Hydrogen Fuel Cells for Cogeneration in Residential Applications

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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I wish to thank my supervisor, Professor Dr. Rui Pedro da Costa Neto and Dr. Ricardo Manuel Anacleto Gomes for their relentless guidance and support throughout this project. Their continuous advice and support were crucial for the conclusion of such an important chapter of my life.

Also, there are no words that can describe the support I have received from my family during these 2 years, always giving me the motivation to keep pushing myself forward. I would not be half the engineer I am today, without my parents. All that I am and all that hope to be, I owe it to them.

Abstract

As a solution to limiting carbon dioxide emissions in the residential sector, multiple technologies have emerged shown promising potential. The aim of the dissertation was to study the feasibility of hydrogen fuel cells for residential applications for cogeneration. The efficiency, emissions and running cost were of fuel cells were calculated and compared against heat pumps and the existing energy system i.e., gas boilers for the city of London and Lisbon. A building, designed in Google Sketchup was simulated using EnergyPlus. The outputs given by the EnergyPlus were indoor temperatures, heating energy demands for all the zones for three floors. After calculations it was found that the emissions saved by switching to heat pumps and fuel cells for both cities were almost two times. The emissions saved is expected to grow more with the use of green hydrogen as opposed the current, grey hydrogen with emission rating of 9.2CO_2 kg/kgH_2. However, the initial cost of investment for fuel cells and heat pumps were €12000 and €7000. The means and technology of hydrogen production and making it available to the end-users were also studied. It is estimated according to the reports of certain projects in the United Kingdom and other parts of Europe, the price of hydrogen could be at 2.5 €/kg in the near future, hence the price spent on heating energy would fall by 15% in Lisbon. To make fuel cells viable, it will be imperative for the Portuguese Government to make policies, provide incentives and invest in suitable infrastructures.

Keywords

EnergyPlus; Fuel Cells; Heat Pumps; Residential sector; Portuguese Government; Decarbonization.

Resumo

Como solução para limitar as emissões de dióxido de carbono no setor residencial, surgiram várias tecnologias com potencial promissor. O objetivo da dissertação foi estudar a viabilidade de células de combustível de hidrogênio para aplicações residenciais para cogeração. A eficiência, as emissões e o custo de funcionamento das células de combustível foram calculados e comparados com as bombas de calor e o sistema de energia existente, ou seja, caldeiras a gás para a cidade de Londres e Lisboa. Um edifício, projetado no Google Sketchup, foi simulado usando o EnergyPlus. As saídas fornecidas pelo EnergyPlus foram temperaturas internas, demandas de energia de aquecimento para todas as zonas de três andares. Após cálculos, descobriu-se que as emissões economizadas ao mudar para bombas de calor e células de combustível para ambas as cidades foram quase duas vezes. Espera-se que as emissões economizadas cresçam mais com o uso de hidrogênio verde em oposição ao atual hidrogênio cinza com classificação de emissão de 9,2CO2 kg/kgH2. No entanto, o custo inicial de investimento para células de combustível e bombas de calor foi de € 12.000 e € 7.000. Os meios e a tecnologia de produção de hidrogênio e sua disponibilização aos usuários finais também foram estudados. Estima-se de acordo com os relatórios de alguns projetos no Reino Unido e noutras partes da Europa, o preço do hidrogénio poderá estar nos 2,5€/kg num futuro próximo, pelo que o preço gasto na energia de aquecimento cairia 15% em Lisboa . Para viabilizar as células de combustível, será imperativo que o Governo português faça políticas, dê incentivos e invista em infraestruturas adequadas.

Keywords

EnergyPlus; Células de Combustível; Bombas de Calor; Setor residencial; Governo Português; Descarbonização.

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1 Introduction

1.1 Motivation

Global warming is the most severe and dangerous crisis humanity has faced in the recent past caused by the advent of industrial revolution until now. Industrial revolution, a major milestone in our evolution, considerably improved comfort, the standard of living and engendered globalization. It has made the world a smaller place, bringing people closer together, allowing co-operation and creating an ecosystem for a healthy competition and thereby, unprecedented progress and development. However, the excessive consumption of the various primary energies (coal, natural gas, petroleum etc.) and unsustainable practices (no treatment of the by-products, restraint on consumption) has created an imbalance in earths delicate ecosystem, Figure 1. Earth offers plenty of resources for all its organisms, however it also needs time to recuperate. Technological advancements have allowed us to access and consume resources at a pace our environment isn't accustomed to. An average human consumed 40 MWh of energy per year in 2020, a 56% increase compared to 1965 [1]. This phenomenon has consistently and considerably lead to an increase in the harmful gases in the atmosphere, rising sea-levels, destruction of natural habitats, extreme temperatures in all seasons and rise in the frequencies of storms, droughts and floods. There is overwhelming evidence for us to agree, the industrial revolution has opened the Pandora's box.

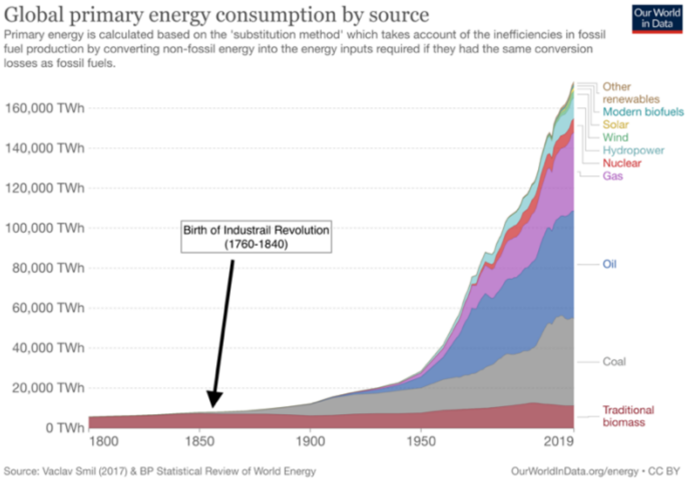


Figure 1 Primary Energy Consumption [1]

According to the Swiss Re Institute, the global economic output would incur a loss of $23 trillion USD by 2050 as a direct result of global warming [2]. An approximate 1°C annual increase in temperature has adverse effects on the abundance, behaviour and survival of all the living organisms, including humans. Climate change has put 10967 species in the endangered category [3]. The International Union of Conservation of Nature has estimated the extinction of 882 species of plants and animals [4]. Pollution, destructive fishing and coral mining has cost the world around 30-50% of the coral reefs [5]. Every year, the environmental factors, due to climate change, takes the lives of around 13 million people [6]. If left unchecked, if we don't make plans for climate change mitigation, extinction of our species will be inevitable.

The Paris Agreement, which came into force on the 4th November 2016, is legally binding treaty signed by 196 nations, as an attempt to curb the rising temperatures to 2 °C, 1.5 °C if possible. As a part of the agreement, the nations have vowed to make economic, technological and social transformation in the way the energy is produced, transported and consumed. This would include phasing out conventional energy sources, research and development of renewable energy systems, investments in innovative energy efficiency technologies and designing conducive energy policies that would promote energy transition.

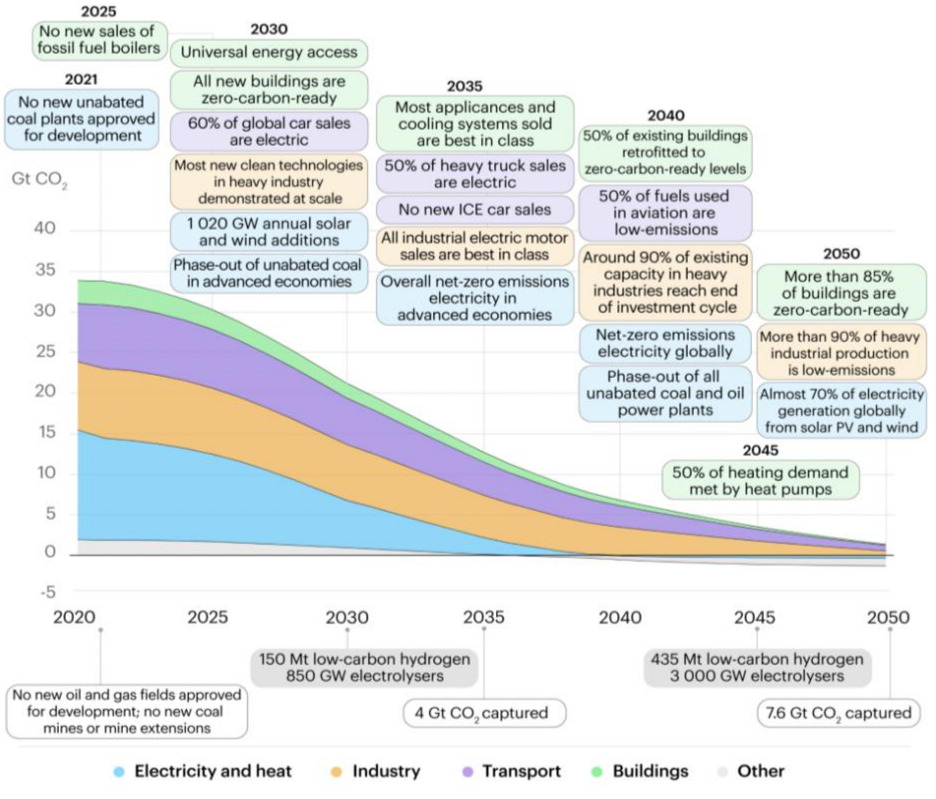


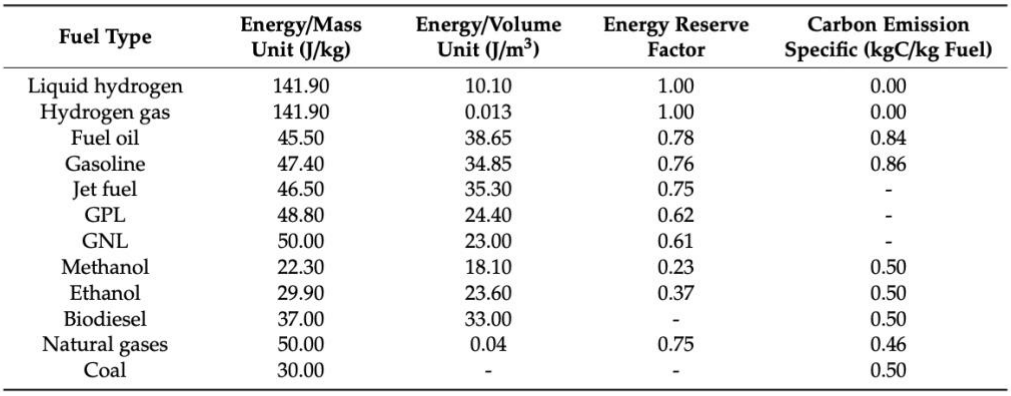
Figure 2 Key Milestones in Pathway to Net Zero [7]

According to a pathway suggested by the International Energy Agency (IEA) to achieve the targets of 2030, Figure 2, there has to be annual additions of 630 GW and 390 GW of solar photovoltaics and wind, respectively, by 2030. The global electric vehicle car sales should account for 60%. The plan also specifies heavy investments in R&D in energy efficient technologies that would allow the reduction in energy consumption at least by 7% despite the growth in world economy by 40%. It also estimates that a 55% reduction in emissions will directly rely on behavioural changes of the society such as choices by the masses in purchasing electric vehicles, retrofitting of houses with energy efficient technologies [7].

1.1.1 Why Hydrogen?

The European Union (EU), adopted a 55% reduction in emission target by 2030 to keep in line with the climate neutral target by 2050. The European Environment Agency (EEA) estimates the measures taken have resulted in the decline of emissions by 34% as compared to 1990 [8]. Although a number of nations have made great strides in energy transition by switching to solar & wind energy technologies, the lack of available recycling technologies for turbine blades & solar panels and destruction of natural habitat while constructing and operating these farms is an issue that no longer be ignored. The intermittent nature of some renewables forces heavy investments in storage technologies, which are not fully developed yet. Hydrogen can be viewed as a solution to this conundrum. Hydrogen produced from intermittent renewables can be used for storage and end-use, thereby reducing the energy loss either due to curtailment. Around 2% (339 TWh) of energy consumption in the present day Europe comes from Hydrogen, the majority of which is produced form natural gas, emitting significant CO_2 emissions, around 38.51 g CO_2 per MJ [9][10][11]. From the Table 1, we can see that hydrogen has the highest energy density with zero emissions. If hydrogen is produced using renewable electricity and water in electrolysers to produce green hydrogen, we can transport it either retrofitting existing gas pipelines or using gas cylinders, to reach the end user, where they can be burnt or supply to fuel cells to produce heat and electricity with zero emissions. There is promising research for hydrogen to be stored in stable solid form. These features has encouraged the European Commission to expedite the use of hydrogen technology and expects 167- 4000 TWh consumption by 2050 [10].

Table 1 Comparison between the main properties of hydrogen and other fuels [12].



Fuel Type	Energy/Mass Unit (J/kg)	Energy/Volume Unit (J/m^3)	Energy Reserve Factor	Carbon Emission Specific (kgC/kg Fuel)
Liquid hydrogen	141.90	10.10	1.00	0.00
Hydrogen gas	141.90	0.013	1.00	0.00
Fuel oil	45.50	38.65	0.78	0.84
Gasoline	47.40	34.85	0.76	0.86
Jet fuel	46.50	35.30	0.75	-
GPL	48.80	24.40	0.62	-
GNL	50.00	23.00	0.61	-
Methanol	22.30	18.10	0.23	0.50
Ethanol	29.90	23.60	0.37	0.50
Biodiesel	37.00	33.00	-	0.50
Natural gases	50.00	0.04	0.75	0.46
Coal	30.00	-	-	0.50

As a part of EU’s strategy for green energy system integration [13], European commission intends to develop renewable hydrogen technologies for industrial processes, heavy duty road and rail transport and for end use applications where direct heating or electrification is not possible. Several member nations like France, the Netherlands, Germany, Portugal and Spain, have already hydrogen strategy [10]. In Figure 3, we can see an illustration of the potential evolution of hydrogen based technologies in the European Energy mix in sectors such as transportation, heating for buildings, industrial use and power generation [14].

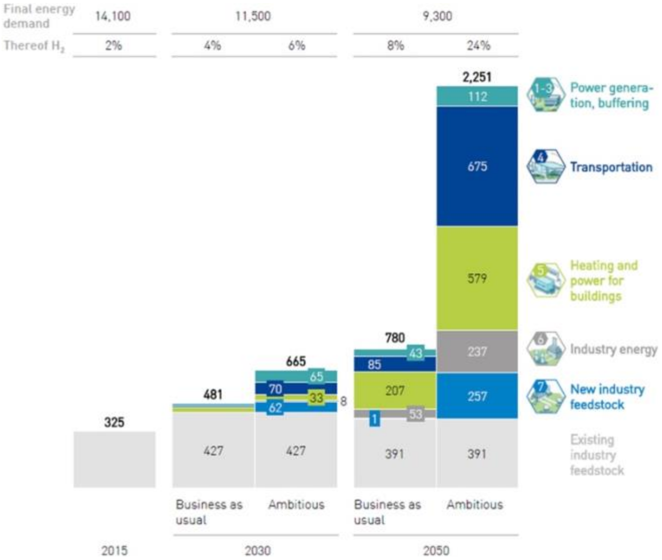
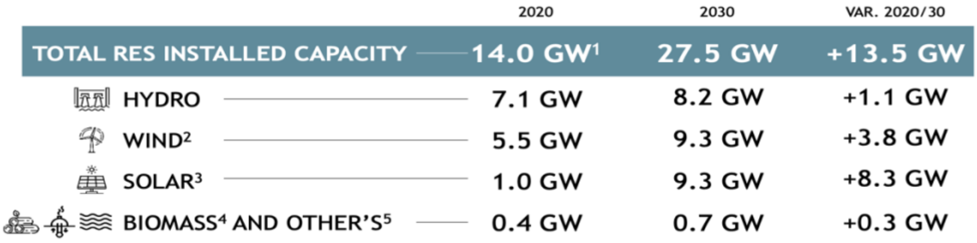


Figure 3 Europe's Ambitious Hydrogen Plan for 2050 [14].

1.1.2 Portuguese Context for a Hydrogen Economy

An abundance in the availability of solar, wind and hydropower has made Portugal 4th in the EU-27 countries with the largest incorporation of renewables in electricity and 7th among countries with high final renewable energy consumption. Hydropower constitutes for 26% of the electricity production, with plans to install additional 1.2 GW by the end of 2023, wind power contributes for the 23% of the electricity produced in 2022 and intends to incorporate an additional 3.8 GW by 2030. In the upcoming years, Portugal will install 8.3 GW of solar photovoltaics [15], Table 2.

Table 2 Portugal Energy Mix (2020-2030) [15].



