Hydrogen Fuel Cells for Cogeneration in Residential Applications

Mervyn Muthukumar
Mervyn.muthukumar@tecnico.ulisboa.pt
Instituto Superior Técnico, Universidade de Lisboa, Portugal.
October 2022

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/kgH2. 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.

1. Introduction

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. 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 [2]. 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.

According to New York Times, the global economic output would incur a loss of $23 trillion USD by 2050 as a direct result of global warming [3]. An approximate 1oC 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 [4]. The International Union of Conservation of Nature has estimated the extinction of 882 species of plants and animals [5]. Pollution, destructive fishing and coral mining has cost the world around 30-50% of the coral reefs [6]. Every year, the environmental factors, due to climate change, takes the lives of around 13 million people [7]. 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 2^0C, 1.5^0C 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. In order to keep with the promise of achieving a circular economy, various strategies and targets have been established [9].

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 [11]. 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 renewables forces heavy investments in storage technologies, which are not fully developed yet. Hydrogen can be viewed as a solution to this conundrum. Around 2% (339 TWh) of energy consumption in the present day Europe comes from Hydrogen, majority of which is produced form natural gas, emitting significant CO_2 emissions, around 38.51 g CO_2 per MJ [12][13][14]. Hydrogen has the highest energy density with zero emissions and has only water as a by-product when used in fuels cells. 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 that would the storage in stable solid form. These features have encouraged the European Commission to expedite the use of hydrogen technology and expects 167- 4000 TWh consumption by 2050.

2. Literature review

2.1 Hydrogen Infrastructure.

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 practically no investment 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.

2.2 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 [24] [1]. 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 [24] [1], 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. 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.

3. Methodology

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 [47] and the simulation was executed on EnergyPlus6.

3.1 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 [49]–[51].
Considered as one of the most advanced, well-known, widespread and accepted building energy simulation software tools over the world [52], [53], 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. **Table *1*** exhibit some of the tools and services supported by EnergyPlus and OpenStudio.

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 [54], [55]. Additionally, as reported by [56], 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 [52].

Table 1. Some of EnergyPlus main features, adapted from [57], [58]

Name	Description and unit
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
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

3.1.1 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

3.1.2 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.

3.1.3 Building Specifications.

The building specifications such as the building geometry were drawn in the 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. 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.

3.1.4 Desired comfort levels

An important practice to be noted is the difference in comfort levels. The average thermostat set point for winter is $20^{0C}$and $18^{0C}$for winter in London and Lisbon respectively, while in summer its $24^{0C}$for London and $26^{0C}$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.

3.1.5 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.

3.1.6 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.

3.1.7 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.

3.1.8 Weather File

The weather file which was obtained from EnergyPlus website for the two locations was in *.epw* format. 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.

3.1.9 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, air infiltration levels, internal heat gains and thermostat settings.

3.1.9 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).

4. 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.

One 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 **Table 2**

Table 2 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) [61].	0.5 Renovation per hour (RPH) [61].

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 *2***
- 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.

5. Results and discussion

4.1 Temperature Profile

Figure 1 and Figure 2 we can see that the hottest months were August and July, where the maximum temperatures going around 35^{0}C and 27^{0}C, for Lisbon and London respectively. 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^{0}C to 27^{0}C for Lisbon and 16^{0}C to 21^{0}C for London.

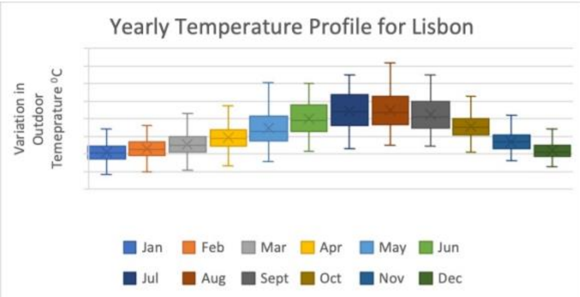

Figure 1 Lisbon Temperture Profile.

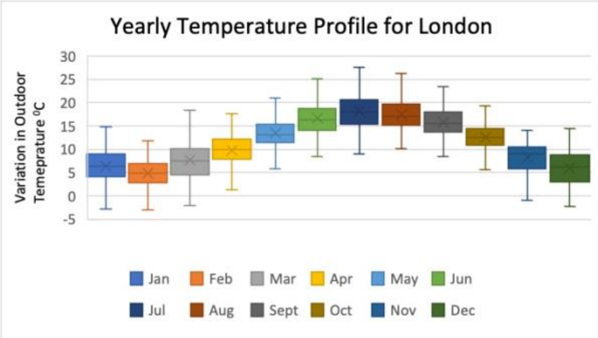

Figure 2 London Temperature Profile.

