
SEPTEMBER	28,617
OCTOBER	29,571
NOVEMBER	28,617
DECEMBER	29,571

The more hours of sunshine, the lower the demand for lighting - this demand will increase or decrease proportionally depending on the hours of night each month. In order to calculate the monthly demand, 6 hours of sleep were taken into account in which no light is required.

	NIGHT HOURS WITH LIGHT DEMAND	kWh/ household*month
JANUARY	8,32	42,41
FEBRUARY	7,28	33,55
MARCH	6,05	30,85
APRIL	4,73	23,36
MAY	3,63	18,53
JUNE	3,05	15,05
JULY	3,32	16,91
AUGUST	4,28	21,84
SEPTEMBER	5,57	27,47
OCTOBER	6,83	34,85
NOVEMBER	8,00	39,48
DECEMBER	8,60	43,86
AVERAGE	**5,80**	**0,954**

On the other hand, the energy demands for cooking and household appliances only vary over the months according to the days of each month. As there was no other significant differentiation to be taken into account:

- Average daily demand for cooking: 1,196 kWh/household
- Average daily demand for household appliances: 4,299 kWh/household

Thus, the monthly demands are summarised in the following table:

	COOKING (kWh/household)	APPLIANCES (kWh/household)
JANUARY	37,08	133,25
FEBRUARY	33,49	120,36
MARCH	37,08	133,25
APRIL	35,88	128,96
MAY	37,08	133,25
JUNE	35,88	128,96
JULY	37,08	133,25
AUGUST	37,08	133,25
SEPTEMBER	35,88	128,96
OCTOBER	37,08	133,25
NOVEMBER	35,88	128,96
DECEMBER	37,08	133,25

Once all the monthly energy demands per area or per dwelling were known, the total energy demands were calculated and are summarised below in kWh/month:

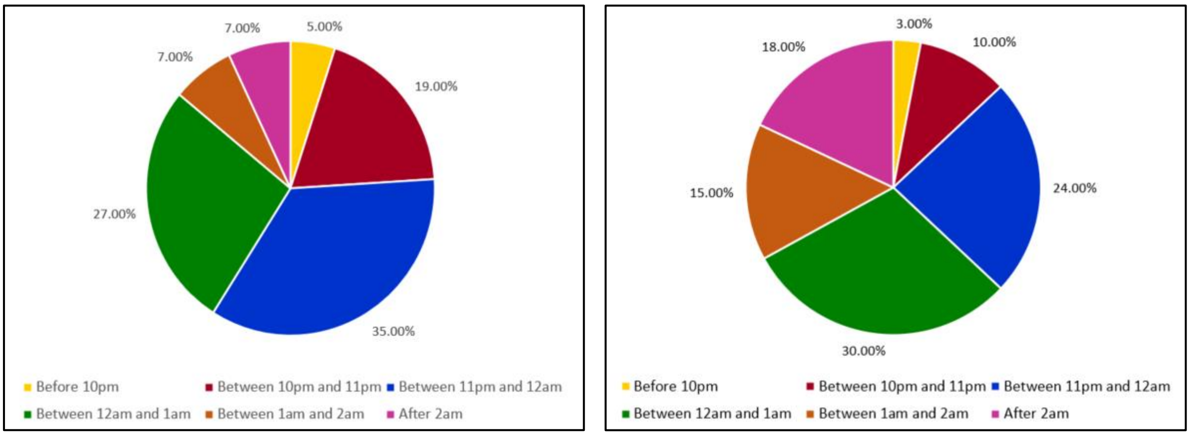
	HEATING	COOLING	DHW	LIGHTING	APPLIANCES	COOKING
JANUARY	4208618,04	0,00	503101,01	175873,33	558866,68	155496,53
FEBRUARY	3827341,39	0,00	445325,54	140026,85	504782,81	140448,48
MARCH	3575113,96	0,00	482976,97	129120,59	558866,68	155496,53
APRIL	2930319,48	0,00	457659,63	98815,06	540838,72	150480,52
MAY	0,00	413767,68	452790,91	79275,40	558866,68	155496,53
JUNE	0,00	479624,36	418709,87	65216,38	540838,72	150480,52
JULY	0,00	559268,41	412542,83	72746,33	558866,68	155496,53
AUGUST	0,00	566088,75	402480,81	92685,45	558866,68	155496,53
SEPTEMBER	0,00	501625,48	408972,43	115452,79	540838,72	150480,52
OCTOBER	0,00	429681,82	442728,89	145281,40	558866,68	155496,53
NOVEMBER	3153253,47	0,00	457659,63	164023,47	540838,72	150480,52
DECEMBER	4007048,56	0,00	493038,99	181718,62	558866,68	155496,53
SUM	**21701695**	**2950057**	**5377988**	**1460236**	**6580204**	**1830846**