	2020	2030	VAR. 2020/30
TOTAL RES INSTALLED CAPACITY	**14.0 GW**[1]	**27.5 GW**	**+13.5 GW**
HYDRO	7.1 GW	8.2 GW	+1.1 GW
WIND[2]	5.5 GW	9.3 GW	+3.8 GW
SOLAR[3]	1.0 GW	9.3 GW	+8.3 GW
BIOMASS[4] AND OTHER'S[5]	0.4 GW	0.7 GW	+0.3 GW

Portugal intends to exploit the abundance of renewable energy output to produce green hydrogen and become the centre of hydrogen technology in the recent future. Portugal’s National Hydrogen Strategy, EN-H2, aims to fasten energy transition and strengthen the national economy. Portugal’s strategy for the 2030 horizon includes a number of key priorities including establishing necessary framework for hydrogen, implementing support mechanisms to green hydrogen production, development of industrial clusters for green hydrogen consumption and develop strategic partnerships with nations to foster a hydrogen market [15] [16] [17]. The objectives on EN-H2 dictate a 5% share of energy consumption from hydrogen by 2030, with special focus on the industry and transport sector and installing 2 GW of electrolysers by 2030 [18]. The country intends to make Sines and Center–North, with special emphasis on Sines with an investment of about 2.85 billion euros to create a H_2 hub which will help them become a leading exporter to Europe and other regions [18]. Portugal believes accelerating the energy transition and the decarbonisation of the economy in the next decade would require investment in production and incorporation of renewable energy into the grid, especially green hydrogen. There are number of ongoing projects with promising potential, Figure 4. The Fusion Fuel company in Evora is very remarkable, as it uses electrical and thermal energy for electrolysis directly from solar radiation with an efficiency rating of 26% [19]. Portugal intends to exploit the strengths such as abundance of renewable resources & water, suitable infrastructure (which will be developed) and close proximity to neighbouring nations which would allow easy export of hydrogen, with strong business models that align with long term objectives of carbon neutrality with hydrogen playing a central role [16] [17].

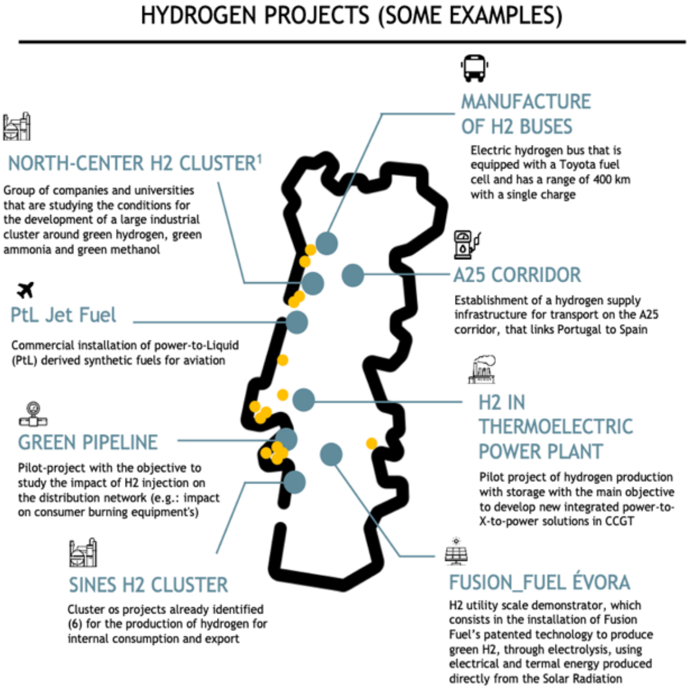


Figure 4 Noteworthy H2 projects in Portugal [15].

1.2 Objectives

This dissertation aims to study the feasibility of integration of various available hydrogen fuel cell technologies for co-generation for residential buildings and weather conditions in Europe. The study considers and compares the outputs of energy modelling for one building located in Lisbon and London, and the viability analysis of using hydrogen fuel cells cogeneration for heating. To achieve the objectives of the present study, the following deliveries are proposed:

- Analyse the production, storage and transport of hydrogen and the necessary changes to be made in the existing infrastructure.
- Calculation of Levelized Cost of Hydrogen (LCOH), internal rate of return (IRR), and Carbon Dioxide Emission analysis.
- Modelling and simulation buildings in Lisbon and London using Energy Plus.

1.3 Structure

Chapter 1

A brief Introduction and Motivation explain the premise and need for the technology under review. Establishing objectives of the dissertation and structure of approach of the analysis.

Chapter 2

Analysis of the production, storage and transportation of hydrogen. Suitable infrastructure associated with the same. Discussion of all the parameters need to be considered for hydrogen to reach the end user.

Chapter 3

Technology review of the hydrogen technologies that will be used for electricity and heat production from hydrogen in residential buildings. Collection of data (H2 fuel cells). Case studies.

Chapter 4

Modelling & Simulation (inputs: data collection for characterization of the building stock// outputs: heating hourly demand) using energy plus.

Results and inferences of Energyplus outputs.

Chapter 5

Conclusion and proposals.

2 A Future with Hydrogen Economy

Hydrogen provides a pathway to clean and sustainable world economy. Although hydrogen is 10th most abundant element found in earth crust, as water and biomass, it is not available in its natural gas molecular form. It is almost always found in combination with other elements like oxygen (water) or carbon (hydrocarbons). Hence the production of hydrogen, which is a significant energy consuming process. It can be produced by domestically available sources like clean coal, nuclear energy and intermittent renewables (solar, wind etc.). Producing hydrogen form solar and wind energy has the potential to significantly reduce the energy lost due to curtailment and boosts efficiency in storage systems. Countries with existing natural gas infrastructure will require considerably less investments considering that hydrogen can be transported to the end user using the gas pipelines. Introducing the use of hydrogen in the energy sector would speed up the decarbonization of world economy as it has number of stationary (buildings, industries) and mobile (heavy duty transport) applications. Figure 5 shows a life cycle of hydrogen.

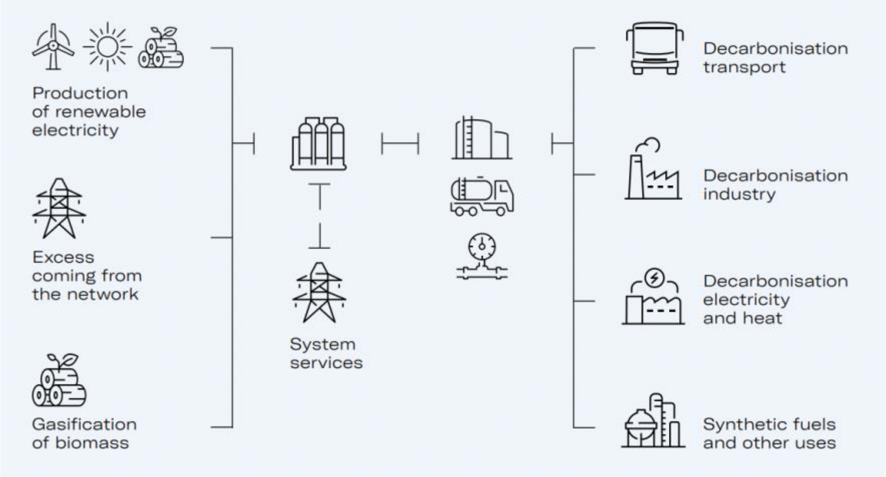


Figure 5 Production, transport and end-use of H[17].

2.1 Production Methods of Hydrogen

Development of clean, sustainable, efficient and cost-effective hydrogen technologies will be essential. With the above parameters in mind, six promising technologies categorized in three sections are discussed below Table 3.

Table 3 Hydrogen Production Processes

Thermal	**Distributed Natural Gas Reforming**
	Coal Gasification
	Thermochemcial Production
Photolytic	**PhotoElectrochemical Hydrogen Production**
	Biological Hydrogen Production
Electrolytic	**Water Electrolysis**

2.1.1 Thermal Process

2.1.1.1 Natural Gas Reforming

The most prolific method of producing hydrogen is natural gas reforming. Around 6% of the total natural gas demand, i.e., 70 million tons was used to produce 60% of hydrogen in 2020 [20] [21]. The three main stages in methane steam reforming is (1) syngas generation, (2) water–gas shift, and (3) hydrogen purification.

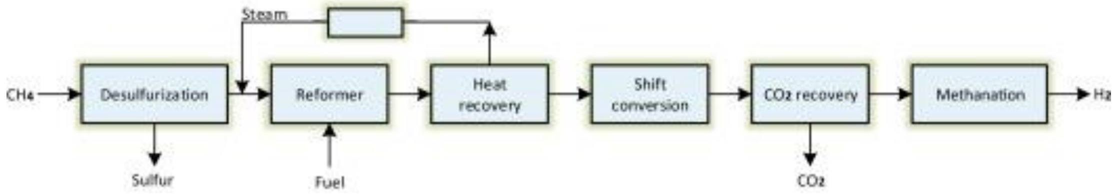


Figure 6 Natural gas reforming flow chart [22].

The desulfurized methane from natural gas is fed to the reformer, where a high temperature steam (700°C–1000°C) with the methane under 3–25 bar of pressure. This reaction is an endothermic reaction, 1. The carbon monoxide (CO) generated from the reforming reaction is then involved in second stage reaction i.e., water gas shift reaction, 2, where CO reacts with steam and generate carbon dioxide (CO_2) and additional hydrogen. In the final stage of the process called pressure swing adsorption, the impurities and by-product gases are eliminated from the gas stream and pure hydrogen is collected at the end. Similar processes are also applicable for hydrogen production from ethanol or propanol [22]. Thermal process to hydrogen production has efficiencies 65% -75% (lower heating value of hydrogen).

Steam Methane Reforming Section.

$$CH_4 + H_2O\ (+Heat) \rightarrow CO + 3H_2 \quad (1)$$

Water Gas Shift Reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

2.1.1.2 Coal Gasification

The process of obtaining hydrogen from coal involves three-stages. Initially the coal is oxidized through traditional combustion. The resulting reaction produces carbon dioxide as a by-product, which acts as a gasification agent in the next step. The carbon dioxide produced reacts with the rest of the coal to produce carbon-monoxide in an endothermic process. The carbon monoxide produced from the second stage is made to react with steam to form hydrogen and release carbon dioxide. An illustration of the process is shown in the Figure 7.

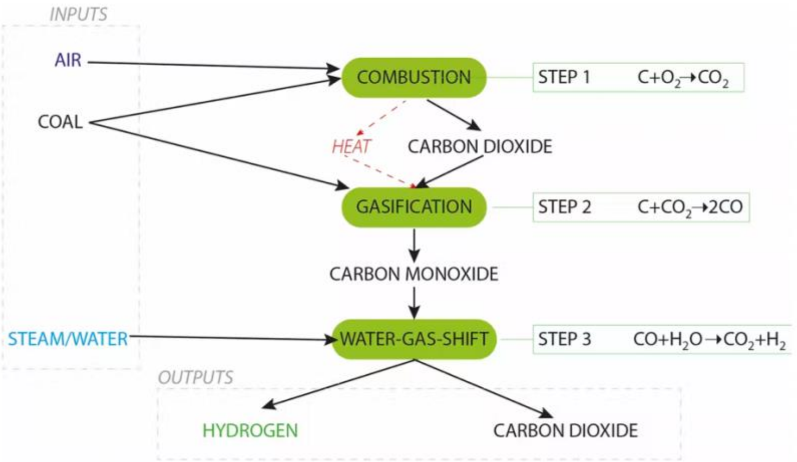


Figure 7 Hydrogen production stages [21].

Around 2% (148.76 Mtons) of the coal consumed in 2020 was used for the production of hydrogen [21]. The cost of hydrogen produced form natural gas and coal is the cheapest among the available existing technologies, which is the primary factor in encouraging the production of hydrogen from fossil despite the emissions exceeding 830 million tons of carbon dioxide per year [21] [23]. The cost of hydrogen production from natural gas and coal is around 0.9-3.2 \$/kg and 1.2-2.2 \$/kg [21], Figure 8.

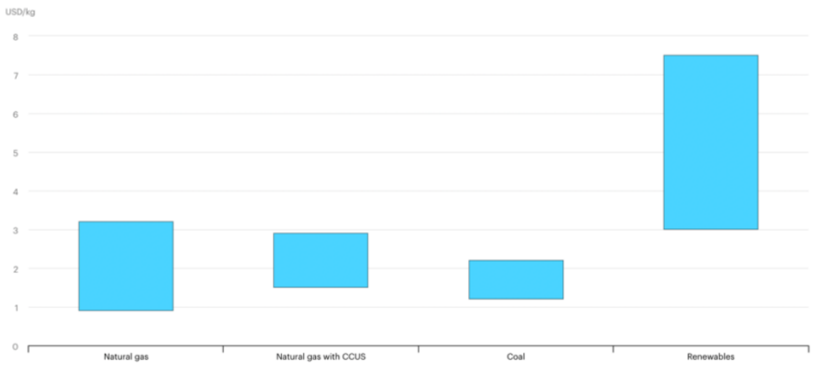


Figure 8 Hydrogen production cost by production source [23]

2.1.1.3 Thermochemical Production

In this method, water is split into hydrogen and oxygen using a heat in a chemical reaction. The process has oxygen and waste heat as its by-products. The reaction or process is called thermochemical water decomposition. The source of heat can be solar or nuclear which allows the process to have high efficiency rates. Solar thermochemical process is the most prominent technology that can produce storable and transportable hydrogen. The process consists of a two-step redox cycle with endothermic solar thermal reduction of a metal oxide (M_XO_Y) releasing oxygen (O) using concentrated solar energy as heat source and the exothermic oxidation of the oxide with water (H_2O) to produce hydrogen (H_2).

High temperature reduction step

$$M_XO_Y \rightarrow M_XO_{Y-1} + 1/2O_2 \tag{3}$$

Hydrolysis step

$$M_XO_{Y-1} + H_2O \rightarrow M_XO_Y + H_2 \tag{4}$$

A study conducted in the US shows with improvements in the efficiency of the process, hydrogen can be produced for about 2.1–3.2 €/kg (2.4–3.6 $/kg) with greenhouse gas emissions of 1.4 kg CO_2-eq/kg [24].

2.1.2 Photolytic Process

2.1.2.1 Photoelectrochemical Hydrogen Production

The process involves the splitting of water to produce hydrogen from the energy from sunlight using specialized semiconductors. The semiconductors are called specialized photoelectrochemical materials, which use light to separate water into hydrogen and oxygen. The process is similar to photovoltaic electricity generation, except this system is placed in a water-based electrolyte, where the sunlight energizes the process. The photoelectrochemical (PEC) system is either in the form of an electrode system or slurry-based particle systems. Photoelectrochemical solar-to-hydrogen conversion efficiencies as high as 7.8% (based on the lower heating value of hydrogen).

In water-splitting PEC cell, the electron excitation in a semiconductor using light leaving a hole that draws electron through adjacent water molecule.

$$H_20 \rightarrow 2H^+ + 1/2\ O_2 \qquad 5$$

This leaves positively charged carriers (H+ ions) in the solution that reacts with another positively charged ion, combining two electrons (e) to form hydrogen gas.

$$2H^+ + 2e^- \rightarrow H_2 \qquad 6$$

2.1.2.2 Biological Hydrogen Production

Abundance in the availability of biomass makes producing hydrogen from organic products a promising solution. Growing biomass captures carbon dioxide from the atmosphere. Hence when hydrogen is produced from biomass using carbon capture and storage technologies, has a feasibly low carbon footprint. The production of hydrogen from biomass involves two stages, *Gasification* and *Water-Gas shift reaction*. Although photosynthesis is a highly successful and replicable biological process in nature, its conversion efficiency from radiant energy to biomass is about 2%.

The process

In this process, organic or fossil-based carbonaceous materials are converted at temperatures greater than 700 °C, without combustion, with a controlled amount of oxygen and/or steam. The carbon monoxide produced then reacts with water to form carbon dioxide and more hydrogen using a water-gas shift reaction. Specially designed membranes can separate the hydrogen from gas stream.

Gasification reaction

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 \quad 7$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+ small amount of heat)} \quad 8$$

In the US with development in agricultural practices, around 1 Billion tons of biomass will be available for energy use every year [25]. The ready availability of biomass coupled with its potential as a recycling medium has encouraged Europe and US to incorporate the use of biomass to produce hydrogen in their energy mix [14], Figure 9.

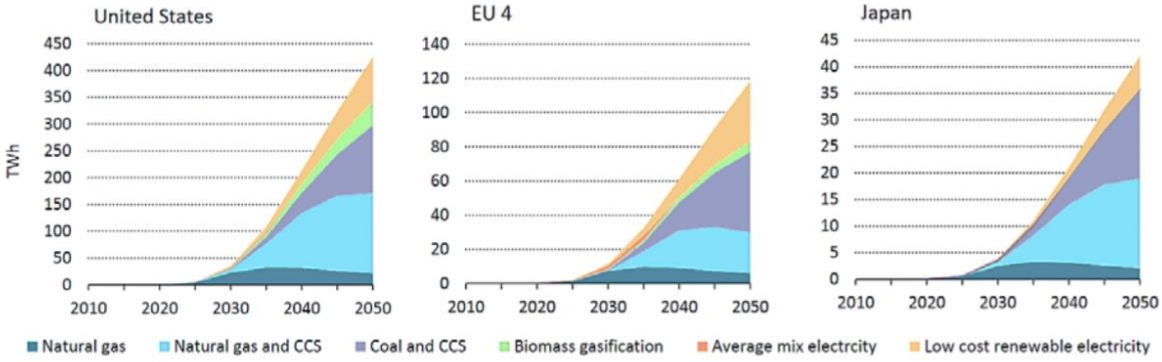


Figure 9 Hydrogen Production Sources [14].

