Integrating Hydrogen in Buildings and Neighbourhoods

A Comparative Study of Hydrogen Solutions and other Widely-accepted Energy System Designs

Hamida Kurniawati

Ir. Siebe Broersma
Prof. Laure Itard
Saleh Mohammadi, PhD.

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Building Technology Graduation Project

[Author]

Hamida Kurniawati
5275407

[Supervisor TU Delft]

Ir. Siebe Broersma
Climate Design and Sustainability

Prof. Laure Itard
Building Energy Epidimiology

[Supervisor Witteveen+Bos]

Saleh Mohammedi, PhD.
Energy Transition PMC

TU Delft

“Hydrogen is today enjoying unprecedented momentum. The world should not miss this unique chance to make hydrogen an important part of our clean and secure energy future”

Dr Fatih Biro

ABSTRACT

Fossil fuel heating within the building sector is responsible for 30% of the United Kingdom's total CO_2 emissions. In response, the United Kingdom government has outlined a hydrogen strategy as part of its 2030 Net Zero Target, particularly for industrial and transportation purposes. However, the integration of hydrogen into building systems remains a subject of ongoing debate.

This research explores the potential for green hydrogen through local solar power, while electricity grid is serving as a backup system to support building energy demand. A comprehensive bottom-up analysis is conducted comparing various energy system configurations involving hydrogen, including grid distribution, fuel cell utilization, natural gas blending, and hybrid hydrogen combined with a heat pump. These systems then compared to the existing technologies, such as natural gas grid system, and all-electric heat pump system. About 25 houses consist of 5 typological buildings have been modelled. The analysis extends to calculate energy consumption, cost-effectiveness, and carbon emission equivalent of each system. An optimized system of integrating hydrogen will be suggested, which will be implemented on a larger scale to assess its impact on costs and other relevant parameters.

The utilization of hydrogen in buildings will become prominent if the source and distribution of hydrogen in industry is becoming widely accessible, then it will be continuously applied in the building use. Coinciding with the increasing visibility of other green alternatives to meet the net zero energy requirement.

The findings indicate that an optimized hybrid hydrogen and heat pump system has significant result than other hydrogen system. This system facilitates the utilization of hydrogen as a heating source during peak hours in the evening and in cold seasons, while a direct heat pump powered by photovoltaics can be employed in the summer and daytime. Therefore, hourly configuration is required to maintain the continuation of the operation. This approach resulted on reducing energy consumption to an half of the non-optimized hybrid system when the heat pump is constantly operated using electricity from the fuel cell solely. Notably, cost efficiency improves significantly with larger scale implementations, the larger the area is, the lower the cost is generated. Ultimately, about 6,882 square meter area is required to provide the appliances of hydrogen production for 234 dwellings in one neighbourhood.

From a cost perspective, while hydrogen is flowed intensively and distributed in the city, hydrogen grid boilers become more viable option. While, blending natural gas boiler serves as a transitional solution during the energy transition phase. Ultimately, natural gas will obviously phase out. With this study, the final words on the implementation of hydrogen in buildings will never be answered explicitly on the basis in which system has the most optimal solution for hydrogen systems; it will always depend on its particular context and location. A further comprehensive analysis of cost-effectiveness and investment rate per scenario, regardless the dynamic model of set-up on hybrid heat pump appliances, is required.

Keywords

Hydrogen system, heat pump, hydrogen boiler, hydrogen fuel cell, hydrogen cost-effective analysis, hydrogen life cycle analysis, hydrogen carbon emissions analysis

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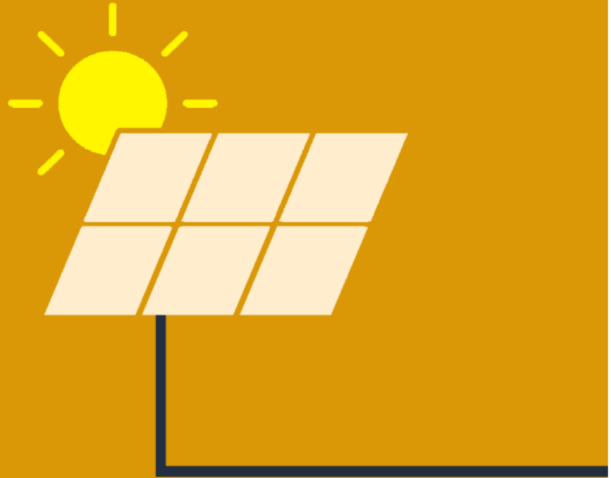


1. INTRODUCTION

The master's thesis explores the comparison study of hydrogen solutions and the common energy systems in building. To fully comprehend the different fields of research, some backgrounds are provided. This background in chapter 3 presents literature reviews on key related themes, some pilot projects are explained. These are correlated with basic properties of hydrogen, reviewing the latest technology and development of hydrogen (pilot projects), different strategies to determine the future possibilities of hydrogen use in buildings. And some background information about three parameters are projected, including the energy performance, the cost feasibility, and the amount of carbon emissions.

In chapter 4, it explains the design development of hydrogen system and other common energy system. The technology's working principle of each system is outlined, and the multicriteria on designing systems are specified. Additionally, the advantage and disadvantage of the system is also documented, highlighting the prominent functions of hydrogen, including advantage and disadvantage of its scenario, which basically will bring the challenge in the future development.