Annex 6 – Hourly Occupancy of a Standard Home Input Data

Table 8 - Typical occupancy (National Institute of Statistics (Spain) Time Use Survey 2009-2010) [66]

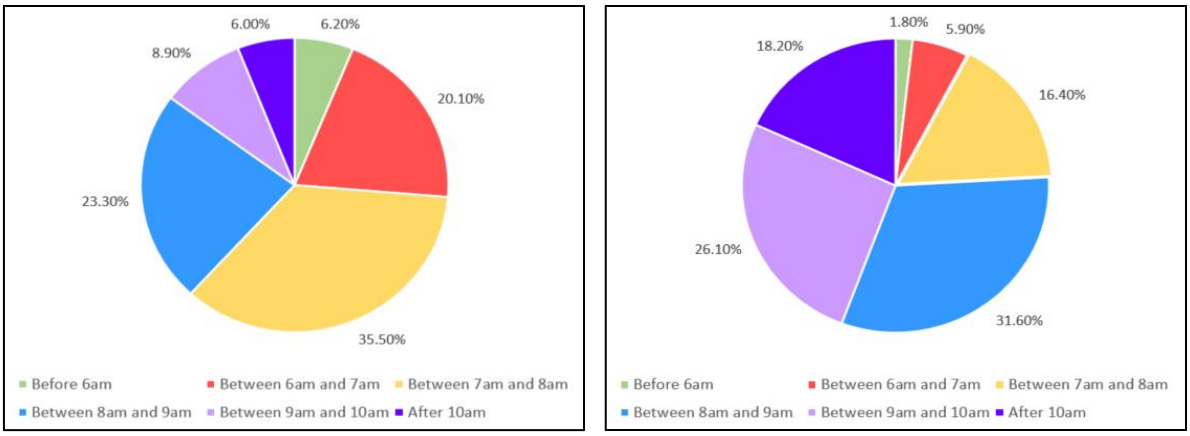
	Weekday	Weekend
24:00	91.8%	85.8%
01:00	95.7%	91.3%
02:00	97.2%	94.2%
03:00	96.7%	95.6%
04:00	98.0%	96.6%
05:00	97.5%	97.2%
06:00	96.2%	96.7%
07:00	90.3%	94.4%
08:00	72.3%	85.5%
09:00	53.1%	74.3%
10:00	46.5%	65.7%
11:00	40.1%	55.7%
12:00	37.8%	49.6%
13:00	42.5%	51.7%
14:00	60.3%	67.0%
15:00	63.2%	73.4%
16:00	52.0%	62.9%
17:00	43.8%	54.5%
18:00	40.9%	48.5%
19:00	40.5%	45.4%
20:00	50.3%	50.7%
21:00	72.1%	70.6%
22:00	81.0%	79.6%
23:00	85.7%	82.0%

Annex 7 – CIS Sleep Input Data



(a) Weekdays *(b) Weekends*

Figure 34 – Pie chart illustrating the times at which Spanish people go to bed [49]



(a) Weekdays *(b) Weekends*

Figure 35 – Pie chart illustrating the times at which Spanish people wake up [49]

Annex 8 – 1.5 MW_e Gensure High Power Fuel Cell Generator Specification Sheet (*Plug Power)*

HIGHLY RELIABLE

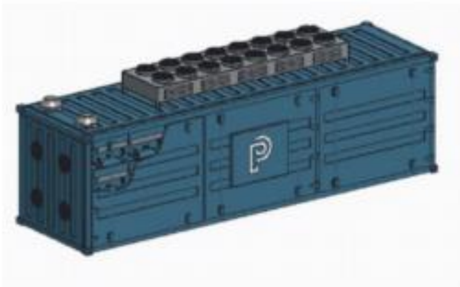
Plug Power's GenSure fuel cell systems perform in hot and cold, humid and arid environments. With minimal moving parts and optional built-in redundancy, these fuel cells are proven to perform reliably in real world conditions.

ZERO-EMISSION / QUIET OPERATION

GenSure fuel cell systems offer zero-emission, quiet operation and are not subject to fuel spill containment and air quality reporting requirements. Our products support load peak shaving and demand response programs without impacting emissions and operating hour limitations.

MINIMAL MAINTENANCE

Fuel cell health and fuel levels may be remotely monitored. Simple maintenance and fewer site visits mean significantly lower operational costs when compared to combustion generators. Infinite hydrogen storage life eliminates expensive fuel polishing requirements associated with combustion generators



LOW ACOUSTIC SIGNATURE

Quiet operation enables GenSure fuel cell solutions to be located anywhere power is required, even in acoustically-sensitive locations.