2.1.3 Electrolytic

2.1.3.1 Water Electrolysis

Water electrolysis is the most promising technology to produce green hydrogen. Electrolysis was once the dominant hydrogen production technique, for 40 years, between 1920 and 1960, but with non-green electricity. Electrolysis lost its dominance to steam reforming around 1950 due to the low cost of natural gas, which made steam reforming the most economically competitive process. The electrolysis process involves using electricity to split water into hydrogen and oxygen. The process virtually emits zero emissions, provided if the energy used to split water is derived only from renewable energy sources like wind, solar, hydro or nuclear power. Hydrogen produced from wind and solar acts as a solution to the energy lost due to curtailment. The inherent variability of wind and solar energy can be mitigated by integrating hydrogen into pipelines and subsequently to fuel cell system with wind or solar farms, thus ensuring flexibility in energy production and maintaining a constant supply of energy. From the 90 Mt of hydrogen produced in 2020 only 0.03% of hydrogen was produced from water electrolysis [20]. Around 290 MW of global electrolyzer is installed globally and 40% of it is in Europe [20].

Water is split into oxygen at the cathode and hydrogen ions at the anode when electricity is passed through it. The electrons flow through an external circuit and the hydrogen ions selectively moves across the PEM to the cathode. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

Anode Reaction

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{9}$$

Cathode Reaction

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{10}$$

2.2 Hydrogen Infrastructure

The Energy transition demands a drastic change in the current power system. In order to implement the consumption of largescale hydrogen energy systems, it will be imperative to make necessary adjustments to the existing infrastructure which mainly consists of coal and natural gas power plants producing electricity which then reaches the end user through transmission lines. Depending on the method (from renewable or low carbon methods) and location of hydrogen production (decentralized or centralized) and its end use (industrial, buildings, transport), the financial feasibility and efficiency, there is a need to make immediate investments and create favorable policy frameworks that engender a hydrogen economy. Some key challenges that need to be addressed are efficient transportation, maintaining hydrogen purity and preventing hydrogen leakages. In the following section potential hydrogen storage and transportation systems are studied and analysed.

2.2.1 Transportation

The density of hydrogen is extremely low with 0.00075kg in one gallon at 1 atm pressure at 0^{o}C [26]. Large quantities of hydrogen transportation require compression into high pressure (350 – 900 Bar) gas or liquid form at compression stations and distribution using trucks with tanks or pipelines.

2.2.1.1 Compression and Transportation for Gasified Hydrogen

Hydrogen is typically produced at very low pressures ranging from 20-30 bar [27]. If it has to be efficiently and economically transported, it must be compressed to 200-500 bar [28]. There are different compressors currently employed, prominent among them being positive displacement compressors or centrifugal compressors. Positive displacement compressors are either reciprocating or rotary. The high compression ratios (outlet/inlet pressure) of these compressors allow them to find applications in compressing hydrogen for transportation using tanks. A tube trailer with steel cylinders stores around 25000 litres of hydrogen under 200 bar pressure, i.e., 420 kg of hydrogen [28]. Research is being conducted for lighter tanks to save expenses on transportation. Lighter tank materials that can carry 39600 litres (666 kg) of hydrogen under 200 bar pressure [28] are under development.

Centrifugal compressors are used for pipeline applications. These compressors can compress high amounts of hydrogen per unit time (i.e., have high throughput, kg/h). Centrifugal compressor uses a high-speed turbine to compress the gas. These compressors rotate at a speed 3 times than for natural gas, as hydrogen has low molecular weight [29]. Hence safety and energy consumption of these compressors become parameters that need serious attention. A typical hydrogen pipeline has 40 Bar pressure and requires compensation mechanisms for an approximate loss of 20 bar pressure [30]. The energy consumption for the compression of hydrogen depends on its higher heating value (HHV) as referred to in Figure 10. On average around 7.2% of HHV of hydrogen is consumed in the compression [31].

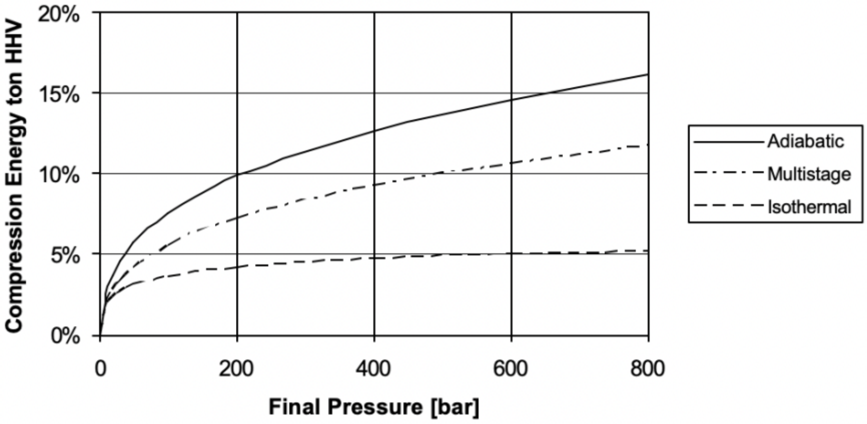


Figure 10 Energy required for the compression of hydrogen compared to its HHV [31].

There are still a number of issues associated with converting compressor stations to support hydrogen. Reciprocating compressors are not ideal for large-diameter pipelines, which are needed for hydrogen pipelines. Also currently it is not feasible to retrofit the gas turbine to handle gas with more than 40% hydrogen [32]. As a remedy, there is a need for new turbines with impellers that are resistant to hydrogen.

Hydrogen can be transported through either existing natural gas pipelines or construction of new pipelines which incur considerable investments. Repurposing of existing natural gas pipelines for hydrogen transport would mean considerable cost savings. Hydrogen can be transported in these pipelines at three times the speed of natural gas and 80% of its full load capacity [29]. However, adjustments have to be made to the materials of some old pipes (embrittlement of steel) and pressure, for hydrogen use. According to Marcogas (Technical Association of the European Gas Industry), pipelines in Europe are 85% compatible with hydrogen.

2.2.1.2 Compression and Transportation for Liquefied Hydrogen.

Hydrogen is transported in liquid forms when there is a high-volume transport is the necessary. Liquefaction of hydrogen is achieved through cryogenic cooling (-253 °C) and transported via liquid tankers. The process of liquefaction consumes around 30% energy content of hydrogen and makes the hydrogen more expensive. Additionally, there is also high chances of loss of hydrogen due to evaporation or boil-off [33]. Cryogenic refrigeration of hydrogen requires complex procedures involving Carnot cycles. A single step Carnot Cycle compression would consume 57 MJ/kg or 40% of the HHV at the rate of 50 kg/hr [31], Figure 11.

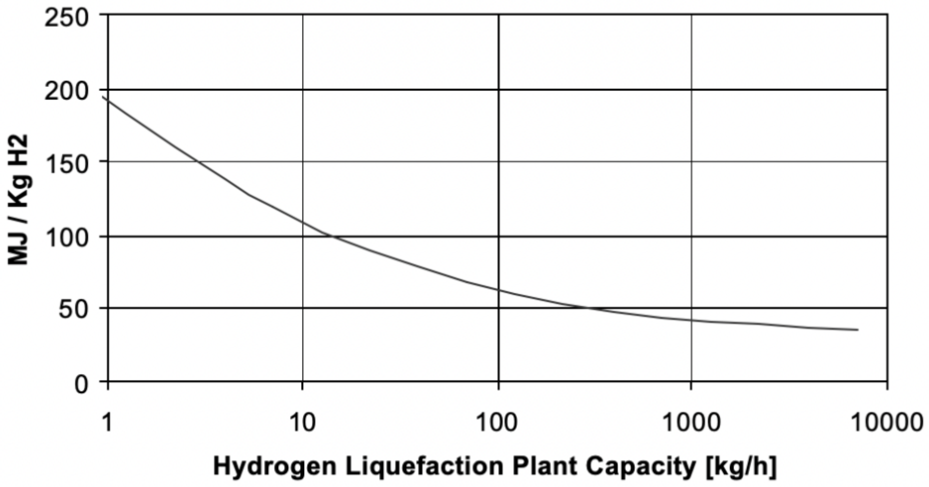


Figure 11 Typical energy requirements for the liquefaction of 1 kg hydrogen [31].

The main mode of transportation of liquid hydrogen is through liquid tankers. Trucking long distance liquid hydrogen is more economical as compared to gaseous hydrogen as it constitutes more mass, hence more energy.

Long distance transmission of hydrogen is preferred using pipelines due to their economic feasibility and efficiency. There are currently 5000 kms of hydrogen pipelines. For short distance transmission and distributions trailer trucks are used as they are more elastic. Trucks are preferred for transmission of hydrogen for less than 300 kms. Long distance transport of hydrogen heats up the hydrogen and increase in pressure. It is cost effective to transport hydrogen in pipelines within 1500 km [21].

2.2.1.3 Blending Hydrogen in Natural Gas

Incorporating new hydrogen supply chains would require considerable investments, adjustments in existing infrastructure, creation of new production, transmission, distribution and storage systems. This would also demand co-operation and co-ordination among various market participants. A potential solution would be to blend hydrogen to existing natural gas infrastructures and save considerable costs. Blending hydrogen with natural gas would mean an increase in the cost of natural gas but also lowers the CO_2 emission associated with it.

However, there will still be need of some investments and changes. For example, a 3% adulteration of natural gas with hydrogen would mean a 12 MtH_2 increase in the demand for global hydrogen [21]. This would require installations of electrolyzers with 100 GW capacity (with 50% load capacity) [21].

Hydrogen blending would also mean an increase in the volume of consumption of gas, as the energy density of natural gas is three times as much as hydrogen as mentioned in Table 1. So, end users would need 3 times greater gas volumes to meet an energy need.

Variability of blending percentage would affect the operation of the equipment and hence the end product. This would require strict blending regulations. The blending percentage will depend on the end-use and might give rise to complications in grid infrastructure. Many heating and cooking appliances are certified to handle 23% hydrogen, while certain chemical industries cannot use natural gas with more than 5% hydrogen [21]. The blending percentage of hydrogen would also depend on the materials of the natural gas pipelines. Figure 12 shows the different blending limits for various applications.

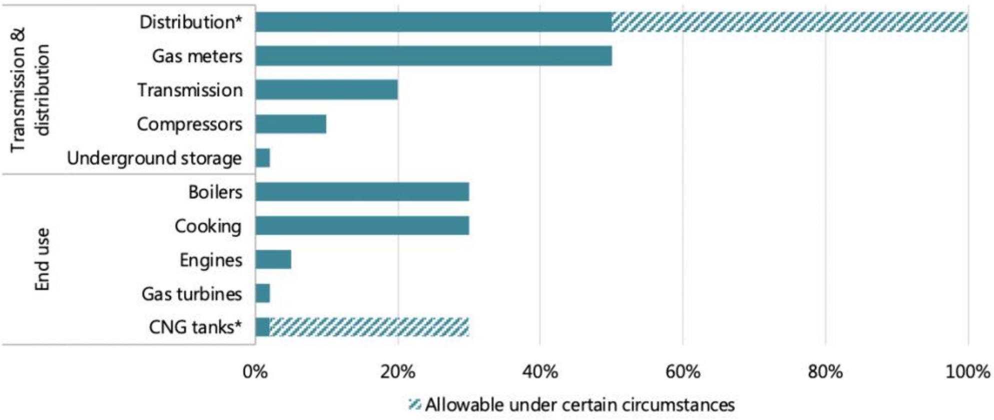


Figure 12 Tolerance of different elements of the natural gas network to hydrogen blend [21].

2.2.2 Storage

Hydrogen produced is usually stored in the form of gas or liquid (similar to natural gas). Depending on the volume of storage and immediacy of use, currently hydrogen is stored either in geological storage mediums or storage tanks. It is economically feasible to store large scale hydrogen in geological storages for the long term and in tanks for small scale and short durations.

Traditionally hydrogen used in industries and chemical facilities are stored in depleted oil/gas reserves, salt caverns and aquifers. These types of storage systems provide high economies of scale, high efficiencies, low operational and land costs. However, care must be taken to make necessary changes to prevent the contamination of hydrogen by impurities or micro-organisms. Salt caverns are the best options for hydrogen storage as they cost 0.6 $\$/kgH_2$, have an efficiency of about 98% and have extremely low chances of contamination [21]. Depleted natural gas reservoirs have to be redesigned to accommodate hydrogen. The huge size of such reservoirs and contaminants present can significantly affect the quality of hydrogen stored. Aquifers are the least mature geological storage technology. They pose a serious threat to the stored hydrogen in terms of reaction with the rocks and other fluids.

Storage tanks can have high capacity and the pressure can be easily regulated. They can be designed to have specific and flexible discharge rates that makes them suitable for small scale applications. Hydrogen’s energy density is much smaller than natural gas or gasoline. This would imply that storage tanks for hydrogen would have to be considerably bigger in size to store the amount of energy. The equipment needed for conversion and reconversion by end-users adds to the cost of hydrogen.

Research is being conducted to increase the energy density of hydrogen and thereby reduce the size of storage mediums. Theoretically, hydrogen stored in solid state materials like metal hydride would be the best possible means to store hydrogen and are in early stages of development.

2.3 Tracking Buildings

Energy consumed in buildings in 2020 for heat and electricity amount to 72.3 EJ and 41.9 EJ respectively, which had a share of 30% in the final energy consumption. Around a third of the energy consumed in buildings goes towards space heating, hot water generation and cooking. The emissions from buildings were estimated to be 9 Gt in 2020 which amounts to 28% of the total CO_2 emitted. Due to covid there could be noted a decline in the CO_2 emissions in the building sector but apart from that there has been a consistent 1% increase every year from

118 EJ in 2010 to 130 EJ in 2020 [21] [34]. In order to keep up with the Net Zero Scenario, according to which, new buildings and 20% of existing buildings must achieve net zero emissions by 2030. Most developing nations are tightening the minimum performance requirements, deploying heat pumps and renewable energy equipment. Most importantly the use of conventional biomass which has caused the deaths of 2.5 million people has to be phased out. Extreme weather events like heatwaves and harsh winters are causing an increase in the purchase and utilization of heating and cooling equipment. The households with access to heating and cooling equipment grew from 27% in 2010 to 35% in 2020 [21] [34], which signifies a progress in the standard of living but also in the consumption of resources, energy and thereby emissions. This growth is much quicker than the improvements bought in energy efficiency of thermal equipment. In the following section an assessment has been made on potential for hydrogen as a primary source for different types of buildings and weather conditions.

Although hydrogen technology seems like a promising application for buildings considering all the positive features as discussed in Table 1, a multitude of variables need to be accounted to ensure its feasibility such as energy load profile of the building, location, weather, efficiency, economic feasibility and overall convenience. These factors imply a possibility of the existence of multiple technologies (hybrid technologies) in the near future, each catering to the unique needs of a specified structure. An in-depth analysis is done in the following section to study the potential pathways for hydrogen to reach buildings, suitable weather profile, fuel cell technology for specific applications (heating, cooling etc) and monetary feasibility.

2.3.1 Fuel Cell Technologies

Depending on the application a number of fuel cell technologies are available. Some structures have high heat requirements, while some have high electricity requirements. The operating temperatures and type of fuel required also play a factor in fuel cell technology. Based on the electricity-heat demand of a building, specific fuel cells with unique technologies can be adopted.

Table 4 gives a detail specifications of various fuel cells.

Table 4 Comparison of Fuel Cell Technologies[35].

Fuel Cell Type	Electrolyte	Operating Temperature	Typical Stack Size	Efficiency
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120^{0}C	<1kW-100kW	60% for direct H_2
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100^{0}C	1-100kW	60%
Phosphoric acid (PAFC)	Phosphoric acid soaked in a porous matrix (PAFC) or imbibed in a polymer membrane	150^{0}C -200^{0}C	5-400kW (Liquid PAFC) <10kW (polymer membrane)	40%
Molten carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600^{0}C -700^{0}C	300kW-3MW	50%
Solid oxide (SOFC)	Yttria stabilized zirconia	500^{0}C -1000^{0}C	1kW-2MW	60%

2.4 Hydrogen for buildings (Cogeneration)

2.4.1 Potential Pathways for Hydrogen to reach Buildings

There are a number of ways for hydrogen to reach end user. For instance, through cylinders, hydrogen pipelines or blending hydrogen in the existing natural gas network. Blending hydrogen with natural gas into the existing pipelines can act as an intermediate solution. This method of hydrogen reaching the end-user significantly reduces the investment needed. There are already projects around the globe that use blending ratios between 5-20%, depending on the green hydrogen availability and safety norms, to provide hydrogen to the end-user [36].