In chapter 5, describes the neighbourhood as a study case in the UK and the household typologies in England, using Tabula to examine the energy demand. The renovation recommendations is also explored in this part thus will conduct three situations; base case, light renovation and heavy renovation.

In chapters 6, 7, 8 assess calculation of each part, in energy performance, cos-effectiveness, and carbon emissions. These topics are vital before exploring to narrow down hydrogen energy system that will be discussed in the following chapter.

Following that, chapter 9 addresses the discussion part based on multicriteria analysis on which system has the most growth potential. Following by the possible solution for local hydrogen and how to implement green hydrogen production in one area.

Chapter 10 will explore the schematic diagram of hydrogen scale management in the neighbourhood which includes the placement of the production. Mentioned the suggestion of hydrogen use in preferable conditions, mentioned the comparison scale of optimized and non-optimized system, and the area required to place the appliances in one neighbourhood.

The thesis closes with a conclusion on chapter 11 where the research questions are answered, and recommendation for further research are provided.

2. RESEARCH FRAMEWORK

2.1 Problem Statements

Renewable energy in the United Kingdom has grown ten times since 2004 and which indicates that it is on track to continue inclined to 42.8% of the UK's total electricity generation. The United Kingdom commits to reduce economy-wide greenhouse gas emission by at least 68% by 2030 [1]. In fact, 85 % of home and 40% of the electricity that is used across the nation still rely on gas [2] However, along with the current ambition, the United Kingdom published The UK Net Zero strategy in 2021 which sets how the UK will deliver on Carbon Budgets and the Nationally Determined Contribution to support 2050 Net Zero Greenhouse Gas Emissions [3]. This urgency needs to be prepared and shifted to the new technology than natural gas and other-emitted-carbon fuels.

The urgency of achieving net zero Greenhouse Gas (GHG) in a building sector

Natural gas produces approximately 117 pounds of CO_2 per million British Thermal Units (MMBtu), while coal and diesel fuel oil create more than 200 and 160 pounds of CO_2 per MMBtu, respectively [4] During combustion, the carbon combines oxygen and producing carbon dioxide in the air. Other greenhouse gas such as methane is also harm in the atmosphere which is 25 more concentrated than carbon dioxide. The methane leak is released from oil and natural gas wells, storage tanks, pipelines, and processing plants [5] Furthermore, Natural gas drilling, exploration, and production also affects the environment, which if it burned on site, the flare produces CO_2 and can release in the air.

A mismatch supply and demand of solar renewable energy

Due to inability to accurately foresee the amount of solar energy produced over a period of time, solar energy frequently experiences period of discrepancy between supply and demand as illustrated in the Figure 1. This might result in an electricity grid overload in the summer or a daytime and the lack of energy-supply in the winter. This mismatch should be solved to avoid the dependency of grid in order to achieve the net zero energy balance. Thus, seasonal storage for long term technology is needed as a back-up sources for the specific time and in unbalanced situations. Therefore, it is necessary to know what are the possible parameters and technologies to help resolving this mismatch, and one of the answers is through hydrogen.

Flexibility for the long term energy storage

Hydrogen has an extremely high specific energy and energy density, allowing it to store an immense quantity of energy per cubic meter of compressed gas. On the one hand, battery storage compensates for the limited capacity with only stands for hours. The possibility to supply energy in the longer time is there, however, a cost reduction by 20% is required for hydrogen-related technologies to initiate hydrogen storage as long-term energy storage for power systems.

Hydrogen use in building is disputed

Hydrogen use today is dominated by industry cluster as a feedstock for high-temperature processes, shipping, and long-term energy storage for electricity production [6], [7] Study from Fraunhover IEE mentioned hydrogen is not viable option when it comes to heating buildings [8]. On the contrary, other studies also described injecting hydrogen in building is possible; Hydrogen could be blended into existing natural gas networks including a direct use of boilers and fuel cells [9]. While heating hydrogen would require 5 to 6 times more renewable electricity than a highly efficient heat pump [10].

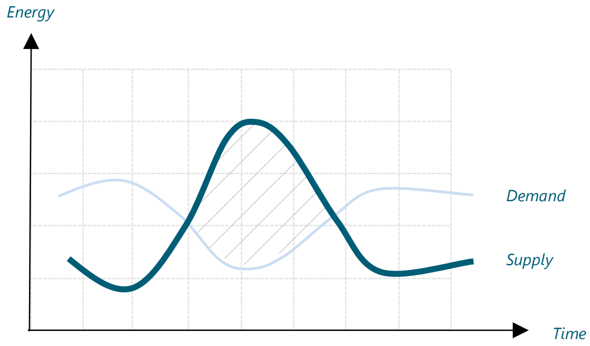


Figure 1. Estimated daily mismatch between supply and demand of energy in a building (author)

An article by David Cebon mentioned that the two most frequently proposed ways to heat buildings in a low-carbon future in the UK are hydrogen to power hot water boilers, or electricity to power heat pumps [11] While in the UK near Gateshead, Northern Gas Networks finalized the transitional steps of running exclusively on hydrogen solely[12]. These numerous recent studies have investigated the areas of implementing hydrogen in buildings, including pilot projects which is optimistically running a developed hydrogen technology. However, some researchers also found adverse outcomes regarding the use of hydrogen in building. A comparison study is needed to understand the role of hydrogen in building with other widely current energy systems regardless the opportunity enlarging the next low carbon energy development. Beside the performance and its efficiency, the role of hydrogen plays in building will depend heavily on its price and the heat production cost. Ultimately, the implication of hydrogen to the environment sustainability related with its emission and its production method should be taken into account.