CONFIGURATION	500KW	1MW	1.5MW
OUTPUT			
MINIMUM ELECTRICAL OUTPUT POWER (CONT)	150kWe		
MAXIMUM ELECTRICAL OUTPUT POWER (CONT)	500kWe	1MWe	1.5MWe
DUTY CYCLE	Stand-by, Prime		
ELECTRICAL EFFICIENCY (PEAK)	>45%		
SYSTEM OUTPUT VOLTAGE	900 VDC (nominal)		
PHYSICAL			
DIMENSIONS	10' ISO Container	30' ISO Container	
WEIGHT	5,000 kg	9,500 kg	15,000 kg
PROTECTION	NEMA 3R Outdoor rated enclosure		
OPERATIONAL			
AMBIENT TEMPERATURE	-30°C to 50°C		
DESIGN LIFE	15 years (Stand-by)		
ELECTRICAL INPUT POWER (START-UP)	13kW	26kW	40kW
NOISE	<65dBA at 150'		
EMISSIONS	Zero Emissions		
OUTPUT HEAT LOAD	750kW (max)	1.5MW (max)	2.25MW (max)
EXHAUST GAS TEMPERATURE	<80°C		
FUEL			
FUEL (FULL SPEC AVAILABLE ON REQUEST)	99.95% Hydrogen		
ENERGY STORAGE	In excess of 48 hours of usable on-site storage (various storage options available)		

Specifications subject to change without notice. Information based on standard products working under normal operating conditions.

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PLUG POWER

062020

Figure 36 - 1.5 MWe Gensure High Power Fuel Cell Generator Specification Sheet (Plug Power) [53]

Annex 9 – 1 MW_e PemGen CHP-FCPS-1000 Specification Sheet (*Nedstack*)

PemGen®
CHP-FCPS-1000

The CHP-FCP-1000 is a PEM Fuel Cell Power System intended for industrial applications, Power-2-Power purposes for solar fields and wind farms and for co-generation applications in the built environment. The CHP-FCP-1000 is optimized for seamless integration in local or collective electricity grids by being able to use all sorts of commercial off-the-shelf power electronics. The PemGen Fuel Cell Power System portfolio is available on a configure-to-order basis. Get in touch to tune this system for your specific application.

GENERAL	Fuel Cell Type	Low Temperature Proton Exchange Membrane (LT-PEM)
	Fuel Cell Model	120 x Nedstack FCS 13-XXL
ELECTRICAL	Nominal power	1000 kWe
	Peak power (BoI)	1252 kWe
	Voltage range	500 - 1000 VDC
	Current range	0 - 2400 A
ENCLOSURE	Weight	29000 kg
	Built Level	40 ft ISO Container (High Cube)
	Length	12.19 m
	Width	2.44 m
	Heigth	2.90 m
	IP-rating	IP 54
HYDROGEN FEED	Quality	Grade ≥ 2.5 (CO < 0.2 ppm)
	Supply pressure	0.3 – 6 barg
	Nominal consumption (BoL)	59 kg/ MWh_e
	Max consumption	80 kg/h
COOLANT	Medium	DI water or BASF FC G20
	Outlet Temperature	Max 65 °C
	Required Cooling Capacity	1800 kW_{th}
	Recoverable heat	>800 kW_{th}
AMBIENT CONDITIONS	Operating Temperature	-5 – 40°C
	Storage Temperature	5 – 60°C (optional -20°C – 60°C)
APPLICATION	Intended use	Residential blocks Commercial and insitutional facilities Chemical sites
	Placement	To be placed on flat concrete surface or steelframe
LIFESPAN	Balance of Plant	20 years
	Stack Refurbishment	24k - 30k running hours
COMPLIANCY	Standards	IEC-62282-2 IEC-62282-3 2006/95/EC 2006/42/EC 2004/108/EC

Nedstack fuel cell technology B.V.
Stationary Power Systems
www.Nedstack.com

To be sure.

Westervoortsedijk 73 VB
6827 AV ARNHEM
The Netherlands

Figure 37 – 1 MWe PemGen CHP-FCPS-1000 specification sheet (Nedstack) [54]