2.4.1.1 The GRHYD Project, France

The GRHYD project in France [37] is an example of successful demonstration in blending hydrogen in natural gas network. In this project, Hythane (a mixture of hydrogen and natural gas) was simulated, demonstrated and assessed to power the housing (heating & hot water) and transportation needs. The housing energy demand and supply was demonstrated in the Le Petite neighbourhood while a fuel station was adapted to support a blend of hydrogen/natural gas for a fleet of 50 buses in the Dunkirk Community. The projects showed positive outcomes which engendered a growth in size of the project.

Key Take-Aways of The GRHYD Project [37]

- Hydrogen was produced exclusively from wind farms, which mitigated the curtailment losses. The blending ration was kept below 20%.
- A proton Exchange membrane electrolyzer with 10 m^3/h capacity and storage of 5 kg in the form of metal hydrides was used to meet the demands of the neighbourhood with an adapted injection equipment.
- At completion of the project, the energy needs of around 200 homes was successfully met.

2.4.1.2 HyDeploy Project, United Kingdom

HyDeploy Project in United Kingdom was studied in phases. The first phase involved blending hydrogen in a gas network in Keele University, Standforshire. Keel university was chosen because of its accessibility to a private gas network and its campus populations which was analogous to a small town. During the 18-month trail, 100 homes and 30 university buildings were powered by blended hydrogen. The effects of the blended hydrogen on the materials found in the existing gas network and appliances and concluded that up to 20% blending of hydrogen had innocuous effects on the concerned equipment [38].

This project with a 20% blending of hydrogen ratio, shows an increase of 6% and 8% in cost for domestic and industrial applications respectively, which comes to £2.5/month additional energy cost for a typical household. Within the UK Hydrogen Strategy, where hydrogen will be produced form reforming rather than electrolysis as compared to the EU, the cost of hydrogen would be £60/MWh [39][40]. The project boasts an impressive removal of 6 million tonnes a year of CO_2 emissions per year [40].
The success of the Keele phase encouraged to demonstrate on a bigger scale with the Winlaton trail of 2021. Winlaton chosen because of its close proximity to the Northern Gas Network near Gateshead and Walton’s gas network itself is similar to a typical UK gas network. The project powered 668 houses, a school, small business and a church. The residency were not charged for the blended hydrogen [38].

Phase 3 of the project is currently in progress and deals with gathering safety evidences that would solidify the project once and for all.

2.4.1.3 Store&Go Project

STORE&GO project aims to create a network throughout Europe that allow generation, transportation and storage of clean gas (hydrogen or methane). The application of the project would seem like an ideal way for hydrogen or methane to reach the end user. This project which was funded by the European Union’s Horizon 2020 research and development program, aims to exploit 100 billion m^3 capacity of Europe’s existing gas storages for renewable hydrogen or renewable methane [41]. It acts an alternative solution to building electricity networks as hydrogen and methane can be transported through gas networks, thereby cutting tremendous expenditures in building a suitable grid infrastructure as graphically depicted in Figure 13 & Figure 14.

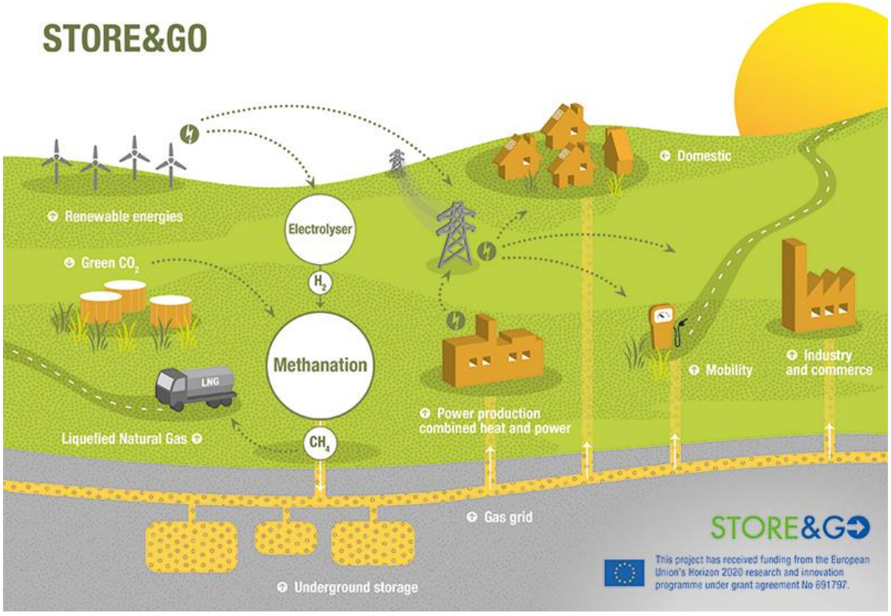


Figure 13 Illustration of STORE&GO project [41].

One of the main goals of the project was to study the carbon footprint of the proposed technology, which would depend on a variety of reasons (location, electricity generation mix, source of CO_2 etc). For a specific case of Troia Plant in Italy, the carbon footprint was assessed to be 14.1 kg/m^3.This value will be reduced by 84% when the plant is exclusively powered by renewables in the near future [41].

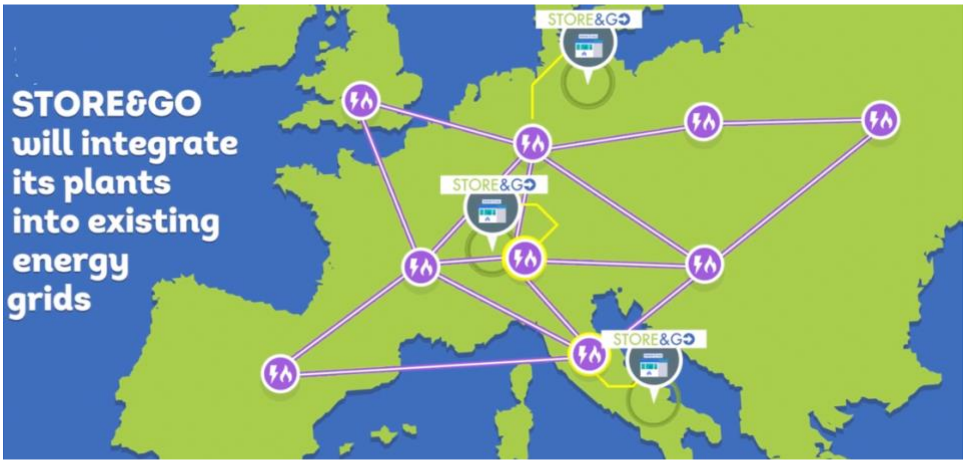


Figure 14 A Graphic of the proposed network in Europe [41].

The projects have three main plants for methanation, each using unique technologies.

1. Italy – Modular milli-structured catalytic reactors.
2. Switzerland – Biological Methanation.
3. Germany – Isothermal catalytic reactors.

2.4.2 Fuel Cell Technology for Buildings

2.4.2.1 ENE – Farm, Japan

ENE-farm technology is one of the most promising technologies to come out of Japan that uses liquefied petroleum gas (LPG) and oxygen from ambient air to produce hydrogen which further will be used in a fuel cell to generate electricity. The system high-efficiency ratios due to its ability to harness residual heat for hot water requirements. The rating of the fuel cell ranges from 0.3 kW to 1 kW, enough to power a typical household [42].

The hot water supply unit has the capacity to hold 200 litres at 60 ºC and when the hot water runs out, the alternative heating equipment comes online [42].

Assuming the supply of green LPG, the ENE-farm system is an incredibly suitable technology for the energy transition. Japan intends to roll out as many 2.5 million units of ENE-farm technology by the end of 2030 [42].

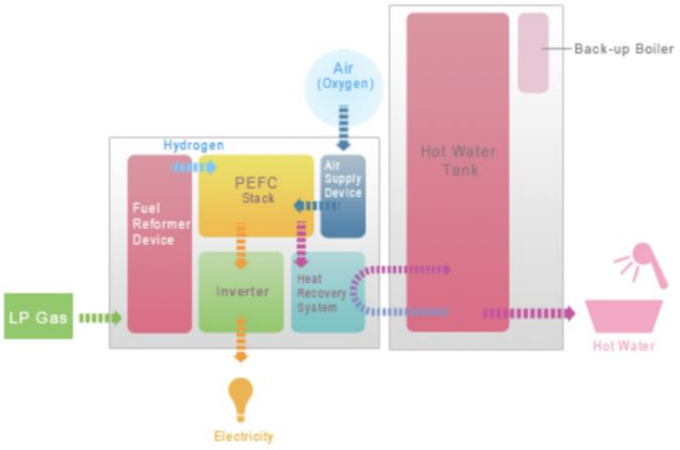


Figure 15 Mechanism of ENE-Farm Fuel Cell [42].

2.4.2.2 ENE.Field, Europe

The ENE.field project was a venture in association with numerous of companies like Baxi Innotech, Bosch, Danthempower, Elcore, Hexis to name a few. The aim of the project was to manufacture a fuel cell (FC) for household applications. Depending on the ratio of electricity to heat demand in a house, two different fuel cells were developed as a prototype, one is heat-led and the other is electricity-led. The specifics of the fuel cells can be found in Table 5[43].

Table 5 Specifications of ENE.field Fuel Cell [43].

Technical Characteristics	**Summary of Products**	
FC technology	LT/HT PEM	Inter/HT SOFC
Electrical rating	1-5kW	0.8-2.5kW
Heat rating	1.4-10kW	1.4-25kW
System Efficiency	85-90%	80-90%
Thermal Efficiency	35%	35-60%

As these FCs are tailored to produce heat and electricity and typically have a rating of less than 50 kW, they are referred to as micro-combined heat and power systems (micro-CHPs). Depending of specific applications and requirements these units are manufactured in different sizes (ranging from 300W-5kW) [43].

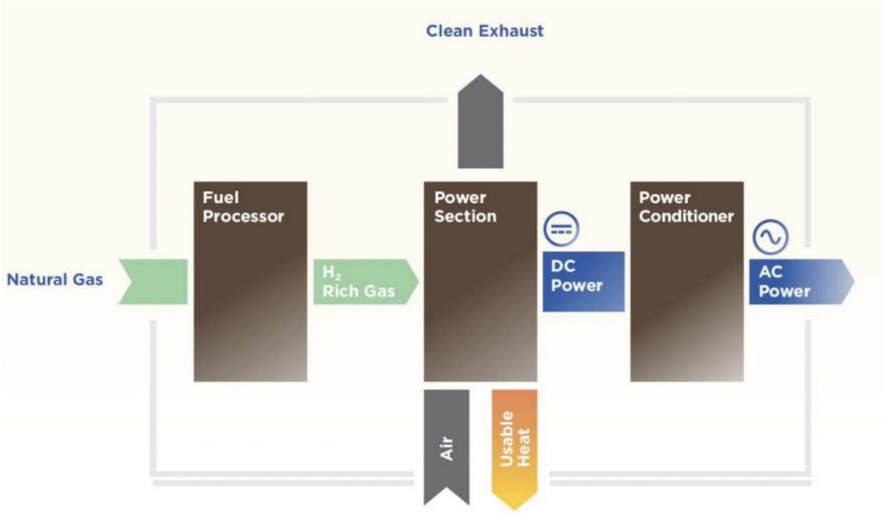


Figure 16 Components of FC micro-CHPs [43].

From the Figure 16 we can see that the FC micro-CHP uses natural gas to produce heat and electricity. Micro-CHPs were installed and operated on 1000 homes which allowed the personnel responsible to draw conclusions about efficiencies, reliability, time & ease of installations and customer receptivity & satisfaction. Of the installed units 603 units were SOFC and 446 units were PEM based. Using sensors and monitoring devices, these units were operated, monitored and observed for 5.5 million hours. During this period, the units produced around 4.5 million kWh of electricity with an installed capacity of 1155 kW[43]. Heat and electricity demand, indoor and outdoor temperatures were analysed for ideal performance.

Route to Market

There were two common ways for the product to reach the end-user, through architects, HVACs system installers or though utility companies. However due to high initial price of in the technology, it seemed feasible to install the units mostly in Germany, as Germany had excellent financial incentives. Around 750 units of the 1046 units have been installed in Germany [43]. It is believed by increasing the scale of production which would depend on the success of the project, the cost of the units will be considerably cheaper.

Efficiency

These systems have high efficiency compared to a typical heat pump or gas condensing boilers. The efficiencies mainly depend on the type of FC (solid oxide or polymer electrolyte) and the environmental conditions of the applications. Based on data collected from the installed units, it was noted that the SOFC and PEM FCs have a thermal efficiency ranging from 30-59% and 48-66% respectively and an electrical efficiency of 28-47% and 28-39% [43]. According to report due to a non-uniform Latent Heat Values (LHVs) across Europe, a nominal value was considered, which may cause a slight deviation from actual values of efficiencies.

Availability of Installed units and Failures.

The availability of the units, is an assessment of the scenarios where the units failed to meet the generate either heat or electricity. The units had displayed an availability of 99% on an average, implying above satisfactory performance. An in-depth analysis of 67 units showed that 45% of the units had 100% availability. The remaining 55% of the units had one or more failures [43]. However, 90% of the micro-CHPs were available for 95% of the time, which was a promising outcome [43].

Of the total failures encountered, only 2% of them was a result of core fuel stack component. This is a positive sign signaling robustness of the units. Around 125 of the failures was attributed to inverters and reformers [43].

Smart Grid Capability.

A serious issue that needed to be addressed is the ability of the unit to be connected to the grid. The system has features that allows remote operation & control, adjustments of variables based on real-time temperature data with fast response times and summation capabilities. These features make the integration of ‘n’ number of units as a virtual power plant, viable. As the technology gains ground among the masses, standardization of the concerned variables that would allow smooth integration into the grid and curb transmission losses.

Life Cycle Assessment (LCA)

An LCA conducted showed that the *Ene.field* micro-CHP fuel cell system is vastly better in terms of saving CO_2 emissions as compared to the alternative available energy sources. The Figure 17 represents a replacement scenario, where the existing different kinds of energy mixes are supplanted by FC micro-CHPs [43].

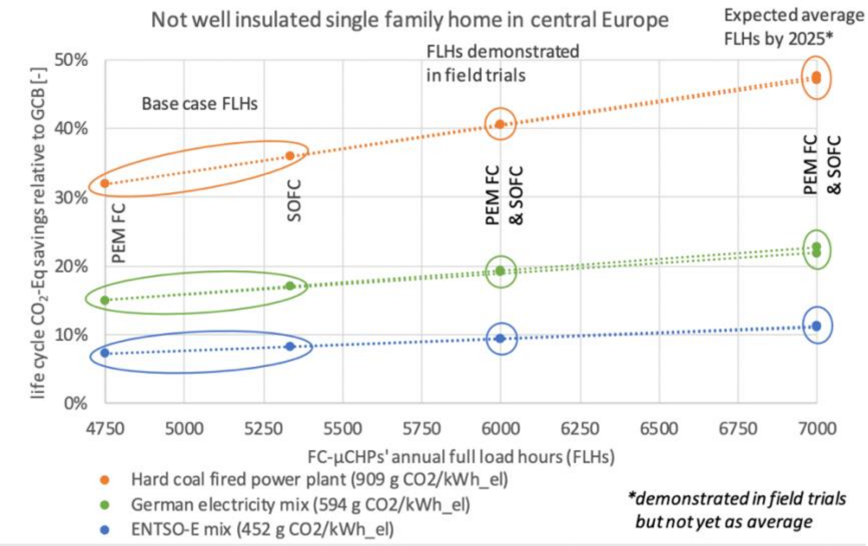


Figure 17 Comparative LCA analysis of FC micro-CHPs with existing energy mix [43].

2.4.2.3 The PACE Project

The success of the *Ene.field* project encouraged the development of the PACE project which was a venture in association with a number of prominent European technology and utility companies. This project aims to deploy over 2800 micro-CHPs across 10 European nations by 2022 with emphasis on homes and small enterprises. The project has an investment of €90 million funded by Fuel Cell and Hydrogen 2 Joint Undertaking [44].

2.5 Building Energy Simulation (BES)

The number of benefits from using Building Energy Simulation (BES) tools are numerous. Chief among them being the ability to evaluate the feasibility of various energy systems for a particular type of building (residential, commercial etc) for a given location (weather profile) with an energy demand and consumption type (electricity, space heating & cooling) and the thermal comfort level demanded by the occupants. The results of the dynamic simulations become more and more accurate and in line with the real-life scenarios depending on the nuances that are being considered in the BES tool. Although the design and simulation become increasing cumbersome with added inputs and detail, there are a number of BES tools available that have very user-friendly interface. For this dissertation a residential building was designed in Google Sketchup [45] and the simulation was executed on EnergyPlus6 [46] for reasons elaborated in section 2.5.1.