Therefore, the problem statement is formulates as follows:

Although hydrogen has been viewed as a promising energy transition alternative, however, the exploration study to understand the effective use of hydrogen in buildings is lagging behind. There is a lack of understanding in which condition hydrogen can be applied in buildings and neighbourhoods, compared to the current available energy systems.

2.2 Research Questions

Based on the problem statement above, certain information of hydrogen solutions is acknowledged. Then, it leads to the following research questions:

How do hydrogen-based energy systems compare to widely-accepted energy systems alternatives in terms of energy performance, cost-effectiveness, and environmental sustainability, and what are the implications for surrounding neighbourhoods?

The research and design assignment will also answer the following sub-questions:

1. *What are the potential hydrogen systems that can be utilized in residential buildings and other alternatives of energy systems?*
   This question focuses on identifying and examining the various systems not only hydrogen but also common alternatives that can be implemented in residential buildings. Comparing these systems is enable to understand their respective advantages, limitations, and applicability in residential settings.

2. *What is the performance comparison of each energy alternatives based on some criteria?*
   This question aims to assess and compare the performance of different alternative based three criteria, include energy efficiency, environmental impact, and cost-effectiveness. By conducting this comprehensive performance analysis, it gains insight, the strengths, and weaknesses of each alternatives and its suitability for different scenarios to be applied in buildings.

3. *How is the implications of hydrogen in building within the neighbourhood?*

   This inquiry seeks insight into neighbourhood-level consequence of using hydrogen in construction. In this delve-deeper question, not every scenario is being investigated. One of the optimum system will be investigated further. Implementing hydrogen in neighbourhood affects the selection of proper sizing of hydrogen tools and technology, as well as the option to determine the potential arrangement of the components whether centralized or decentralized system. This also includes the local production of hydrogen and other renewable energy such as solar panels which balance the energy consumption of the neighbourhood. The recommendation of a specified design or a layout of hydrogen placement in the neighbourhood also will be assessed.

2.3 Objectives

General Objective

Although, the highlighted problem statements indicate a discrepancy with the prevalent debate on hydrogen heating in buildings, additional research is required to comprehend this hydrogen application in the further development. In this study, certain number of plenty solutions, including commonly wide-used energy systems in buildings, are evaluated. The objective of this research is to explore design solutions for integrated hydrogen-based energy system for residential buildings, utilizing a comparative approach to identify the most effective hydrogen system based on energy performance, cost effective and carbon emission. The study then be generated to determine the implication of hydrogen use within the neighbourhood, in relation to the components and energy production of local renewable hydrogen. This study will also be completed with the amount of Renewable Energy needed, including the number of solar panels and hydrogens applied.

This research was conducted to support the UK's vision, to bring the innovation of hydrogen, compelling the development of hydrogen in building, lays out the route of UK hydrogen strategy with the holistic approach of a long term direction of 2030 net zero transition ambition. With this project, a new perspective technology with the potential advantages is concerned, without disregarding the possibilities of outdated technology has been made. The houses stock in the UK is being calculated, using a Tabula database, and with the same number of domestic heating and electricity needs, will be measuring the performance of energy in each solution; the primary energy will be determined. A prediction of local hydrogen cost is explained with the Capital Expenditures and Operational Expenditures are measured. Therefore, the Return on Investment will be projected. Ultimately, the last parameter of Carbon emission is accounted. From this three parameters then generated to the most optimal system of hydrogen.

Final Products

1. Energy Demand Modelling – utilizing excel data calculation for five typical dwellings in the UK.

2. Energy System Schemes / Diagram – delivers the proper visualization of energy systems effectively.

3. Comparative Graphics of each scenario based on energy performance, cost-effectiveness and carbon emission.

4. A Levelized Cost of Energy (LCOE) – including estimating the production cost of hydrogen in the neighbourhood including the investment cost, operation cost, and the payback time.

5. A recommendation of hydrogen application in building or in the neighbourhood.

6. Design illustrations of Hydrogen plant (local-production) with the total area mentioned in the neighbourhood

7. Report and Presentation with literature research to build the fundamental base of the project

2.4 Boundary Conditions

This research focuses on the exploration of hydrogen system and the possibility of further development of hydrogen energy system. Three parameters are evaluated with the outcome of the most effective energy system encompassing hydrogen. Given the breadth of the research topic, it is crucial to establish well-defined boundaries to ensure a focused and feasible investigation. These boundaries primarily revolve in these aspects.

Firstly, a specific data limitation pertains to the availability of the energy demand within the UK building stocks. However, this limitation will be managed by employing a publicly available dataset of Tabula. Based on the data with specific U-value. Then it proceeds in the energy demand modelling and validate the analysis with the previous dataset to enhance the robustness of the research.

Cost prediction of certain components, particularly specialized new cutting-edge technologies, can be challenging. The availability of cost data for these components are limited, giving the precise forecasting difficult. To address this limitation, the research will make reasonable assumptions based on the market standards and utilize established cost estimation methodologies.