Annex 10 – *HOMER* Thermal and Electrical Load User Input Prompts

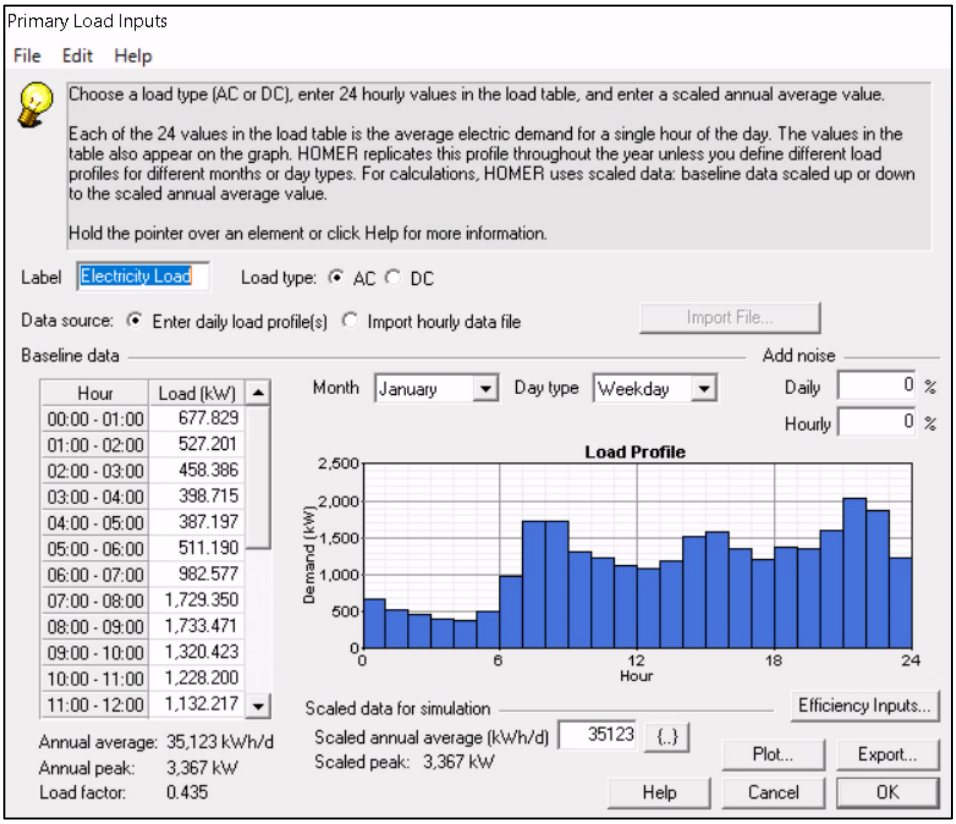

Figure 38 - HOMER electrical load input prompt

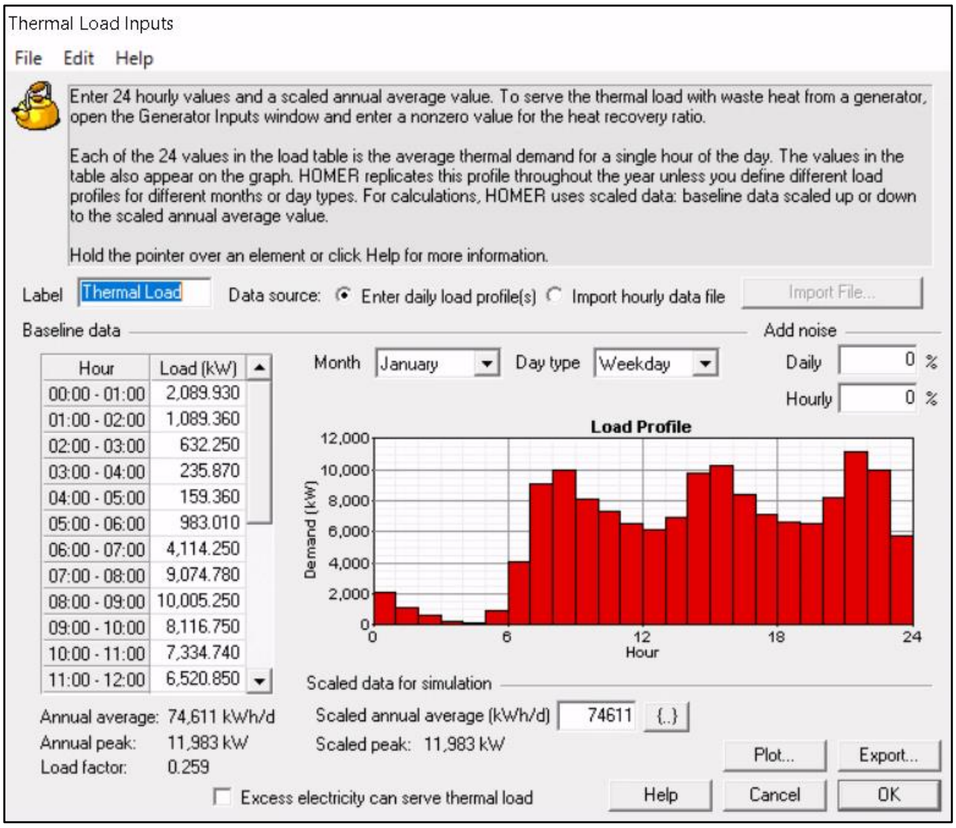