2.5.1 EnergyPlus

EnergyPlus is the official building simulation program of United States DOE. This program is promoted through the Building and Technology Program of the Energy Efficiency and Renewable Energy Office, and EnergyPlus team includes National Renewable Energy Lab, Lawrence Berkeley National Laboratory, and DOE, among others.

Considered as one of the most advanced, well-known, widespread and accepted building energy simulation software tools over the world [47], [48], EnergyPlus, as defined by the official website (EnergyPlus, no date), “is a publicly-available whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption — for heating, cooling, ventilation, lighting and plug and process loads — and water use in building”. DesignBuilder allows to visualize and concept the building, since EnergyPlus does not have a visual interface. Figure 18, Figure 19 and Figure 20 exhibit some of the tools and services supported by EnergyPlus and OpenStudio.

Figure 18: Public and private-sector tools and services supported by EnergyPlus, obtained from [49]

Some of the most relevant inputs of the software are the geometry and materials of the building, internal loads and an extensive HVAC characterization. Relevant outputs as energy needs and consumption, costs, thermal comfort are obtained on at least 15min time resolution [52], [53]. Additionally, as reported by [54], other capabilities included are solar thermal and also photovoltaic systems and fuel cells. Regarding the features, some of them are modular systems that are user-configurable and integrated with the heat and mass balance of the zone simulation, or the data structures of inputs and outputs that help third party interface development [50]. Table 6 exhibits some of its notable features and capabilities.

Table 6: Some of EnergyPlus main features, [50], [51]

Features	EnergyPlus
Inputs	Text, IDF/IDD
Outputs	Extensive summary and detailed reports with user specified time steps
GUI	Simulation engine only; Third party GUIs: OpenStudio, DesignBuilder, etc.
Algorithms	Surface Heat Balance; Zone Air Heat Balance
Limitations	Potentially long run time for detailed models
Time Step	Sub-hourly, user definable
Weather Data	Hourly or sub-hourly

Features	EnergyPlus
HVAC	Component based; user configurable with some limitations
User customization	Energy Management System, External Interface, Functional Mock-up Interface for co-simulation
Interoperability	gbXML, Industry Foundation Classes
Language	Fortran
Copyright	Free download: Open Source
Other features	Illuminance and glare calculations
	Advanced fenestration models
	Several lighting control strategies and built-in HVAC
	Integrated, simultaneous solution of thermal zone conditions and HVAC system response
	Combination of heat and mass transfer taking into account air movement between zones

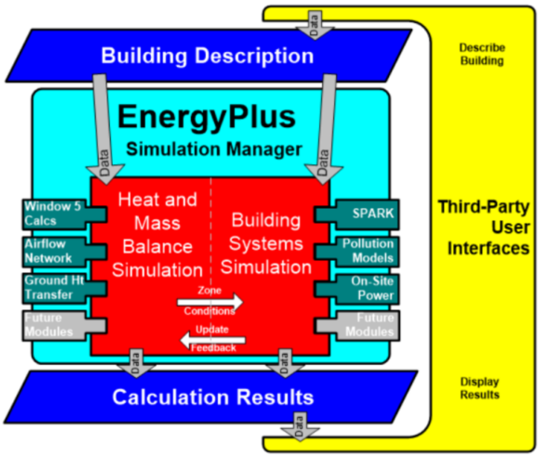


Figure 19 EnergyPlus general characterization, [59]

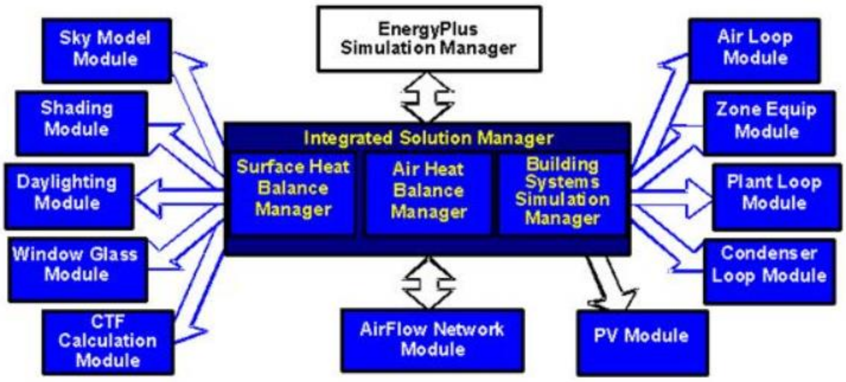


Figure 20: Internal elements of EnergyPlus, [52]

Moreover, EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution provides accurate space temperature prediction crucial for occupant comfort and occupant health calculations[53].

3 Case studies

As mentioned in the sections above, the aim of the dissertation is to study the feasibility of fuel cells for cogeneration in a residential building, as compared with more conventional HVAC equipment.

A building was designed with three floors each having four zones based on geographical orientation, using Google Sketchup. The locations chosen for the analysis were London and Lisbon. As inputs the main parameters of focus were the building geometry, indoor comfort temperature setpoints, outdoor temperature (from weather file), air infiltration, occupancy schedule, activity schedule, and constructive solutions which were all adjusted in the EnergyPlus *idf* editor. The intention was to draw conclusions from the energy demand for the two locations throughout the year. The HVAC system chosen in the simulation was an ideal load air system. This ideal HVAC system is assumed to be 100% efficient, where the range heating and cooling limits, airflow ratio, air humidity are pre-set.

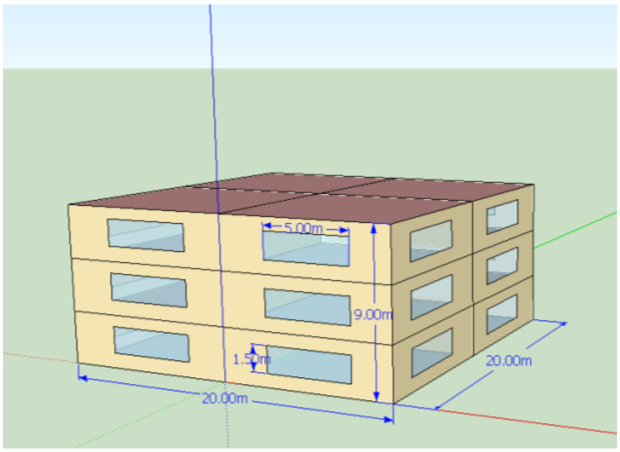


Figure 21 Building [45]

Table 7 Building characterization for Lisbon and London

	Lisbon	**London**
Co-ordinates	38.7223° N, 9.1393° W	51.5072° N, 0.1276° W
Dimensions of Building	(20x20x9) meters	
Dimensions of Windows	(5x1.5) meters	
Wall construction	Plaster/brick/air space/brick/plaster,	Plaster/brick/8cm EPS insulation/air space/brick/plaster.

Roof construction	Concrete/air space/roof tile.	Concrete/6cm wool insulation/air space/roof tile.
Indoor HVAC setpoint	18-26ºC (when occupied)	20-24ºC (when occupied).
Air infiltration	1 Renovation per hour (RPH) [54].	0.5 Renovation per hour (RPH) [54].

The key parameters that need to be noted are:

- Buildings from two cities, London (38.7223° N, 9.1393° W) and Lisbon (51.5072° N, 0.1276° W) were studied.
- Both buildings have the same dimensions, Table 7.
- From the construction characteristics, HVAC setpoint and the air infiltration levels, we can see that buildings in London are very well insulated and the people have a higher standard of required comfort level as compared to Lisbon.

4 Methodology

The output of focus from the simulation are primarily indoor temperatures and the heating and cooling energy demand per hour throughout the year for each zone of different floors. This data was then used to calculate the overall heating and cooling needs of each floor. The energy demand was then tried to be placated by different energy systems like the existing system (gas boilers), heat pumps and fuel cells. The performance of the energy systems was compared against parameters like efficiency/coefficient of performance (COP), carbon footprint (CO_2eq kgs/kWh), running costs and overall ease of operation.

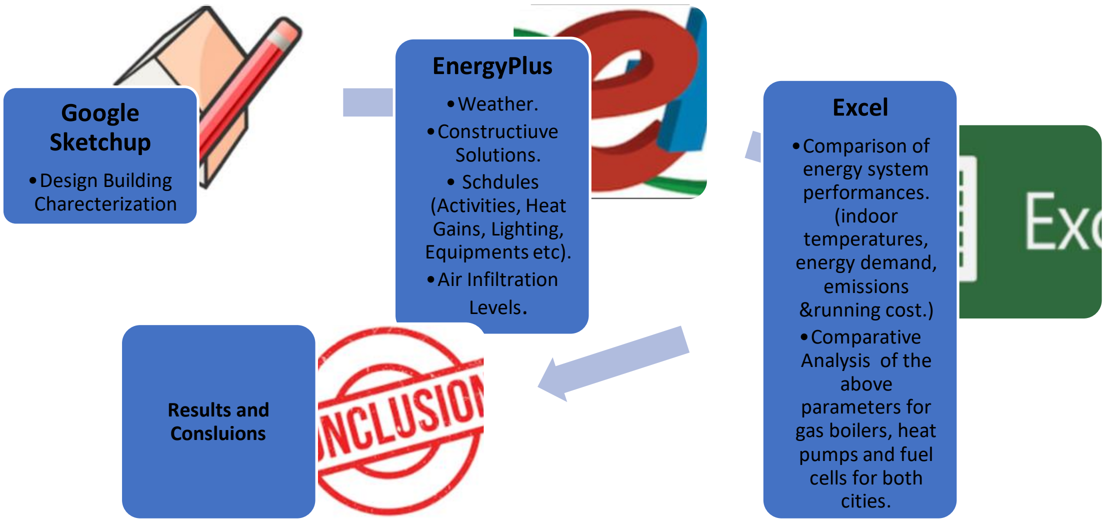


Figure 22 Graphic Representing a General Overview of the Methodology.

4.1 Weather file

The typical weather file used in the EnergyPlus for the two locations is in the *epw (energyplus weather)* format, where the weather data is in *epw* file is in a *comma-separated-value(csv)* form. The weather file primarily contains the ambient temperature, the wind speed and direction, pressure, humidity and solar radiation for every hour of the day for the entire year. The weather data contained in this file is a result of compilation of the most typical days from every month from the past thirty years. The file would contain 8761values, each with data corresponding to weather profile to every hour of every day of the year. The important point to be noted about the *epw* weather file is that the data contained is according to real weather conditions but corresponds to a typical value from the past thirty years. So, the values of weather profile are not an average but a carefully analysed and chosen value from the past thirty years [46] [55].

4.2 Geometry creation

The energy simulation software considered in this paper was the EnergyPlus version 6 (DOE, 2018) and the geometry was defined using Google Sketchup 7 (Google, 2016). The building created in Google Sketchup 7, was a simple one with, three floors and each floor consisting of four apartments. Every apartment was designed to have two windows. The orientation of the building, location co-ordinates, materials of construction, terrain (city, suburbs etc.), temperature tolerance etc. can be added and saved in Sketchup and later edited in *idf* editor in EnergyPlus.

4.3 Inputs/Outputs

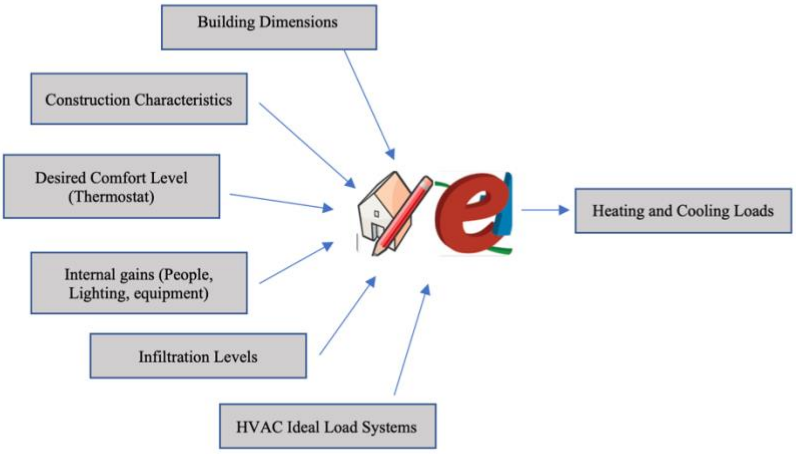


Figure 23 Graphic Representation of the Simulations.

4.3.1 Building Specifications

The building specifications such as the building geometry were drawn in SketchUp. Open studio converted it to the energy plus *idf* file.

The major difference in the construction specifications for the buildings in two locations under consideration is the thermal insulation of buildings in London city (see 3). This could have a major impact on the difference heating and cooling energy needs for both cities. The building was segregated into four zones based on orientations i.e., North East, North West, South East and South West. Zone wise division based on orientations is important as it would adversely affect the heating and cooling loads due to wind and solar shading.

4.3.2 Desired comfort levels

An important practice to be noted is the difference in comfort levels. The average thermostat set point for winter is 20^{0}C and 18^{0}C for winter in London and Lisbon respectively, while in summer its 24^{0}C for London and 26^{0}C for Lisbon. This along with the infiltration levels, discussed in the next section, have serious consequences on the differences in the energy demand of the buildings.

4.3.3 Air Infiltration Levels

The infiltration levels in EnergyPlus are defined as the number of air change (i.e., the total volume of air in the room being replaced by the ambient air) per hour. This value was set to be 1 for Lisbon and 0.5 for London. However, the infiltration levels cannot be set to be uniform throughout the year. In summer as the chances of windows being open are high the infiltration values were high as compared to winter. This was adjusted and accounted for in the simulation using *schedules*.

4.3.4 Internal Heat Gains

One of the most important parameters to be considered to provide accurate heating and cooling loads are the internal heat gains. The heat gains due to people whose values will depend on the type of activity they do, for instance whether sitting, sleeping walking etc., was taken into account. The heat gained by the electrical equipment and lights were fairly standard values, which would also vary throughout the year and with the hour of the day. The internal heat gains like infiltration levels, were adjusted to vary for seasons and time of day using the *schedule* parameters Table 8.

Table 8 Inputs for Energy Plus.

Activity Heat Gains	**Schedule Name**	Occupancy Schedule	**Lighting Heat Gains**	**Schedule Name**	Lighting Schedule
	People Calculation Method	Area/Person		**Design Level Calculation Method**	Watts/Area
	Zone Floor Area per Person m2/person	25		**Watts per Zone Area W/m2**	3
	Fraction Radiant	0.3	**Equipment Heat Gains**	**Schedule Name**	Equipment Schedule
	Sensible Heat Fraction	Auto Calculate		**Design Level Calculation Method**	Watts/Area
	CO2 Emission rate m3/sW	3.80E-08		**Watts per Zone Area W/m2**	4
	Zone	All Zones			

4.3.5 HVAC ideal Load System

As the motive is to compare the performance of different HAVC systems, the HVAC considered in the simulation was an ideal one i.e., it had 100% efficiency. The results of the simulation were then affected by the typical efficiency of gas boiler, heat pump and fuel cell.

4.3.6 Weather File

The weather file which was obtained from EnergyPlus website for the two locations was in *.epw* format [55]. The weather file primarily contains the ambient temperature, the wind speed and direction, pressure, humidity and solar radiation for every hour of the day for the entire year. It was assumed to have a non-leap year.

4.3.7 Schedule Compact

Schedule compact is an important parameter in EnergyPlus. In schedule compact the schedules of varies activities or uses was set throughout the year on an hourly basis. The time of day when an equipment will be on/off or the fraction of the full load that is being used was also set in schedule compact. Similarly, inputs for the number of people and their schedule were adjusted with some estimations. The schedule compact feature allows a more accurate estimations of the results through specific scheduling of desired comfort level 4.3.2, air infiltration levels 4.3.3, internal heat gains 4.3.4 and thermostat settings 4.3.5.

4.3.8 Outputs

The type of output from the simulations can be demanded as we see fit. In this dissertation we aimed to analyse only the heating and cooling loads of the buildings in the two cities. Hence the heating and cooling loads of each zone of each floor was extracted in an excel file for every hour of every of the year. This amounted to a total of 8761 sets of values (8760 hrs. in a year).

5 Results And Discussion.

As mentioned in the section 4.3.8, the results of focus were the heating and cooling loads of the buildings in the two cities. This was obtained in an excel format. The output file returned values of outdoor temperature, indoor temperature for every zone and heating and cooling loads in all the zones of every floor for an hourly time period resolution.

5.1 Temperature Profile

From Figure 24 and Figure 25 we can see that the hottest months were August and July, where the maximum temperatures going around 35^0C and 27^0C, for Lisbon and London respectively.