The scenarios created to obtain the great comprehensive understanding of hydrogen energy systems in three parameters, whereas not the whole scenarios will be implemented in the neighbourhood. The selected system applied in a compact small area will act as a controlled testbed, enabling the research to make informed assumptions and draw meaningful conclusions regarding the viability and practically energy systems, offering valuable insights for energy planning and decision-making at larger scales.

Lastly, considering the inclusion of three parameters and the need for a comprehensive analysis. The research recognizes the constraints of time. The research will prioritize the selection of appropriate of evaluation methods focused on certain approach and utilizing efficient data analysis techniques, the study aims to strike a balance between the depth of the analysis and the available research time.

By clearly defining these boundaries, this research project establishes a robust framework for exploring the most effective hydrogen energy system. The identified limitation regarding data gathering, hydrogen-components cost prediction, and time constraints are vital consideration that will shape the research methodology and ensure the feasibility and integrity of the study.

2.5 Scientific and Societal Relevance

This research has the potential to deliver different contributions to the society and relevant research. The potentially contributing outcomes of this research hold significant in scientific and societal relevance.

- Scientifically, by systematically evaluating different energy system scenarios and analysing their energy performances, cost-effectiveness, and carbon emissions, this research expands our understanding of the complex interplay between technology, economics, and environmental considerations.

Furthermore, the incorporation of hydrogen as a potential energy carrier aligns with the growing interest in renewable energy alternatives and decarbonization efforts. For architect and building engineer, this study will help to understand the possible systems to use whether hydrogen or other solutions that can be integrated to the built environment and how to compare of each system.

- Societally, this research addresses key challenges related to building energy efficiency, greenhouse gas emissions reduction, and energy transition. The findings of this study can inform policymakers, energy professionals, and stakeholders involved in urban planning and infrastructure development, providing valuable insights into selecting the most effective energy system in building. This study will consider hydrogen will be a possible view of contributing 2050 UK net zero target and clearly be essential to UK heat decarbonisation. Especially for a climate change mitigation goals improving the energy efficiency specifically for old and thermally inefficient building stocks.

2.6 Research Design and Method

The thesis has been planned as follows:

Phase 1 : Literature research and system design development
Phase 2 : Energy demand modelling (case studies) and Energy Performance analysis based on its energy consumption. cost-effectiveness and carbon emissions analysis (comparative study)
Phase 3 : Optimizing System and neighbourhood application and sizing
Phase 4 : Conclusion and reporting

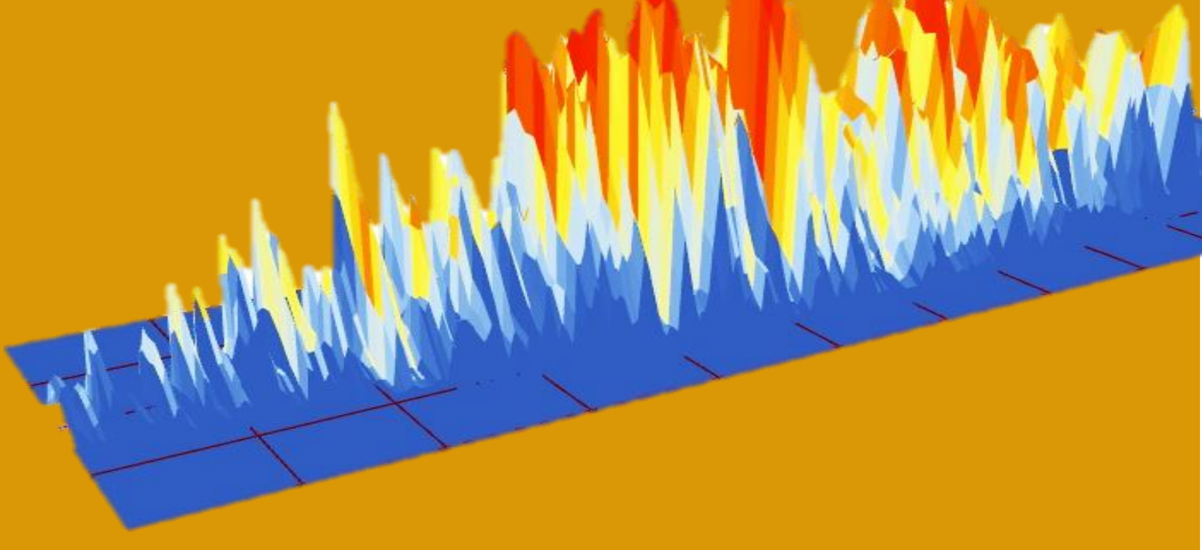
Phase 1 focuses on the comprehensive the knowledge and the principle of hydrogen system, while other common systems also explained. A development schemes of hydrogen energy systems then designed based on the literature review. Some information of the cost and emissions will be used for the next development.

Phase 2 deals with the fundamental research on the analysis of each parameter to finalize on the optimum or effective system based on three criteria, will have a structured approach that allows comparison of the three criteria simultaneously. The weights assigned to each criterion based on its relative importance. In this stage, analysis plays crucial role to have a grasp of several energy systems and have a background to opt which system has a valuable

Phase 3, the neighbourhood implementation will focus on how the system designs and run in the neighbourhood. How is the sizing of hydrogen, the placement of this energy center, the amount production of local green hydrogen, the levelized cost of hydrogen production and the return of investment within the neighbourhood.