Figure 39 - HOMER thermal load input prompt

Annex 11 – *HOMER Thermal and Electrical Load Profiles*

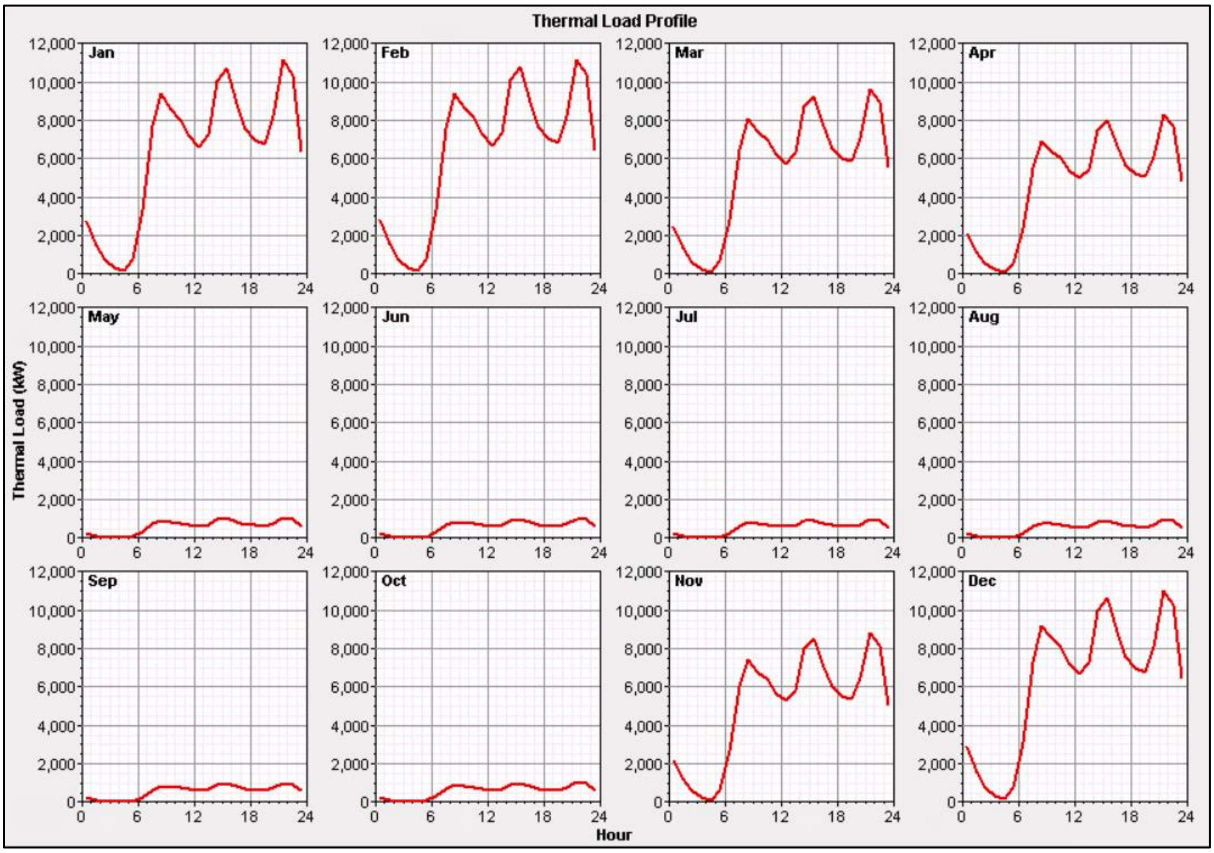

Figure 40 – Average 24-hour thermal load profiles for each month as generated on HOMER