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.

4.2 Energy Load Profile.

We observed 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. Referring, Table 3, Table 4 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.

Table 3 Zonewise Enery 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 4 Zonewise 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

4.3 Energy System Performance.

Table 5, Table 6 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) [63].
- The losses incurred in the heat pump system was considered as 24% [64].
- The efficiency of a typical boiler was taken as 92% [65].
- The fuel cell systems were considered to have an efficiency of 125% [66].

Table 5 Energy System Performance Comparison Lisbon.

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 6 Energy System Performance Comparison London.

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

4.4. Running Cost.

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. The cost of operation of heat pumps however depends on the COP, which in turn depends on the temperature gradient. So, it was calculated, 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 7.

Table 7 Energy Prices.

	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.

4.3 Emissions

The emissions of the energy systems depend heavily on the energy mix of the respective countries. 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.

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

Table 8 Emission Rating.

	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	

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 8, we can see that the emission rating of natural gas is 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.

1. 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.

References

[1] H. Ritchie and M. Roser, “Energy Production and Consumption,” Our World in Data. [Online]. Available: https://ourworldindata.org/energy-production-consumption#citation

[2] “The Economics of Climate Change.,” Apr. 2021. [Online]. Available: https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-economics-of-climate-change.html

[3] International Union For Conservation of Nature, “Species and Climate Change,” 2019. [Online]. Available: https://www.iucn.org/sites/dev/files/species_and_climate_change_issues_brief-2019-12.pdf

[4] “International Union Of Conservation Of Nature,” *www.iucnredlist.org*, 2021. https://www.iucnredlist.org/search/stats?redListCategory=ex

[5] Office of Habitat of Conservation, “NOAA Fisheries,” Sep. 27, 2021. https://www.fisheries.noaa.gov/national/habitat-conservation/restoring-coral-reefs#:~:text=Coral%20reefs%20are%20damaged%20due,of%20its%20coral%20reefs%20already.

[6] “Climate Change and Health,” World Health Organization, Health Report, Mar. 2021. [Online]. Available: https://cdn.who.int/media/docs/default-source/climate-change/fast-facts-on-climate-and-health.pdf?sfvrsn=157ecd81_5

[7] “Summary for Policy Makers,” International Energy Agency., May 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/7ebafc81-74ed-412b-9c60-5cc32c8396e4/NetZeroby2050-ARoadmapfortheGlobalEnergySector-SummaryforPolicyMakers_CORR.pdf

[8] “Trends and Projections in Europe 2021,” Oct. 2021. [Online]. Available: https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2021

[9] “Hydrogen,” *energy.ec.europa.eu*. https://energy.ec.europa.eu/topics/energy-system-integration/hydrogen_en

[10] J. Cihlar and V. Lejarreta, “Hydrogen Generation In Europe (Cost review and Key benefits)),” European Commission, Directorate-General for Energy, 2021. [Online]. Available: https://data.europa.eu/doi/10.2833/821682

[11] R. Howarth and M. Jacobson, “How Green is Blue Hydrogen?,” Park foundation and Cornell University, Dec. 2021. [Online]. Available: https://doi.org/10.1002/ese3.956

[12] S. Mekhilef, S. Rahman, and A. Safari, “Comparative study of different fuel cell technologies,” *Renewable & Sustainable Energy Reviews*, vol. 16, pp. 981–989, Jan. 2012, doi: 10.1016/j.rser.2011.09.020.

[13] “An EU Strategy for Energy System Integration.” European Comission. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0299&from=EN

[14] European Comission and Fuel Cells and Hydrogen Joint Undertaking., “Hydrogen Roadmap Europe: A Sustainable Pathway For European Energy Transition.,” European Comission. [Online]. Available: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

[15] J. Cunha, “Portugal Energy Strategy Towards Decarcobinzation.,” Lisbon, Jan. 2022.

[16] “EN H2: Estrategia Nacional Para O Hidrogenio,” Ambiente e Ação Climática, Portugal, May 2020. [Online]. Available: https://participa.pt/contents/consultationdocument/Estrate%CC%81gia%20Nacional%20para%20o%20Hidroge%CC%81nio%20DRAFT%20publicac%CC%A7ao.pdf

[17] J. Brandao and R. Pinto, “National Hydrogen Strategy,” PLMJ, Jun. 2020. [Online]. Available: https://www.plmj.com/xms/files/00_Trending_Topics/NI_National_Hydrogen_Strategy.pdf

[18] “Portugal National hydrogen Strategy (EN-H2),” República Portuguesa. [Online]. Available: https://kig.pl/wp-content/uploads/2020/07/EN_H2_ENG.pdf