Phase 4 will provide general conclusion and recommendation of the system. The recommendation can be the development of the previous scenario measured in the research. And the result which has been assed will be documented in a presentation and report.

This research will answer the research question, proceeded by obtainment of knowledge from the relevant literatures and a case study within the location of Stoke-On-Trent, United Kingdom.



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3. LITERATURE REVIEWS; DEVELOPMENT OF HYDROGEN TECHNOLOGY

3.1 Background

This chapter presents a literature review on key related themes to the use of Hydrogen as an energy source. Reviewing the latest technologies of hydrogen system among the multiple energy sectors, many different strategies have been investigated to determine the future utilization of hydrogen in buildings. The key takeaways for each field are:

1. Energy performance in buildings: This chapter deals with introduction of energy efficiency, the ratio between energy used by the building and the energy consumed within it. This chapter allows the formulation of energy use to find the energy consumption based on its efficiency.

2. Basic energy systems: In this part, encompassed a comprehensive understanding of the energy chain in buildings and the built environment, involves energy supply, conversion, storage & distribution. In this research, energy supply is utilized photovoltaic, grid, and natural gas. And the energy conversions are focusing boilers, heat pumps, and fuel cells. The prominent theme about hydrogen technology will be covered on the further sub-chapter.

3. Basic hydrogen properties: Delved into the fundamental characteristic of hydrogen, explores key properties of hydrogen such as its energy content, hydrogen production methods, hydrogen storages, and hydrogen safety.

4. Hydrogen pilot projects: Explained the initiatives designed of practical application of hydrogen technologies in real-world settings. This part is important to identify the latest hydrogen system development that currently is happening, accelerating the deployment of hydrogen technologies worldwide.

5. Cost-Effectiveness of Hydrogen and other widely-accepted alternatives: Referred to the evaluation of their economic efficiency and performance in achieving desired outcomes or benefits in comparison to their costs. Cost-effectiveness is assessed by considering both the upfront capital costs (CAPEX) and ongoing operational costs (OPEX) associated with their implementation and utilization.

6. Carbon emissions of hydrogen and other widely-accepted alternatives: Demonstrated the amount of carbon dioxide (CO2) and other greenhouse gases emitted (if any exists) during their production, conversion, and utilization. This critical to understand environmental impact, having low-carbon to contribute decarbonization, achieving climate mitigation goals.

3.2 Energy Performance in Buildings

The need for improving energy efficiency is crucial in energy performance criteria. Expressed in primary energy, is utilized for both compliance with minimum energy performance requirements [13], is achieved by the use of the main energy performance of a building. Technical building systems (heating, air conditioning, ventilation, lighting) and electrically powered appliances (computers, appliances) used by building occupants all contribute to primary energy use, which is calculated using primary energy factors per energy carrier.

At the design stage, calculated energy needs can be converted into primary energy by applying the relevant primary energy factors. These factors were responsible for any system losses and inefficiencies caused by energy systems utilized in buildings[13]. Total energy consumption is calculated for heating, hot tap water, ventilators, lighting, and cooling [14] Ir. M. Kuijpers Van Gaalen described the energy used for heating is determined by the following aspects:

- The demand for heating in a house. The amount of heat to keep the temperature at the required level.
- The efficiency of the system. This represents the energy losses that occur between the demand side (the amount of heat required in a room) and the generating side of the distribution system.
- Building Construction material including the heat transport mechanism; insulation material, heat transport through conduction, radiation, and convection. Solar gain and infiltration.

Net heat demand is the difference between the amount of heat lost via transmission and ventilation and the amount of heat generated by the sun and human and mechanical sources [14]. A system will achieve thermal equilibrium if the sum of all heat transfers is sufficient to cause the desired change in temperature.

$$Q_{out} = Q_{in} \qquad [w] \qquad (1)$$

$$Q_0 = Q_{trans} + Q_{inf} + Q_{vent} - Q_{sol} - Q_{int} \qquad [w] \qquad (2)$$

Where Q_0 is a heat balance; Q_{trans} is a heat flow of transmission; Q_{inf} is heat flow of infiltration; Q_{sol} is heat flow of solar load; and Q_{int} is the internal heating in the buildings.

While heat loss through transmission occurs through physical layers of the buildings; the outer walls and roofs, windows, doors and glazing, and via the floor at ground [14]. The heat accumulated within the material construction processed to the temperature progression, adapting with the new situation depending on the mass of the construction. All materials are taken into consideration, including building insulations within the material layers. This is beneficial when accompanied by favourable U-values, since it enhances and functions as a thermal bridge which will slow down the heat transfer.

$$Q_{trans} = \sum U \cdot A \cdot \Delta T \qquad [w] \qquad (3)$$

$$U = \frac{1}{R} \qquad [W/m2K] \qquad (4)$$

Defined with Q_{trans} is the heat flow of transmission; U is U-Value of the window glazing; ΔT is the temperature difference between the high and the low temperature [15].