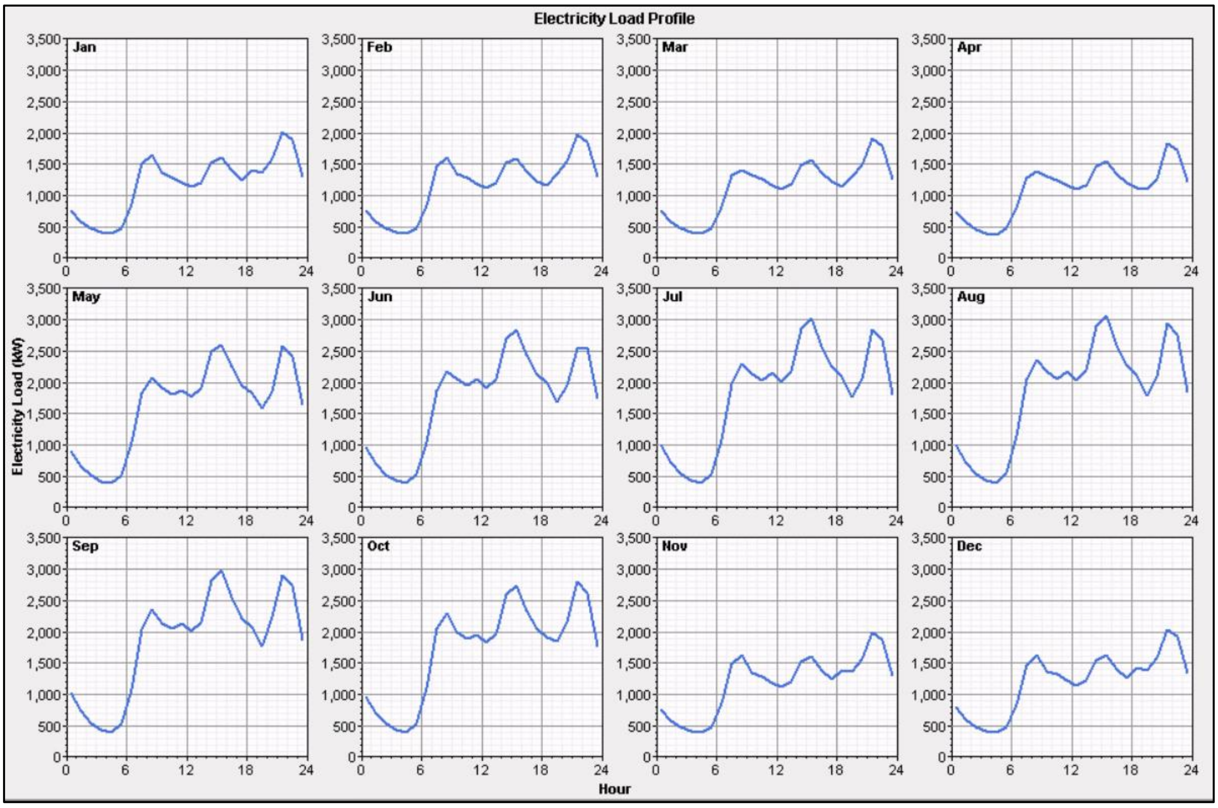

Figure 41 - Average 24-hour electrical load profiles for each month as generated on HOMER