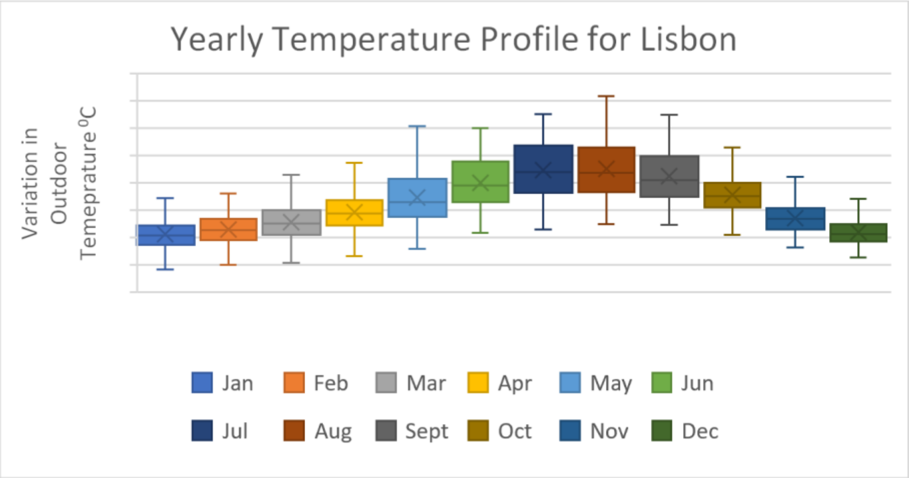


Figure 24 Ambient Temperature Lisbon

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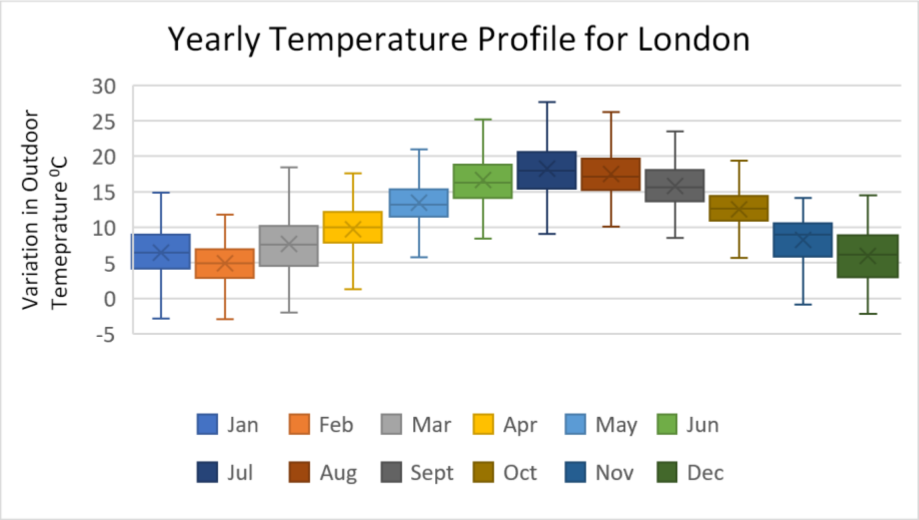

Figure 25 Ambient Temperature London.

However, these are extreme values and cannot be assumed to be the average. A better inference would be the that most of the time in the hottest months the temperature was in the range of 18^0C to 27^0C for Lisbon and 16^0C to 21^0C for London.

We can also concur that the coldest months for Lisbon would be January and December with the temperature varying from 6^0C to 12^0C. Similarly in London the coldest months would be January, February and December, where the temperature fluctuated between from -1^0C to 4^0C.

From the temperature profile, we can conclude that London is cold city, hence will not have cooling needs, even during the summer as the temperatures seldom goes beyond 25^0C. In Lisbon there are no cooling energy systems due relatively comfortable temperatures in summer and as a result of the socio-economic choices in the country.

5.2 Energy Load Profile

Table 9 and Table 10 shows the heating loads for each floor for each city. Immediately we can observe that London as higher heating needs. A building in London requires 129.87MWh of heating needs for a typical year, while for Lisbon its around 80MWh. We can see that the higher we go from the ground, there seems to be a slightly higher demand in the heating energy needs.

Table 9 Floor Heating Needs Lisbon.

Lisbon					
Month	**Floor_0 Heating (MWh)**	**Floor_1 Heating (MWh)**	**Floor_2 Heating (MWh)**	**Total Monthly Heating Needs MWh**	**Total Monthly Heating Needs kWh/m^2.year**
Jan	6.502	6.705	6.795	20.001	16.67
Feb	4.687	4.875	4.959	14.521	12.10
Mar	3.435	3.703	3.793	10.931	9.11
Apr	1.555	1.805	1.879	5.239	4.37
May	0.295	0.480	0.530	1.305	1.09
Jun	0.004	0.027	0.034	0.065	0.05
Jul	0.000	0.000	0.000	0.000	0.00
Aug	0.000	0.000	0.000	0.000	0.00
Sept	0.000	0.000	0.000	0.000	0.00
Oct	0.123	0.211	0.234	0.568	0.47
Nov	2.667	2.906	2.982	8.555	7.13
Dec	5.957	6.167	6.255	18.379	15.32
Heating needs for the building year MWh				**79.565 MWh**	**5.53 kWh/m^2**

Table 10 Floor Heating Demands London.

London					
Month	**Floor_0 Heating (MWh)**	**Floor_1 Heating (MWh)**	**Floor_2 Heating (MWh)**	**Total Monthly Heating Needs MWh**	**Total Monthly Heating Needs kWh/m^2.year**
Jan	27.697	27.720	27.682	23.083	19.24
Feb	27.030	27.014	27.003	22.513	18.76
Mar	19.691	19.879	19.994	16.546	13.79
Apr	12.035	12.443	12.620	10.305	8.59
May	4.838	5.533	5.699	4.464	3.72
Jun	0.465	0.759	0.870	0.582	0.48
Jul	0.167	0.388	0.459	0.282	0.23
Aug	0.145	0.419	0.519	0.301	0.25
Sept	1.070	1.671	1.851	1.276	1.06
Oct	8.954	9.356	9.510	7.728	6.44
Nov	21.393	21.633	21.679	17.974	14.98
Dec	29.890	29.767	29.698	24.821	20.68
Heating needs for the building year				**129.875 MWh**	**9.02 kWh/m^2**

Table 11 Zone wise Energy Demand Lisbon

Lisbon				
Month	**South East kWh/m2**	**South West kWh/m2**	**North East kWh/m2**	**North West kWh/m2**
Jan	15.07	15.27	18.13	18.20
Feb	10.55	11.01	13.26	13.59
Mar	7.96	8.36	9.88	10.23
Apr	3.64	3.98	4.77	5.08
May	0.89	1.09	1.09	1.29
Jun	0.04	0.06	0.05	0.06
Jul	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00
Sept	0.00	0.00	0.00	0.00
Oct	0.28	0.31	0.62	0.68
Nov	5.83	5.96	8.35	8.38
Dec	13.54	13.64	17.06	17.02

Table 12 Zone wise Energy Demand London

London				
Month	**South East kWh/m2**	**South West kWh/m2**	**North East kWh/m2**	**North West kWh/m2**
Jan	18.59	18.47	20.02	19.86
Feb	18.02	17.76	19.80	19.48
Mar	12.78	12.32	15.33	14.72
Apr	7.75	7.27	10.00	9.34
May	3.46	3.14	4.35	3.93
Jun	0.44	0.33	0.67	0.50
Jul	0.15	0.18	0.28	0.33
Aug	0.18	0.11	0.43	0.29
Sept	0.63	0.61	1.56	1.45
Oct	5.57	5.43	7.51	7.26
Nov	14.40	14.22	15.76	15.54
Dec	19.99	19.82	21.57	21.35

Referring to Table 11, Table 12, Figure 26 & Figure 27 we can analyse the zone wise variation in energy consumption in the both buildings. We can infer that in both buildings the North East and North West zones demand higher heating needs, especially during winter. This can be attributed to the fact that both cities come in the northern hemisphere and during winter, the solar insolation is considerably less.

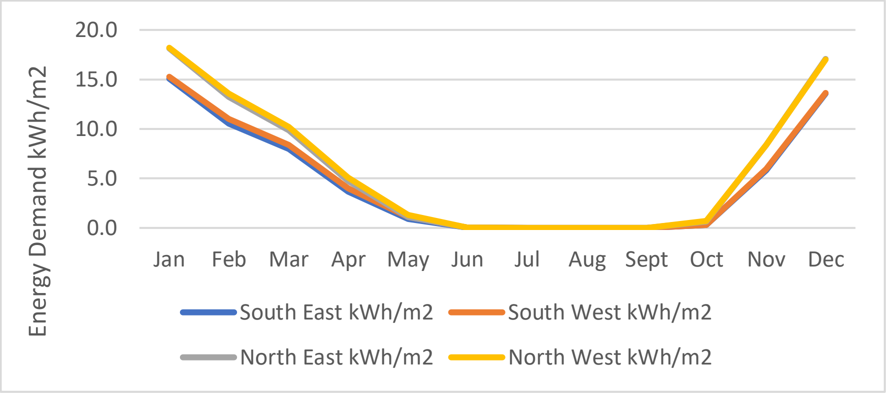

Figure 26 Average Energy Demand per Building Orientation Lisbon.

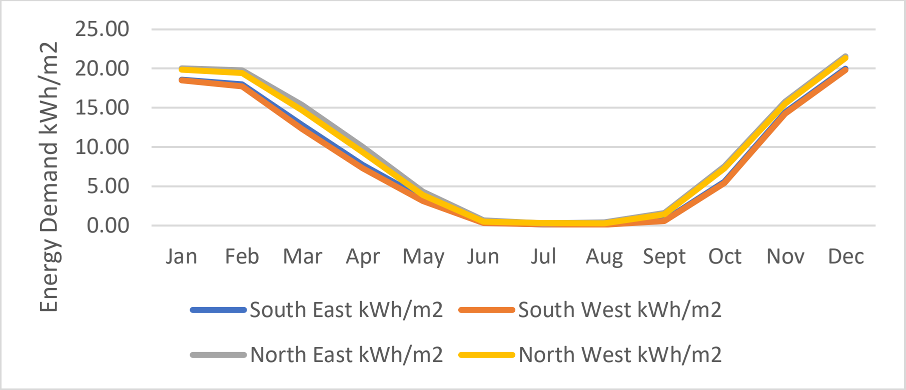

Figure 27 Average Energy Demand per Building Orientation London.

5.3 Energy Systems Performance

Table 13 & Table 14 summarizes the efficiency performance of different energy systems for heating needs in each city. The energy system under analysis is the existing system i.e., Gas Boilers and proposed systems i.e., Heat pumps and Fuel cells. In order to have a better understanding of the efficiencies of each system certain calculations need to be explained.

- The Coefficient of Performance (COP) of a heating system was calculated as a function of the temperature gradient between indoor and outdoor temperatures.

COP = Indoor Temp/(Indoor temp - Ambient temp) [56]. 11

- The losses incurred in the heat pump system was considered as 24% [57].
- The efficiency of a typical boiler was taken as 92% [58].
- The fuel cell systems were considered to have an efficiency of 125% [59].

Table 13 Energy Profile Lisbon (Demand and Consumption).

Lisbon				**Gas Boilers**	**Heat Pumps**	**Fuel cells**
	Month	**Energy needs Heating (MWh)**	**Energy needs Heating (kWh/m2)**	**Energy Consumption (MWh)**	**Energy Consumption (MWh)**	**Energy Consumption (MWh)**
The whole building	**Jan**	20.0	16.6678	21.7	9.7	16.0
	Feb	14.5	12.1010	15.8	6.4	11.6
	Mar	10.9	9.1091	11.9	4.1	8.7
	Apr	5.2	4.3657	5.7	1.6	4.2
	May	1.3	1.0879	1.4	0.3	1.0
	Jun	0.1	0.0542	0.1	0.0	0.1
	Jul	0.0	0.0000	0.0	0.0	0.0
	Aug	0.0	0.0000	0.0	0.0	0.0
	Sept	0.0	0.0000	0.0	0.0	0.0
	Oct	0.6	0.4730	0.6	0.1	0.5
	Nov	8.6	7.1294	9.3	2.8	6.8
	Dec	18.4	15.3162	20.0	8.5	14.7

Table 14 Energy Profile London (Demand and Consumption).

London				**Gas Boilers**	**Heat Pumps**	**Fuel Cell**
	Month	**Energy for Heating MWh**	**Energy needs Heating (kWh/m2)**	**Energy Consumption (MWh)**	**Energy Consumption (MWh)**	**Energy Consumption (MWh)**
The whole building	**Jan**	23.08	19.24	25.1	18.8	18.5
	Feb	22.51	18.76	24.5	20.6	18.0
	Mar	16.55	13.79	18.0	12.4	13.2
	Apr	10.31	8.59	11.2	6.5	8.2
	May	4.46	3.72	4.9	1.9	3.6
	Jun	0.58	0.48	0.6	0.2	0.5
	Jul	0.28	0.23	0.3	0.1	0.2
	Aug	0.30	0.25	0.3	0.1	0.2
	Sept	1.28	1.06	1.4	0.4	1.0
	Oct	7.73	6.44	8.4	3.6	6.2
	Nov	17.97	14.98	19.5	12.7	14.4
	Dec	24.82	20.68	27.0	21.0	19.9

5.4 Running Costs

Table 15 and Table 16 displays the running cost of all the energy systems.

Table 15 Running cost of Energy Systems Lisbon.

Running Cost (€)/Flat Lisbon			
Month	**Gas Boiler**	**Heat Pumps**	**Fuel Cells**
Jan	167.48	174.85	144.66
Feb	121.73	115.11	105.03
Mar	91.89	73.34	79.06
Apr	44.43	28.79	37.89
May	11.68	5.64	9.44
Jun	1.32	0.23	0.47
Jul	0.80	0.00	0.00
Aug	0.80	0.00	0.00
Sept	0.78	0.00	0.00
Oct	5.53	2.16	4.11
Nov	72.07	50.12	61.88
Dec	153.96	153.78	132.93
Total Cost/ year	**672.47**	**601.72**	**575.47**

Table 16 Running cost of Energy Systems London.

Running Cost (€)/flat London			
Month	**Gas Boiler**	**Heat Pumps**	**Fuel Cells**
Jan	216.163	344.488	83.716
Feb	210.768	377.569	81.649
Mar	155.167	227.977	60.006
Apr	96.918	119.576	37.373
May	42.451	35.227	16.190
Jun	6.202	3.443	2.109
Jul	3.429	1.356	1.022
Aug	3.607	1.543	1.091
Sept	12.678	7.819	4.627
Oct	72.900	65.504	28.027
Nov	168.465	232.519	65.185
Dec	232.375	384.702	90.018
Total Cost/ year	**988.747**	**1801.723**	**471.012**

It can be observed that in Lisbon gas boilers seem to be more expensive, while in London heat pumps incur a higher running price. Fuel cells are the cheapest to operate due to it's the low price of hydrogen and high energy density (refer Table 1 & Table 17). The cost of operation of heat pumps however depends on the COP, which in turn depends on the temperature gradient *11*. So, we can see from Figure 28 that for values of COP higher than 2.8, heat pumps become more economical to operate compared to traditional gas boilers. The price of electricity, gas charges, hydrogen and other charges associated with energy consumption can be found in Table 17.

Table 17 Utilities Features/Values[60][61][62][63][64].

	Electricity Price €/kWh	**Gas Price €/kWh**	**Gas Standing Charge €/day**	**Present Hydrogen €/kg**	**Estimated Hydrogen €/kg**
Lisbon	0.22	0.103	0.31	4.52	2.26
London	0.217	0.092			

The fact that the temperature gradient varies directly with the cost of operation, increases the cost of operation significantly in London but not as much in Lisbon. This can be attributed to the fact that temperatures in London tends to be much lower than Lisbon. Also, in Lisbon the comfort level 18^0C in winter while in London its 20^0C. These factors result in a higher gradient in temperature, which decreases efficiency and increases the operating cost of heat pumps in locations with weather profile similar to London.

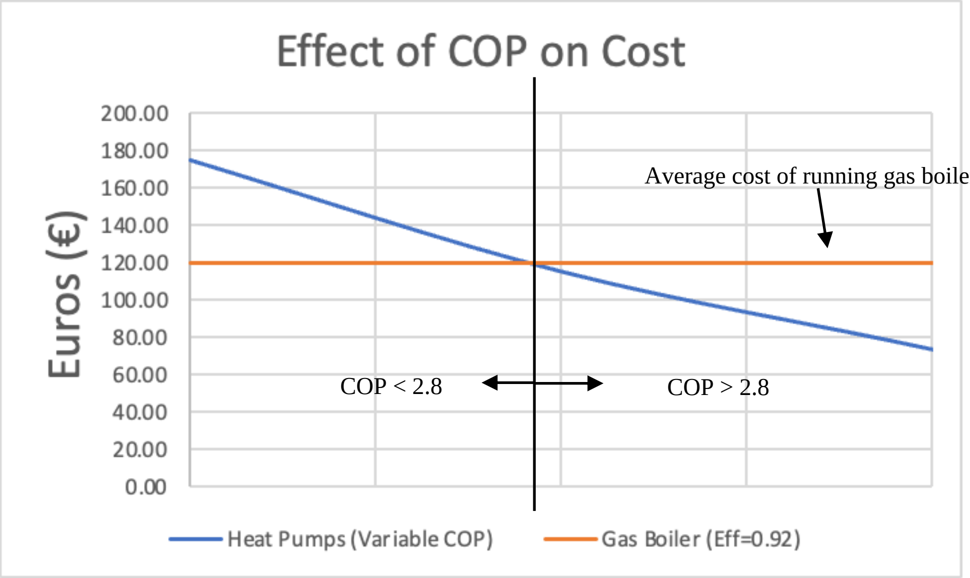

Figure 28 Running Cost of Heat pump and Gas boiler with eff 0.92

5.5 CO_2 Emissions

The emissions of the energy systems depend heavily on the energy mix of the respective countries. The Table 18 shows that although the efficiency of the utilities in both nations seem to be similar, the energy mix of London seems to have more constituents of renewable energy as compared to Lisbon for residential applications.