Heat loss through ventilation and infiltration is the total amount of energy consumption that is required to heat air supplied from the outside up to the temperature in the room. This includes air that finds the way out via cracks and gaps, or even ventilation system by the occupants for opening the doors and windows [14].

$$Q_{ventilation} = \rho \cdot c \cdot n \cdot V/3600 \cdot \Delta T \qquad [W] \qquad (5)$$

Where ρ and c are described as the density and thermal conductivity of the air (ρc = 1200 J/Km^3, ρ_{air} = 1.2 [kg/m^3], c_{air} = 1000 J/kgK); *n* illustrates the air change rate (per hour); V is the volume of the room; and ΔT is temperature difference [15].

Additionally, the second major energy performance characteristic in a building is the ability to control solar heat gain through the glazing. The total solar energy that enters the room is determined by the total area of the window, and g-value, defined as the coefficient difference used to measure the transmittance of solar gain through glazing. The heat flow of solar gain is formulated as follows.

$$Q_{solar} = g . A_{window} . E_{sun\ load} \qquad [W] \qquad (6)$$

Where Q_{solar} is the heat flow of solar which g is value of solar transmittance; A is the total area of window; and E is solar load (600 W/m^2). While $Q_{internal}$ is defined as the heat load comes within the buildings, users, appliances, or even the lightings.

$$Q_{internal} = Q_{int,\ people} + Q_{int,\ lighting} + Q_{int,\ appliance} \qquad [W] \qquad (7)$$

The effect on the energy demand profiles is then to be generated to the basis calculation of the 'fitted' energy performance calculation recommendation. To be considered, as mentioned in the earlier paragraph, the energy performance calculation will also depend on the efficiency of the energy system.

$$\eta \text{ (efficiency)} = \text{Energy Output} / \text{Energy Input} \times 100\% \qquad [\%] \qquad (8)$$

Energy efficiency defined as the ratio between the output and the input of energy conversion process, from here, energy consumption or primary energy can be calculated. The less use of energy input (primary energy) the more efficient the system is. In the end, less energy consumption increases the resilience and reliability of environmental and community benefits, save money for the future comfort and a healthier living environment.

Conclusion

In conclusion, energy performance analysis in buildings is vital for promoting improvement of energy efficiency and sustainability. It involves calculated energy needs into primary energy using relevant factors. Energy consumption then has been known considering various parameters such as demand for heats. Which allows to be calculated using the formula mentioned. The net heat demand is determined by the difference between heat losses through transmission and ventilation and the heat generated from solar and internal sources. The efficient energy systems and controls of solar heat gain are essential to reduce the energy consumption and achieve thermal equilibrium. Then from the heat demand, the energy consumption can be calculated considering the efficiency of the total system.

3.3 Basic Energy Systems

There are four basic parts of a general energy chain in buildings: Firstly, energy is produced from the natural resources such as coal, gas, sun and wind. Secondly, these are transformed into energy such as heat and electricity in an energy conversion process. Thirdly, this energy subsequently sent to the user as an energy demand and by a way of an energy distribution network. Fourthly, the energy that was produced can be momentarily be stored to the storage.

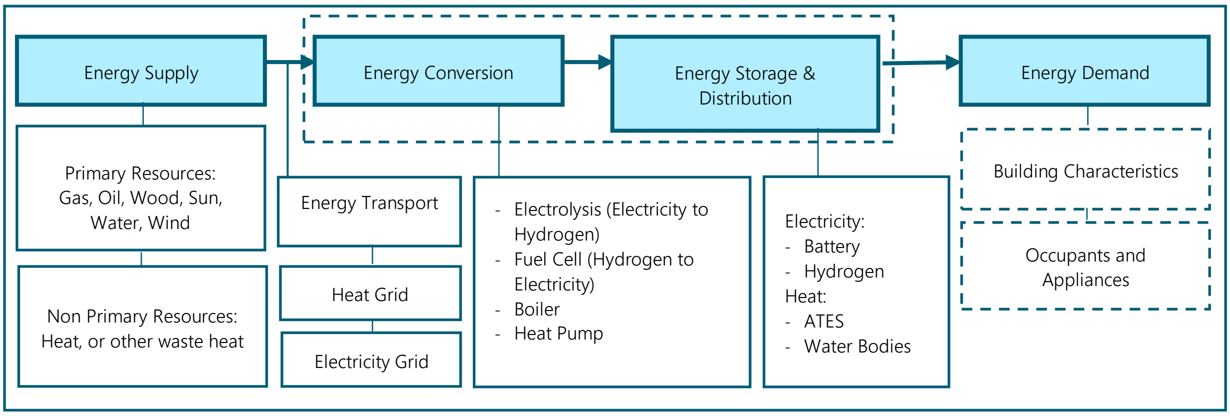


Figure 2. Energy chain in buildings, edited. Retrieved from Bueren et al., 2012

The framework of energy chain as explained in Figure 2, this scheme must be adapted to facilitate analysis of the next energy development. The larger energy demand, the larger the energy conversion system should be, therefore the more natural resource will be used to manufacture and will cause a higher costs [16].

3.3.1 Boilers

Boilers are essential heat-generating devices used in various industrial, commercial, and residential applications. Operating on the principles of heat transfer, boilers utilize a fuel source such as natural gas, oil, biomass, electricity or even the new-edge technology; hydrogen.