Annex 12 – *HOMER* Generator User Input Prompt

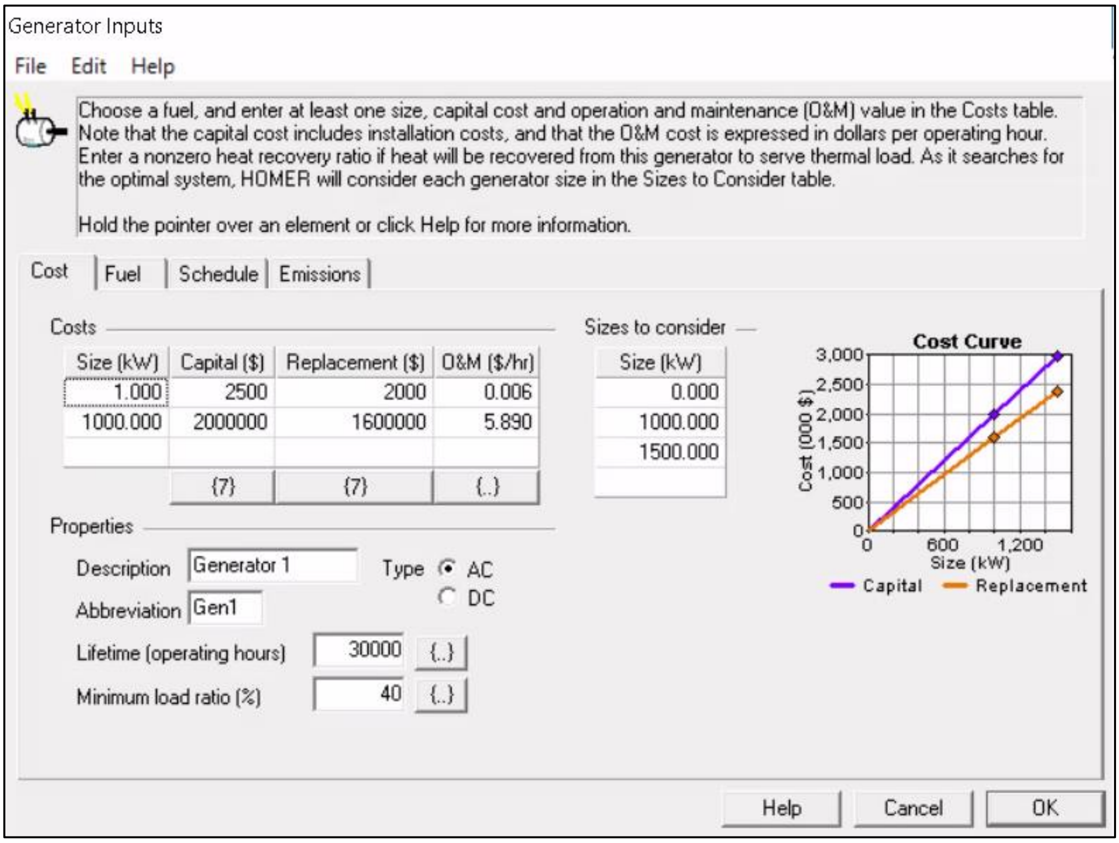

Figure 42 - HOMER Generator cost user input prompt

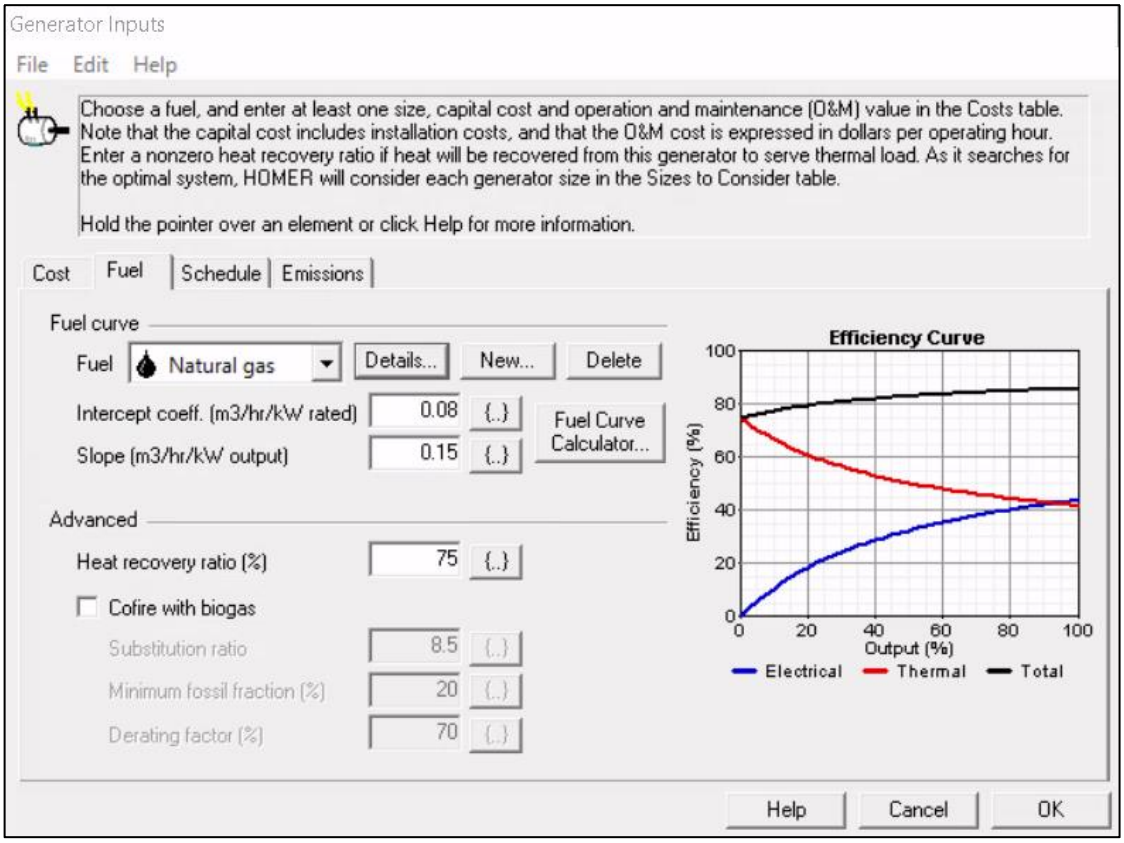

Figure 43 - HOMER Generator fuel user input prompt

Annex 13 – Grid Tariffs