Table 18 Utilities efficiency and Emissions[65][66][67].

	Efficiency (%)	Emissions for Residential Applications ($C0_2$ kg/kWh)	Natural Gas emission rating ($C0_2$ kg/kWh)
Lisbon	0.42	0.27042	0.26
London	0.43	0.193	

The emissions associated with the operation of gas boilers for a 100 m^2 flat in Lisbon gives 1.86 tons/year of CO_2, while heat pumps and fuel cells emit 0.75 tons/year and 1.17 tons/year. For a flat with dimensions in London, we can observe that the emissions are 3.06 tons/year, 1.58 tons/year and 1.92 tons/year for boilers, heat pumps and fuel cell respectively Figure 29

& Figure 30. The emissions rating for the electricity is expected to go down in the future with increasing penetration of the renewables in the grid.

According to the current energy scenario in both countries, fuel cells and heat pumps seem to be more eco-friendly than gas boilers. From Table 18, we can see that the emission rating of natural gas lower than the electricity emission rating. However, with the progressive integration of renewables in the grid, the use of fuel cells and heat pump would consistently save more emissions.

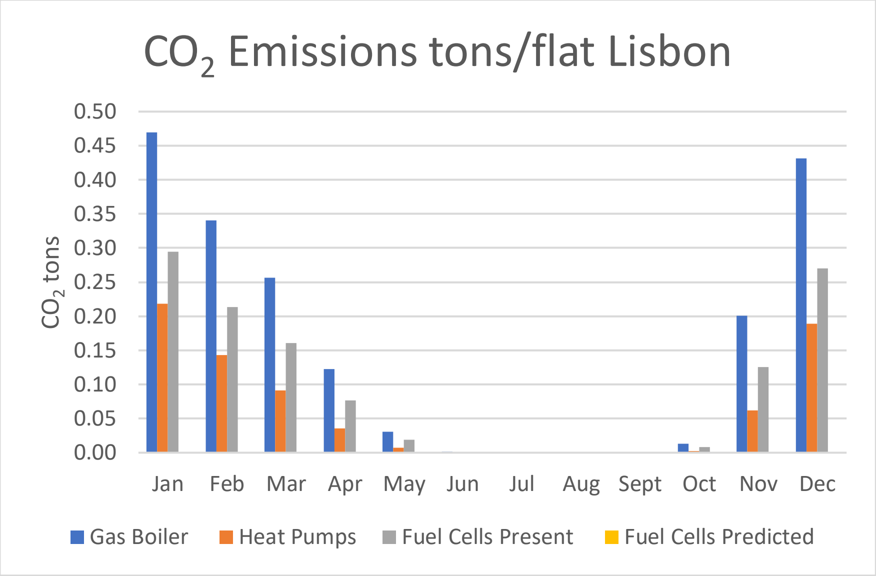

Figure 29 CO_2 emissions Lisbon.

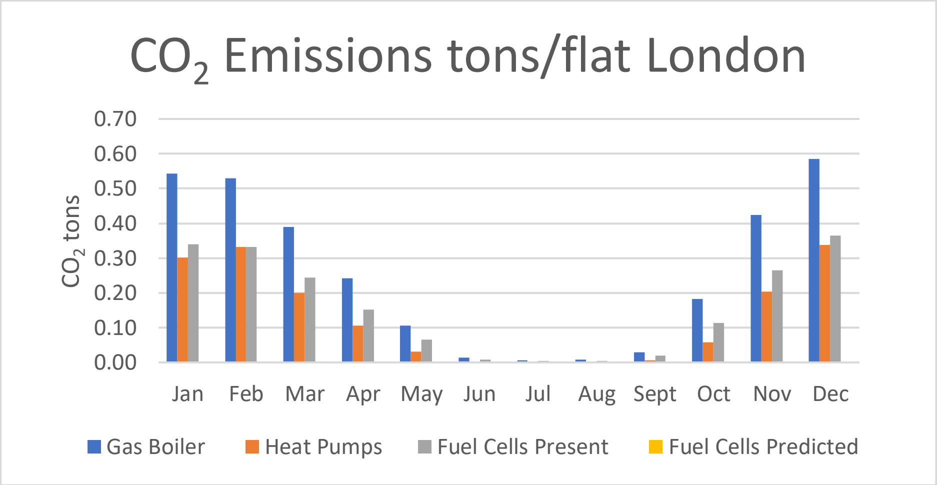

Figure 30 CO_2 emissions London.

6 Conclusions and future work

The dissertation aims to understand the potential and the future scope of hydrogen fuel cell systems to support the heating and cooling loads of residential houses, in the city of Lisbon and London. To have a clear idea about its feasibility, the performance, emissions and running costs of the fuel cell system were compared against the gas boilers and heat pumps. From the output of the building energy simulation and after calculations using excel, it was found that the heating energy needs for London and Lisbon were 9.2 kWh/m^2 and 5.53 kWh/m^2 respectively. This difference in heating energy demand can be attributed to the fact that London is a relatively cold city with temperatures ranging from -1^0C to 4^0C in winter, while for Lisbon it was 6^0C to 12^0C. Another reason would be the difference in standard comfort level and constructive solutions. For instance, in London, the thermostats are usually set to 20^0C in winter, while in Lisbon it was 18^0C.

Before analysing the energy consumed, tons of CO_2 emissions and running cost of each energy system for both cities, it is imperative to have knowledge and understanding of efficiencies of utilities, electricity price, gas price, price of hydrogen and the emission rate of the concerned utilities and fuels. The efficiencies of both utilities in both countries aren't much different with 0.42 and 0.43 for Portugal and The United Kingdom respectively. Now, although Portugal has a higher penetration of renewables in the energy mix compared to the UK, only 27.97% of final residential electricity consumption comes from clean energy sources. This explains the emission factor of residential electricity consumption of 0.193 CO_2 kg/kWh and 0.270 CO_2 kg/kWh for London and Lisbon, respectively. The major suppliers of natural gas in Portugal and the UK, have declared the natural gas being 100% non-renewable and hence with an emission rating of 0.259 CO_2 kg/kWh. As a result of the energy mix in the utilities of both countries, which is still dominated by fossil fuels, the use of heat pumps and fuel cells over gas boilers, although beneficial, the difference is not quite significant yet, in terms of emissions. The emission ratings of boilers and fuel cells were calculated to be 0.283kg/kWh and 0.177 kg/kWh. For heat pumps, it varied between (0.051- 0.177) kg/kWh.

However, in the future, there is expected to be an improvement in the emission rating of electricity all over the world. With the advent of green hydrogen, the operation and use of fuel cells have the potential to be 100% clean. The energy demand for a $100m^2$ flat in Lisbon is

6.63 MWh while in London is 10.82 MWh for a year. As elaborated earlier, this results from colder temperatures in London and the difference in desired comfort levels between the two nations. As a house/flat in London consumes more energy, it would be natural to have higher values of energy consumed, running costs and emissions.

The current price of hydrogen in Europe was estimated to be about 4.5 €/kg. This contributes to savings worth almost 100 €/year in Lisbon and 270 €/year in London while switching to fuel cells from boilers. In the future with the maturity of HyDeploy and Store&Go, projects, hydrogen price is expected to fall to 2.6 €/kg for the end-user, further increasing the cost savings.

However, it becomes interesting to compare the operating cost of boilers and heat pumps in the two cities. The running cost of heat pumps is higher than boilers in London, while the contrary is true in Lisbon. This is a direct result of the coefficient of performance (COP) of heat pumps in the two regions. The COP of heat pumps varies inversely with the temperature gradient. The desired indoor temperature in London is around 19^0C-22^0C while the average outdoor temperature throughout the year is 11.43^0C, and for Lisbon its 16.29^0C for outdoors and around 21^0C for indoors. The average temperature gradient in Lisbon is 4.62^0C but in London, it is 9^0C, which is almost twice that of Lisbon. This has adverse effects on the efficiencies of heat pumps, hence the operation cost as well. The climate of Portugal provides economic conditions for the operation of heat pumps. Fuel cells might be better suited for London.

Although the heat pumps have a higher initial investment (as much as three times boilers i.e., €7000), they have a lower energy consumption due to their supreme efficiency ratings as compared to boilers. We can infer the same for fuel cells in terms of efficiency as compared to gas boilers. However, the initial investment i.e., the cost of the fuel cell which is around €12000, is a serious drawback in this comparison, despite having significantly fewer running costs. However, if hydrogen is made available to residences, similar to gas in pipelines, the existing gas boilers can be retrofitted to run on hydrogen. This has already been executed in several homes as part of the Hy4Heat programme in The United Kingdom. These retrofitted hydrogen boilers, can mitigate the high running price and initial investment, involved with heat pumps and reduce emissions, provided the hydrogen is produced from green energy sources. So, the potentially feasible alternatives for gas boilers in the UK, are either adapting the existing gas boilers for hydrogen or switching to fuel cells.

For Lisbon, Portugal we can say, with certainty, although fuel cells consume less energy and release fewer emissions compared to gas boilers, heat pumps would be ideal, considering, the abundance of wind and solar energy in Portugal, which can be used to produce green electricity, and the higher coefficient of performance (COP) ratio of heat pumps in locations with a Mediterranean climate. Fuel cells considered in this analysis is a high-temperature fuel cell with an efficiency rating of 1.25, which would be a close second alternative for Portugal but the high cost of these fuel cells would be unattractive for the Portuguese market. Portugal lacks the infrastructure to supply green hydrogen to the end-users, as opposed to the United Kingdom where there are several projects already supplying hydrogen to homes. However, with continuous research and development, relying on incentives provided by the government, gradual reduction in the price of energy systems with an increase in the scale of production and retrofitting gas pipelines to transport pure or blended hydrogen, the potential for fuel cells with zero emissions, is very likely in the near future.

Nevertheless, serious amendments in the energy policy framework are mandatory to support any innovative technology. The Government has shown promise by striving towards providing support and incentives for industries and stakeholders that would be directly responsible for the manufacturing of fuel cells and green hydrogen. It would also be prudent to develop and maintain relationships with neighbouring nations to ensure a consistent and cheap supply of raw materials and to exploit the benefits of exporting locally produced fuel cell systems and hydrogen.

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8 Annexes

Table 19 to Table 24 show an analysis of the actual heating energy demand, the energy consumed by the gas boilers, heat pumps, and fuel cells after considering their efficiencies, the CO_2 and running cost in a for the cities of London and Lisbon.

Table 19 Energy Performance Summary Boilers.

London				Boilers		
	Month	Energy for Heating MWh	Energy needs Heating (kWh/m2)	Energy Consumption (MWh)	C02 (ton)	Running Cost (€)
The whole building	Jan	23.08	19.24	25.1	6.5	2594
	Feb	22.51	18.76	24.5	6.4	2529
	Mar	16.55	13.79	18.0	4.7	1862
	Apr	10.31	8.59	11.2	2.9	1163
	May	4.46	3.72	4.9	1.3	509
	Jun	0.58	0.48	0.6	0.2	74
	Jul	0.28	0.23	0.3	0.1	41
	Aug	0.30	0.25	0.3	0.1	43
	Sept	1.28	1.06	1.4	0.4	152
	Oct	7.73	6.44	8.4	2.2	875
	Nov	17.97	14.98	19.5	5.1	2022
	Dec	24.82	20.68	27.0	7.0	2788

Table 20 Energy Performance Summary Heat Pumps.

London				Heat Pumps		
	Month	Energy for Heating MWh	Energy needs Heating (kWh/m2)	Energy Consumption (MWh)	C02 (ton)	Running Cost (€)
The whole building	Jan	23.08	19.24	18.8	3.6	4133.9
	Feb	22.51	18.76	20.6	4.0	4530.8
	Mar	16.55	13.79	12.4	2.4	2735.7
	Apr	10.31	8.59	6.5	1.3	1434.9
	May	4.46	3.72	1.9	0.4	422.7
	Jun	0.58	0.48	0.2	0.0	41.3
	Jul	0.28	0.23	0.1	0.0	16.3
	Aug	0.30	0.25	0.1	0.0	18.5
	Sept	1.28	1.06	0.4	0.1	93.8
	Oct	7.73	6.44	3.6	0.7	786.0
	Nov	17.97	14.98	12.7	2.4	2790.2
	Dec	24.82	20.68	21.0	4.0	4616.4

Table 21 Energy Performance Summary Fuel Cells.

London				Fuel Cell					
	Month	**Energy for Heating MWh**	**Energy needs Heating (kWh/m2)**	**Energy Consumption (MWh)**	**C02 (ton) Present**	**C02 (ton) Future**	**Running Cost (€) Present**	**Running Cost (€) Future**	**Hydrogen Consumed Kgs**
The whole building	**Jan**	23.08	19.24	18.5	4.1	0.0	2003	1005	443
	Feb	22.51	18.76	18.0	4.0	0.0	1954	980	432
	Mar	16.55	13.79	13.2	2.9	0.0	1436	720	318
	Apr	10.31	8.59	8.2	1.8	0.0	894	448	198
	May	4.46	3.72	3.6	0.8	0.0	387	194	86
	Jun	0.58	0.48	0.5	0.1	0.0	50	25	11
	Jul	0.28	0.23	0.2	0.0	0.0	24	12	5
	Aug	0.30	0.25	0.2	0.1	0.0	26	13	6
	Sept	1.28	1.06	1.0	0.2	0.0	111	56	24
	Oct	7.73	6.44	6.2	1.4	0.0	671	336	148
	Nov	17.97	14.98	14.4	3.2	0.0	1560	782	345
	Dec	24.82	20.68	19.9	4.4	0.0	2154	1080	477

Table 22 Energy Performance Summary Boilers.