[19] “Fusion Fuel.” https://www.fusion-fuel.eu/

[20] “Global Hydrogen Review 2021,” International Energy Agency., 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

[21] “The Future of Hydrogen,” International Energy Agency., 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[22] C. W. Tan and H. S. Das, *Hybrid Renewable Energy Systems In MicroGrids*. 2020. [Online]. Available: https://www.sciencedirect.com/book/9780128217245/hybrid-renewable-energy-systems-and-microgrids

[23] “Coal Analysis and Forecast to 2025.,” International Energy Agency., 2020. [Online]. Available: https://www.iea.org/reports/coal-2020

[24] C. Falter and A. Sizmann, “Solar Thermochemical Hydrogen Production In The USA,” MDPI, 2021. [Online]. Available: https://doi.org/10.3390/su13147804

[25] “U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry,” Bioenergy Technologies Office, United States of America., Mar. 2018. [Online]. Available: https://www.energy.gov/sites/default/files/2015/01/f19/billion_ton_update_0.pdf

[26] “Hydrogen Delivery,” Office of Energy Efficiency and Renewable Energy. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-delivery

[27] “Gaseous Hydrogen Compression,” Office of Energy Efficiency and Renewable Energy. [Online]. Available: https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-compression

[28] C. Azzaro-Panthel, *Hydrogen Supply Chains Design, Deployment and Operation*. 2018. [Online]. Available: https://doi.org/10.1016/C2016-0-00605-8

[29] “Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure: Overview of existing studies and reflections on the conditions for repurposing,” ACER (European Union Agency for Co-operation of Energy Regulators), Jul. 2021. [Online]. Available: https://extranet.acer.europa.eu/official_documents/acts_of_the_agency/publication/transporting%20pure%20hydrogen%20b

y%20repurposing%20existing%20gas%20infrastructure_overview%20of%20studies.pdf

[30] S. Schuster and H. Josef Dohmen, "Challenges of compressing hydrogen for pipeline transportation with centrifugal-compressors," 2020. [Online]. Available: https://www.researchgate.net/publication/345413645_Challenges_of_compressing_hydrogen_for_pipeline_transportation_with_centrifugal-compressors

[31] B. Eliasson, "Energy and Hydrogen Economy.," ABB Switzerland Ltd., Switzerland. [Online]. Available: https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

[32] C. Findlay, "Hydrogen infrastructure: The practical conversion of long-distance gas networks to hydrogen operation," Siemens, Nowega and Gascade, 2020.

[33] "Liquid Hydrogen Delivery," Office of Energy Efficiency and Renewable Energy. [Online]. Available: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery

[34] "Tracking Buildings 2021," International Energy Agency., Paris, Nov. 2021. [Online]. Available: https://www.iea.org/reports/tracking-buildings-2021

[35] "Fuel Cells," Energy.gov, United States of America. [Online]. Available: https://www.energy.gov/eere/fuelcells/types-fuel-cells

[36] Dolci et al, Hylaw et al, and Staffell t al, "Special Focus on Gas Infrastructures, IEA Analysis," IEA, 2019. [Online]. Available: https://www.iea.org/articles/special-focus-on-gas-infrastructure

[37] "The GRHYD Demonstration Project," Engie, France. [Online]. Available: https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project

[38] "HyDeployment Phases UK," HyDeploy, United Kingdom. [Online]. Available: https://hydeploy.co.uk/project-phases/#phase-1-keele

[39] "UK Hydrogen Strategy," The United Kingdom. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_

[40] T. Issace, "HyDeployment Keele University," Fraunhofer Report Response. [Online]. Available: https://hydeploy.co.uk/app/uploads/2018/02/Fraunhofer-Report-Response_blog-by-Tommy-Isaac-Head-of-Hydrogen-Research.pdf

[41] "STORE&GO Report," STORE&GO, Switzerland. [Online]. Available: https://www.storeandgo.info/about-the-project/results/index.html

[42] "ENE - Farm." [Online]. Available: https://www.j-lpgas.gr.jp/en/appliances/index.html#ENE-FARM

[43] E. Ravn Nielsen, C. Brorson Prag, and Technical University of Denmark, "Learning points from demonstration of 1000 fuel cell based micro-CHP units," Ene.Field, Oct. 2017. [Online]. Available: http://enefield.eu/wp-content/uploads/2017/10/ene.field-Summary-Report.pdf

[44] "Summary report on specifications for newest model deployment in PACE.," The Pace Project., Brussels, Belgium, D1.7, May 2021. [Online]. Available: https://pace-energy.eu/wp-content/uploads/2021/05/PACE-D1.7-2021-update-FV.pdf

[45] "Google SketchUp." https://www.sketchup.com/

[46] "EnergyPlus," Department of Energy. [Online]. Available: https://energyplus.net/

[47] A. Abdullah, B. Cross, and P. Will, "Whole Building Energy Analysis : A Comparative Study of Different Simulation Tools and Applications in Architectural Design," pp. 1–12, 2014.