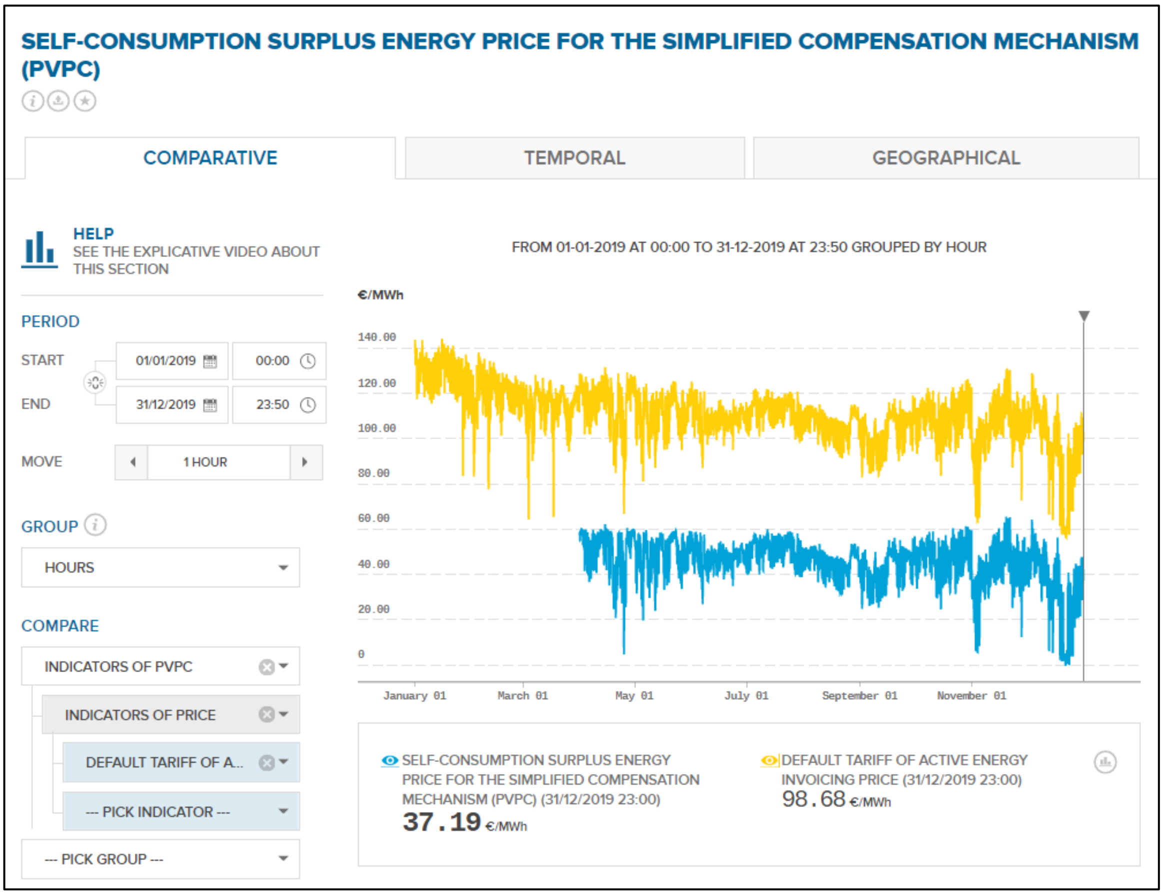

Figure 44 - Grid tariffs taken from ESIOS website [57]

Annex 14 – Details of Operation of Fuel Cell Generator

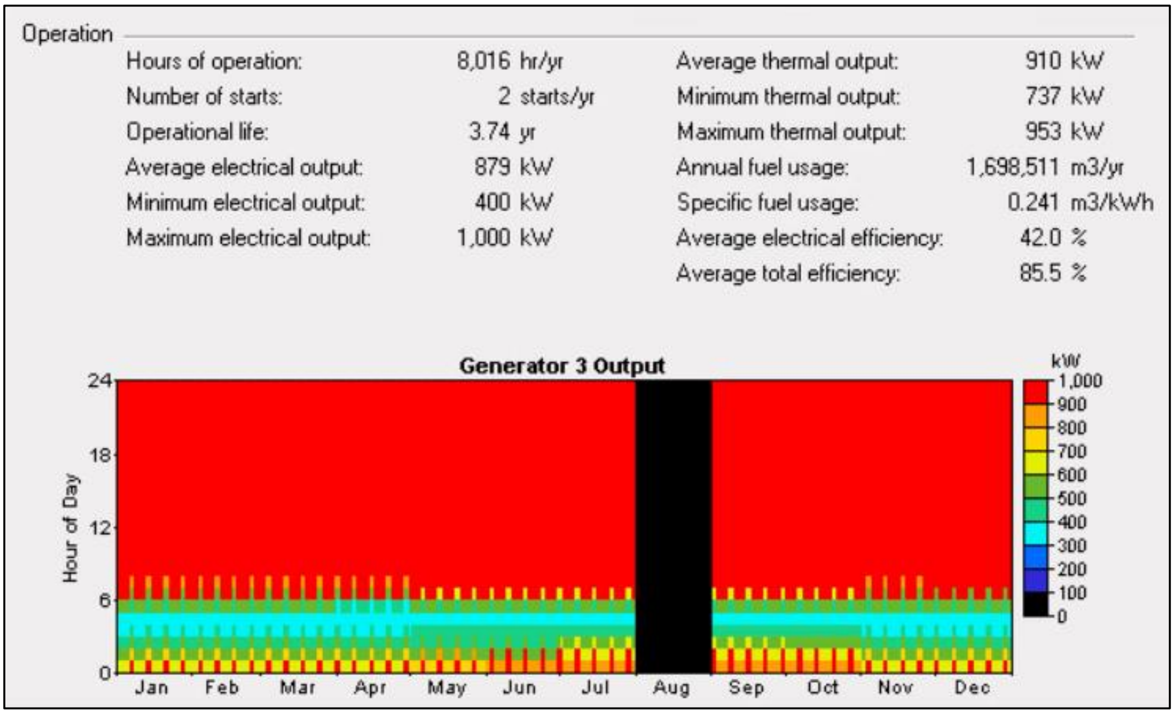

Figure 45 - Details of Operation of Fuel Cell Generator on HOMER