Some factors can impact the efficiency of a boiler system include the age and condition of the boiler, the condition of the piping, the design and layout of the heating system, and the type and quality of the fuel used. There are three main types of boilers to be installed: Combi boilers, regular or conventional boilers, and system boilers. Figure 3 explains the difference of three systems, combi boilers are utilized for both heating of space and domestic hot water without any external tanks within the unit, while system boilers is for larger homes, most components are built-in, and storage space is need for a hot water cylinder. And regular boilers generates heat for central heating and use water cylinder for storing hot water.

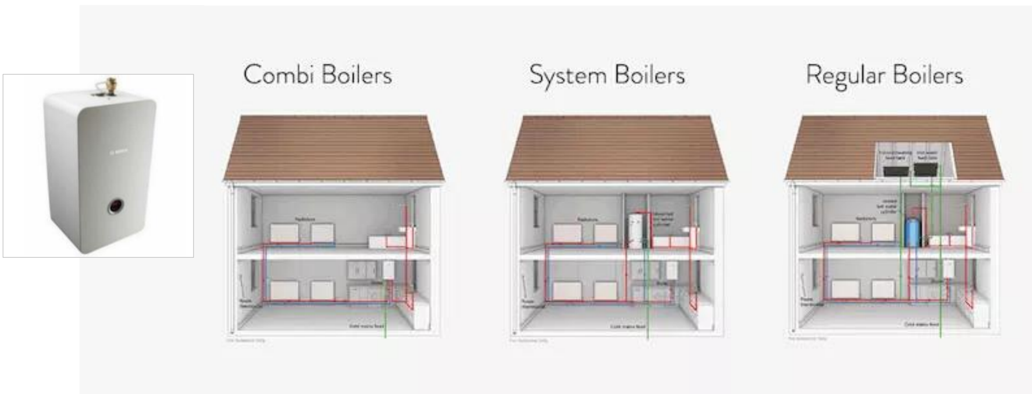


Figure 3. Various types of boilers in the market, retrieved from https://www.warrantypeople.co.uk/, accessed 20 March 2023

Table 1. The analysis of boiler system

Requirements	Description		Reference
Efficiency	87% - 90%		[17]
Cost	(Depends on the size of Boiler) Range 450€ - 1400€ Bosch (1395€ | 24 kW capacity | Combi boilers)		[18] [19]
Rated Heating Capacity (for single house)	1-2 bedrooms	24-27 kW	[20], [21]
	2-3 bedrooms	28-34 kW	
	4+ bedrooms	35-43 kW	
Average Heat-up Temperature	45ºC – 60ºC (regular boilers) 70ºC – 90ºC (condensing boilers)		[22]

3.3.2 Heat Pumps

In this section, the technology of heat pump is explained and considered to have positive impact in the future growth. Although heat pump has a small number of users in the UK, an ambitious plan to increase the heat pump installation is perceived to meet the demand for 2050. Heat pumps have the potentials to reduce global carbon dioxide emissions by at least 500 million tons in 2030 [7].

A heat pump is extracting heat from a source such as surrounding air, geothermal energy stored in the ground, or nearby sources of water or also a waste heat of the factory or other big facilities. It then amplifies and transfers the heat to where it is needed. Because most of the heat is transferred rather than generated, heat pumps are far more efficient than conventional heating technologies such as boilers or electric heaters.

However, currently, less than a quarter of a million of the UK's 29 million homes have heat pumps [23]. Compared to the 20 countries in Europe, the UK has the second lowest installation in homes after Hungary as the lowest with only 7 of 1000 homes installed, and the highest achieved by Norway with 517 homes fitted heat pumps. This means that heat pump is counted only for 1% in the UK market [24]. According to one of the studies, the forecast a 20-45% market share for heat pumps in 2040, with roughly 50% of the number being hybrid installations, with heat pump technology is involved [25]

Table 2. CoP of heat pumps and the expected cost of installation, retrieved from Energy Future Lab, 2022 [25]

Heat Source	Theoretical CoP[1,2] (SPF)[3]	Observed SPF[4]	Cost of Installation[5]
Air-to-water	2.5 – 2.8 (2,6)	2.45	£8,750 - £21,550
Air-to-air	2.5 – 2.8 (2.6)	2.45	£2,400 - £8,800
Ground-to-water	3.5 -4.5 (3.2)	2.82	£13,200 - £27,350

Notes to table4
- Source: Mitsubishi Electric (2020)
- Source: Kensa Heat Pumps (2021)
- Source: EHPA (2021c)
- Source: Lowe et al. (2017)
- Source: Mvers et al. (2018)

Figure 4. Heat pumps with different capacities (Sprsun), retrieved from https://sprsunheatpump.com/ accessed 20 March 2023

Currently, the government implements the "Boiler Upgrade Scheme" that designs to help homeowners with provides grants of £5,000 for air source heat pumps installed and £6,000 for ground source heat pumps. This will run for three years to April 2025 and benefits to 9,000 homes are expected [26] Table 3 below explains one of the general heat pump criteria for the system

Table 3. The analysis of heat pump systems

Requirements	Description		Reference
Efficiency (COP)	250-450% (2.5-4.5)		[23]
Cost (Based on capacity)	Range £2,400- £27,350 or €2,700 - €31,000 Sprsun (18,500€ | 92 kW capacity | air to air)		[23]
Rated Heating Capacity (dependent on the capacity of the system)	Air source heat pump	5kW to 16kW, 21 KW	[27], [28]
	Ground water heat pump	10-25 kW 39-100kW	[28]
	Air source to water Heat Pump	10.5 kW 17.5 kW-27 kW	[28]
Average Heat-up Temperature	Varies between -10ºC – 60ºC		[28]

3.3.3 Combined Heat and Power (CHP)

Combined heat and power (CHP) is also known as cogeneration is a suite of technologies that can use a variety of fuels to generate not only electricity or power, but also allowing heat that would normally be lost in the power generation process to be recovered to provide needed heating and/ or cooling.