[48] J. Sousa, "Energy simulation software for buildings: Review and comparison," *CEUR Workshop Proceedings*, vol. 923, pp. 57–68, 2012.

[49] Energy Efficiency & Renewable Energy, "EnergyPlus | Department of Energy," 2014. https://www.energy.gov/eere/buildings/downloads/energyplus-0 (accessed Sep. 02, 2021).

[50] X. Zhou, T. Hong, and D. Yan, "Comparison of Building Energy Modeling Programs: HVAC Systems," no. August, p. 83, 2013.

[51] "EnergyPlus | EnergyPlus." https://energyplus.net/ (accessed May 09, 2021).

[52] "Getting Started - EnergyPlus Documentation." https://www.energyplus.net/sites/default/files/docs/site_v8.3.0/GettingStarted/GettingStarted/index.html (accessed May 09, 2021).

[53] Rallapalli, "EnergyPlus Modular Structured Code," Department of Energy, 2010. [Online]. Available: https://www.energy.gov/sites/default/files/2014/04/f14/Volume%203.pdf

[54] R. Gomes, A. Ferreira, and R. Costa Neto, "Retrofit measures evaluation considering thermal comfort using building energy simulation: two Lisbon households," Iinstituto Superior Tecnico., Lisbon. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/17512549.2018.1520646?journalCode=taer20

[55] "EnergyPlus Weather File." Department of Energy., Updated. [Online]. Available: https://energyplus.net/weather-region/europe_wmo_region_6

[56] "Heat Pump Efficiency Vs Temperature Graph (COP At 0°F To 60°F)," *Learn Metrics*. https://learnmetrics.com/heat-pump-efficiency-vs-temperature-graph/

[57] García-Céspedes, Arnó, Herms, and de Felipe, "Characterisation of efficiency losses in ground source heat pump systems equipped with a double parallel stage. A case study," Universitat Politècnica de Catalunya, Barcelona, Spain. [Online]. Available: https://upcommons.upc.edu/bitstream/handle/2117/127435/J.Garc%C3%ADa-C%C3%A9spedes%2Bet%2Bal.pdf

[58] Luis Antonio Gómez Pérez, "Heat Pump vs Boiler Comparison Guide (2022)," United Kigdom, Jul. 14, 2022. [Online]. Available: https://www.boilerguide.co.uk/articles/boilers-vs-heat-pumps-which-is-best-for-your-home#:~:text=Most%20top%20gas%20boilers%20are,electricity%20the%20heat%20pump%20uses.

[59] "Providing Clean Power and heating for Residential Building." Sunfire-Home, Germany. [Online]. Available: https://www.sunfire.de/files/sunfire/images/content/Produkte_Technologie/factsheets/Sunfire-Factsheet-Home-en.pdf

[60] "Electricity price statistics," European Comission, Apr. 2022. [Online]. Available:

https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

[61] “Electricity Price in EU and Portugal.,” Aug. 06, 2021. [Online]. Available: https://www.edp.com/en/edp-stories/electricity-price-portugal-and-europe

[62] “United Kingdom natural gas prices,” *www.globalpetrolprices.com*. https://www.globalpetrolprices.com/United-Kingdom/natural_gas_prices/#hl216

[63] “The UK Hydrogen Economy: Policy Announcements Support a 10GW Ambition,” FTI Consulting. [Online]. Available: https://www.fticonsulting.com/emea/insights/articles/uk-hydrogen-economy-policy-announcements-support-10gw-ambition

[64] “Energy bills support factsheet,” Gov.UK, Oct. 2022. [Online]. Available: https://www.gov.uk/government/publications/energy-bills-support/energy-bills-support-factsheet-8-september-2022#:~:text=Average%20standing%20charges%20for%20customers,customer%20paying%20by%20direct%20debit.

[65] Lavagne d’Ortigue, Taylor, Francoeur, and Trudeau, “Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels,” International Energy Agency., Jul. 2008. [Online]. Available: https://iea.blob.core.windows.net/assets/acaecb98-4430-4395-a4fa-d1a4d5ccb3d3/EnergyEfficiencyIndicatorsforPublicElectricityProductionfromFossilFuels.pdf

[66] EDP, “Origin of quarterly energy.” https://www.edp.pt/origem-energia/

[67] “Carbon tracker.” https://www.edp.pt/origem-energia/