Lisbon				Boilers		
	Month	**Energy needs Heating (MWh)**	**Energy needs Heating (kWh/m2)**	**Energy Consumption (MWh)**	**C02 (ton)**	**Running Cost (€)**
The whole building	**Jan**	20.0	16.668	21.7	5.6	2010
	Feb	14.5	12.101	15.8	4.1	1461
	Mar	10.9	9.109	11.9	3.1	1103
	Apr	5.2	4.366	5.7	1.5	533
	May	1.3	1.088	1.4	0.4	140
	Jun	0.1	0.054	0.1	0.0	16
	Jul	0.0	0.000	0.0	0.0	10
	Aug	0.0	0.000	0.0	0.0	10
	Sept	0.0	0.000	0.0	0.0	9
	Oct	0.6	0.473	0.6	0.2	66
	Nov	8.6	7.129	9.3	2.4	865
	Dec	18.4	15.316	20.0	5.2	1848

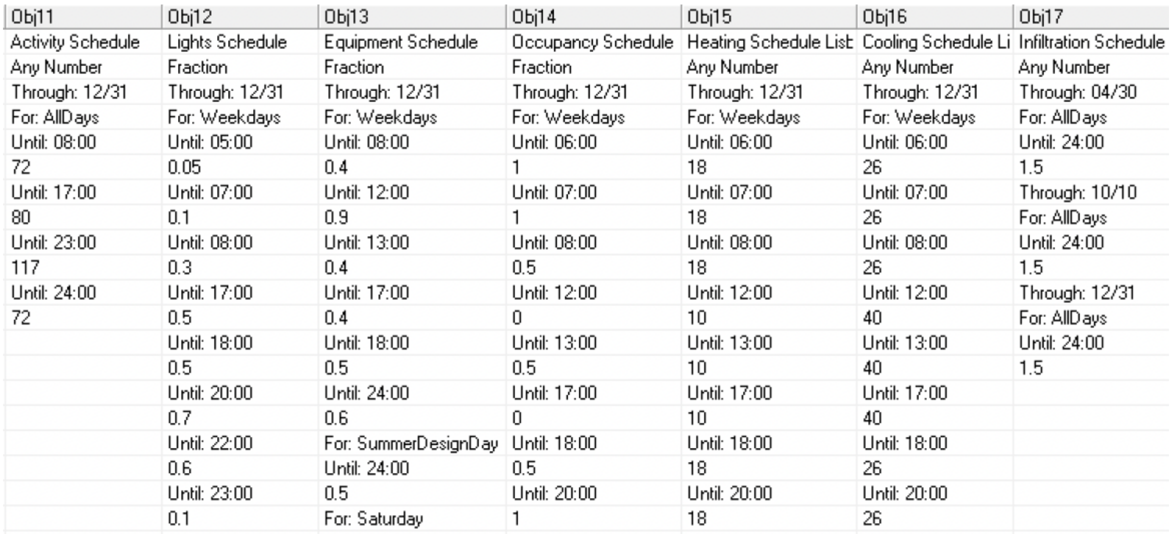
Table 23 Energy Performance Summary Heat Pumps

Lisbon				Heat Pumps		
	Month	Energy needs Heating (MWh)	Energy needs Heating (kWh/m2)	Energy Consumption (MWh)	C02 (ton)	Running Cost (€)
The whole building	Jan	20.0	16.668	9.7	2.6	2098.2
	Feb	14.5	12.101	6.4	1.7	1381.3
	Mar	10.9	9.109	4.1	1.1	880.1
	Apr	5.2	4.366	1.6	0.4	345.5
	May	1.3	1.088	0.3	0.1	67.7
	Jun	0.1	0.054	0.0	0.0	2.7
	Jul	0.0	0.000	0.0	0.0	0.0
	Aug	0.0	0.000	0.0	0.0	0.0
	Sept	0.0	0.000	0.0	0.0	0.0
	Oct	0.6	0.473	0.1	0.0	25.9
	Nov	8.6	7.129	2.8	0.7	601.5
	Dec	18.4	15.316	8.4	2.3	1817.6

Table 24 Energy Performance Summary Fuel Cells

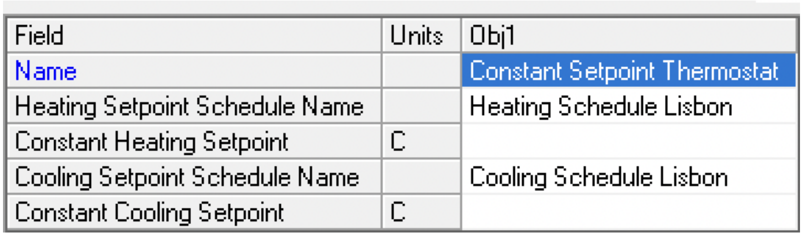
Lisbon				Fuel cells					
	Month	Energy needs Heating (MWh)	Energy needs Heating (kWh/m2)	Energy Consumption (MWh)	C02 (ton) Present	C02 (ton) Future	Running Cost Present (€)	Running Cost Future (€)	Hydrogen Consumed Kgs
The whole building	Jan	20.0	16.668	16.0	3.5	0.0	1736	870	384
	Feb	14.5	12.101	11.6	2.6	0.0	1260	632	279
	Mar	10.9	9.109	8.7	1.9	0.0	949	476	210
	Apr	5.2	4.366	4.2	0.9	0.0	455	228	101
	May	1.3	1.088	1.0	0.2	0.0	113	57	25
	Jun	0.1	0.054	0.1	0.0	0.0	6	3	1
	Jul	0.0	0.000	0.0	0.0	0.0	0	0	0
	Aug	0.0	0.000	0.0	0.0	0.0	0	0	0
	Sept	0.0	0.000	0.0	0.0	0.0	0	0	0
	Oct	0.6	0.473	0.5	0.1	0.0	49	25	11
	Nov	8.6	7.129	6.8	1.5	0.0	743	372	164
	Dec	18.4	15.316	14.7	3.2	0.0	1595	800	353

Figure 32, Figure 33, Figure 34, Figure 35, Figure 37, Figure 36 and Figure 38 show the inputs of the EnergyPlus files to take into account the internal heat gains (people, equipment, and lighting), thermostat settings, and air filtration levels. The schedules of the above-mentioned parameters were adjusted in Schedule Compact, refer to Figure 31.



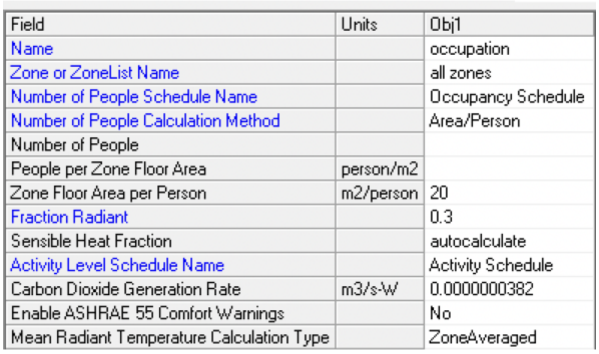
Obj11	Obj12	Obj13	Obj14	Obj15	Obj16	Obj17
Activity Schedule	Lights Schedule	Equipment Schedule	Occupancy Schedule	Heating Schedule Lis	Cooling Schedule Li	Infiltration Schedule
Any Number	Fraction	Fraction	Fraction	Any Number	Any Number	Any Number
Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 04/30
For: AllDays	For: Weekdays	For: Weekdays	For: Weekdays	For: Weekdays	For: Weekdays	For: AllDays
Until: 08:00	Until: 05:00	Until: 08:00	Until: 06:00	Until: 06:00	Until: 06:00	Until: 24:00
72	0.05	0.4	1	18	26	1.5
Until: 17:00	Until: 07:00	Until: 12:00	Until: 07:00	Until: 07:00	Until: 07:00	Through: 10/10
80	0.1	0.9	1	18	26	For: AllDays
Until: 23:00	Until: 08:00	Until: 13:00	Until: 08:00	Until: 08:00	Until: 08:00	Until: 24:00
117	0.3	0.4	0.5	18	26	1.5
Until: 24:00	Until: 17:00	Until: 17:00	Until: 12:00	Until: 12:00	Until: 12:00	Through: 12/31
72	0.5	0.4	0	10	40	For: AllDays
	Until: 18:00	Until: 18:00	Until: 13:00	Until: 13:00	Until: 13:00	Until: 24:00
	0.5	0.5	0.5	10	40	1.5
	Until: 20:00	Until: 24:00	Until: 17:00	Until: 17:00	Until: 17:00	
	0.7	0.6	0	10	40	
	Until: 22:00	For: SummerDesignDay	Until: 18:00	Until: 18:00	Until: 18:00	
	0.6	Until: 24:00	0.5	18	26	
	Until: 23:00	0.5	Until: 20:00	Until: 20:00	Until: 20:00	
	0.1	For: Saturday	1	18	26	

Figure 31 Schedule Compact.



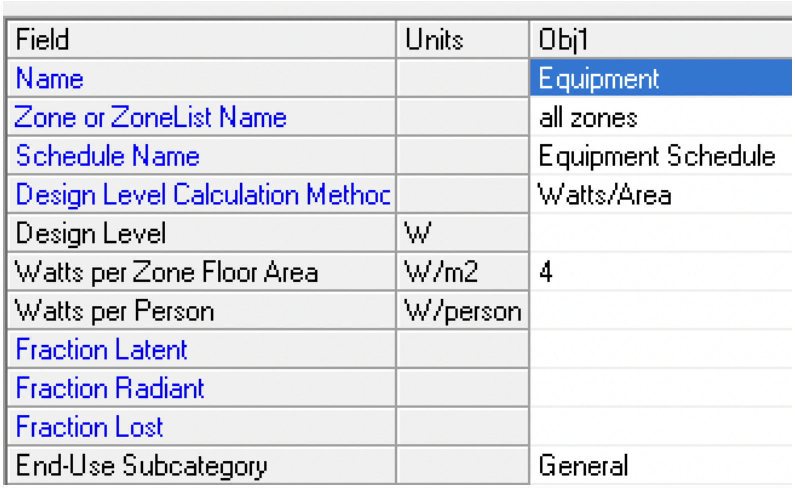
Field	Units	Obj1
Name		Constant Setpoint Thermostat
Heating Setpoint Schedule Name		Heating Schedule Lisbon
Constant Heating Setpoint	C	
Cooling Setpoint Schedule Name		Cooling Schedule Lisbon
Constant Cooling Setpoint	C	

Figure 32 Thermostat Setting in EnergyPlus.



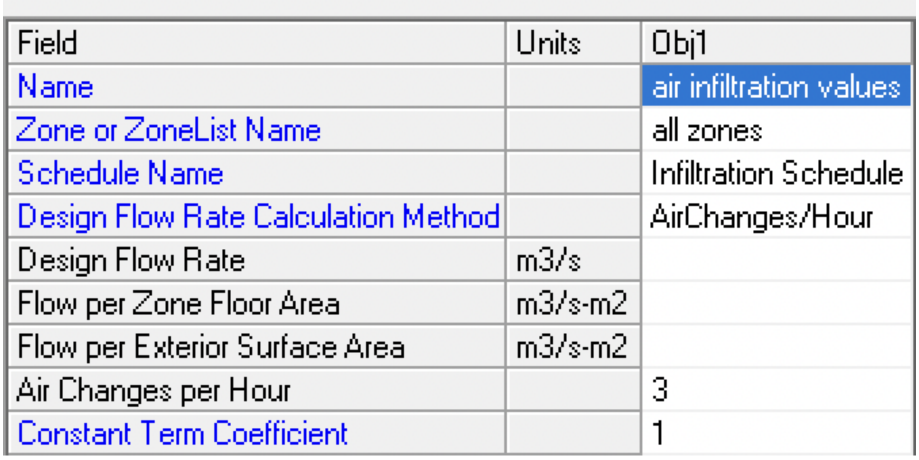
Field	Units	Obj1
Name		occupation
Zone or ZoneList Name		all zones
Number of People Schedule Name		Occupancy Schedule
Number of People Calculation Method		Area/Person
Number of People		
People per Zone Floor Area	person/m2	
Zone Floor Area per Person	m2/person	20
Fraction Radiant		0.3
Sensible Heat Fraction		autocalculate
Activity Level Schedule Name		Activity Schedule
Carbon Dioxide Generation Rate	m3/s-W	0.0000000382
Enable ASHRAE 55 Comfort Warnings		No
Mean Radiant Temperature Calculation Type		ZoneAveraged

Figure 33 Occupancy Schedule In EnergyPlus.



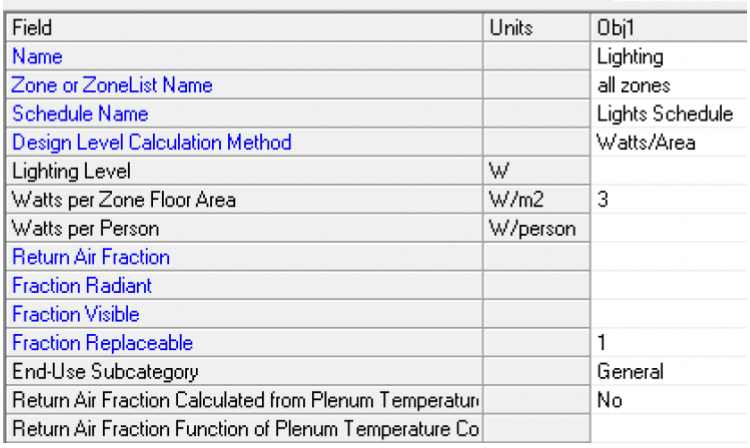
Field	Units	Obj1
Name		Equipment
Zone or ZoneList Name		all zones
Schedule Name		Equipment Schedule
Design Level Calculation Methoc		Watts/Area
Design Level	W	
Watts per Zone Floor Area	W/m2	4
Watts per Person	W/person	
Fraction Latent		
Fraction Radiant		
Fraction Lost		
End-Use Subcategory		General

Figure 35 Equipment Settings in EnergyPlus.



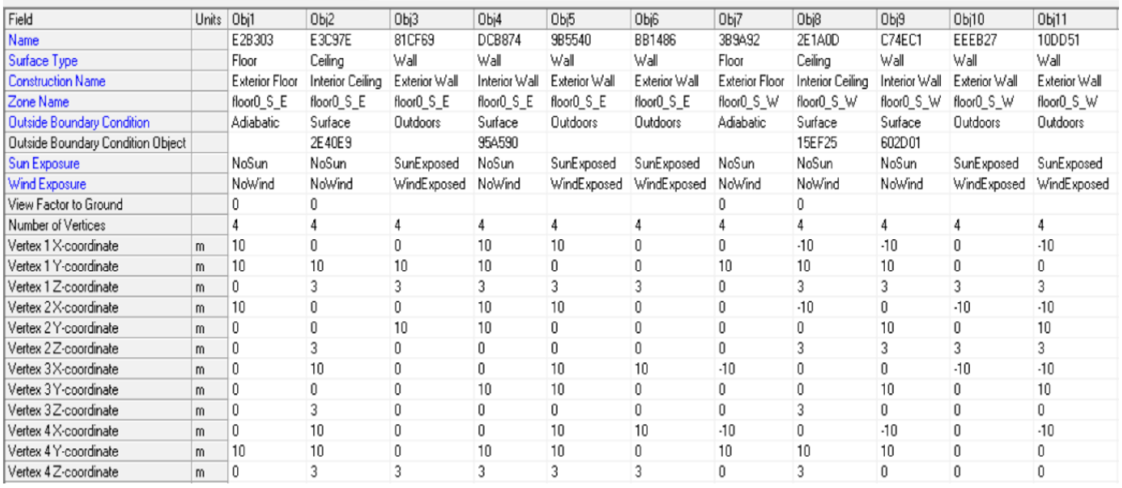
Field	Units	Obj1
Name		air infiltration values
Zone or ZoneList Name		all zones
Schedule Name		Infiltration Schedule
Design Flow Rate Calculation Method		AirChanges/Hour
Design Flow Rate	m3/s	
Flow per Zone Floor Area	m3/s-m2	
Flow per Exterior Surface Area	m3/s-m2	
Air Changes per Hour		3
Constant Term Coefficient		1

Figure 37 Air Filtration Setting in EnergyPlus.



Field	Units	Obj1
Name		Lighting
Zone or ZoneList Name		all zones
Schedule Name		Lights Schedule
Design Level Calculation Method		Watts/Area
Lighting Level	W	
Watts per Zone Floor Area	W/m2	3
Watts per Person	W/person	
Return Air Fraction		
Fraction Radiant		
Fraction Visible		
Fraction Replaceable		1
End-Use Subcategory		General
Return Air Fraction Calculated from Plenum Temperatur		No
Return Air Fraction Function of Plenum Temperature Co		

Figure 36 Lighting Settings In EnergyPlus.



Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8	Obj9	Obj10	Obj11
Name		E2B303	E3C97E	81CF69	DCB874	9B5540	BB1486	3B9A92	2E1A0D	C74EC1	EEEB27	10DD51
Surface Type		Floor	Ceiling	Wall	Wall	Wall	Wall	Floor	Ceiling	Wall	Wall	Wall
Construction Name		Exterior Floor	Interior Ceiling	Exterior Wall	Interior Wall	Exterior Wall	Exterior Wall	Exterior Floor	Interior Ceiling	Interior Wall	Exterior Wall	Exterior Wall
Zone Name		floor0_S_E	floor0_S_E	floor0_S_E	floor0_S_E	floor0_S_E	floor0_S_E	floor0_S_W	floor0_S_W	floor0_S_W	floor0_S_W	floor0_S_W
Outside Boundary Condition		Adiabatic	Surface	Outdoors	Surface	Outdoors	Outdoors	Adiabatic	Surface	Surface	Outdoors	Outdoors
Outside Boundary Condition Object			2E40E9		95A590				15EF25	602D01		
Sun Exposure		NoSun	NoSun	SunExposed	NoSun	SunExposed	SunExposed	NoSun	NoSun	NoSun	SunExposed	SunExposed
Wind Exposure		NoWind	NoWind	WindExposed	NoWind	WindExposed	WindExposed	NoWind	NoWind	NoWind	WindExposed	WindExposed
View Factor to Ground		0	0					0	0			
Number of Vertices		4	4	4	4	4	4	4	4	4	4	4
Vertex 1 X-coordinate	m	10	0	0	10	10	0	0	-10	-10	0	-10
Vertex 1 Y-coordinate	m	10	10	10	10	0	0	10	10	10	0	0
Vertex 1 Z-coordinate	m	0	3	3	3	3	3	0	3	3	3	3
Vertex 2 X-coordinate	m	10	0	0	10	10	0	0	-10	0	-10	-10
Vertex 2 Y-coordinate	m	0	0	10	10	0	0	0	0	10	0	10
Vertex 2 Z-coordinate	m	0	3	0	0	0	0	0	3	3	3	3
Vertex 3 X-coordinate	m	0	10	0	0	10	10	-10	0	0	-10	-10
Vertex 3 Y-coordinate	m	0	0	0	10	10	0	0	0	10	0	10
Vertex 3 Z-coordinate	m	0	3	0	0	0	0	0	3	0	0	0
Vertex 4 X-coordinate	m	0	10	0	0	10	10	-10	0	-10	0	-10
Vertex 4 Y-coordinate	m	10	10	0	10	10	0	10	10	10	0	0
Vertex 4 Z-coordinate	m	0	3	3	3	3	3	0	3	0	0	0

Figure 38 Building Dimension.