3.3.3.4 Fuel Cell

Fuel cell is an electrochemical device in which the chemical energy is directly converted into electrical energy[29], [30]. The core of the device is the unit cell, the component in which the device converts the chemical energy in electrical energy. This technology is growing significantly by 40% in the market, of which 95% is accounted of portable fuel cell, while 97% of fuel cells used PEMFC technology [36].

Debates continue regarding hydrogen fuel cells advantages and disadvantages, but despite the current limitations, hydrogen can still be an environmentally friendly alternative to fossil fuels and can be used to provide flexible and high-density power and propulsion for a wide range of industrial plant and modes of transportation using hydrogen fuel cell technology. Table 4 explains the advantages and disadvantages of using fuel cells in a building energy system.

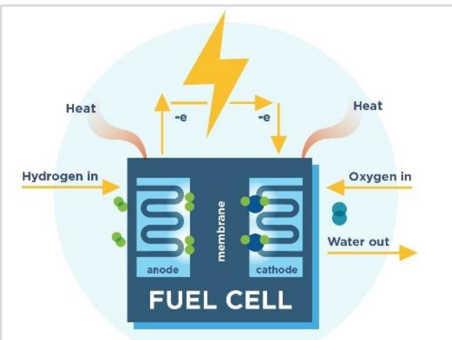


Figure 5. The principle work of fuel cell system (left), PEM fuel cell by Nedstack (right). Retrieved from Netdstack.com/en. Accessed 21 March 2023

A fuel cell works by passing hydrogen via the anode and oxygen through the cathode as explained in the Figure 5. At the anode, the process of electrolysis causes the hydrogen molecules to undergo a dissociation reaction, resulting in the separation of electrons and protons.

Fuel cell works like batteries, they produce electricity and heat as long as fuel is supplied. Table 5 shows the analysis performance of the system, with efficiency of the system is about half of the energy supplied. Hydrogen fuel cell consists of two electrodes, a negative and a positive electrode. The fuel is fed, then a catalyst separates hydrogen molecules to protons and electrons, the electrons go through an external circuit, creating electricity [31].

Table 4. The analysis of fuel cell system with hydrogen gas

Requirements	Description	Reference
Efficiency (COP)	40-60% [32] 60% [33]	[32]
Cost	100W - 300W | $2,400 - $6,200 1kW- 5 kW | $6,200 - $22,000	[34]
Rated Heating Capacity	100-300W, 3kW-5 kW, 30kW- 50 kW	[34]
Waste Heat Temperature	(40 - 70ºC)	[33]
Carbon Emissions	0 k/kWh (only when the fuel from green hydrogen)	[31]

3.3.4 Photovoltaics

Solar photovoltaics (PV) have emerged as the predominant technology for household and commercial energy generation due to their widespread adoption. The significant increase in energy prices has resulted in a substantial reduction of approximately 50% in the cost of alternative technologies, such as Solar PV. Figure 6 illustrates the presence of two distinct categories of photovoltaics. Table 5 provides an explanation of the distinction and analytical framework.

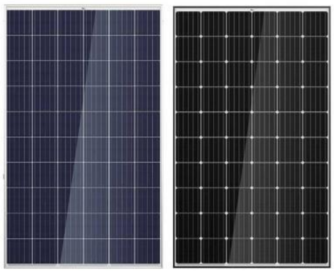


Figure 6. Polycrystalline (left) and Monocrystalline (right) photovoltaic. Retrieved from https://solarquotes.com/ accessed 21 March 2023

Nevertheless, the disparity between the supply and demand of energy has emerged as a critical concern in meeting the energy requirements of buildings. In many instances, the supply during a certain seasonal period may be insufficient or excessive to meet the energy demand. Table 5 presents an elucidation of the potentials and limitations of photovoltaics, facilitating the identification of the benefits associated with the use of this technology. In the first half of 2022, the United Kingdom experienced a substantial increase of 80% in newly installed solar photovoltaic (PV) systems. The observed expansion has brought to light the potential of photovoltaic (PV) as a feasible alternative for electricity generation. It is quite unlikely that photovoltaic solar cells will achieve a 100% efficiency level. Indeed, it is important to note that not all of the incident sunlight on a photovoltaic (PV) system is effectively converted into electrical energy. On average, a PV solar panel is capable of converting approximately 25-18.7% of the total solar energy it receives into usable power [35].

Table 5. The analysis of photovoltaics system

PV type Module	Monocrystalline	Polycrystalline	Thin Film	Reference
Efficiency				

Theoretical Efficiency	25.0%	20.4%	18.7%	[35]
Practical Efficiency	15-20%	13-16%	9-11%	[35]
Cost				
Operation	0.75$/Watt /year	0.62$/Watt /year	0.7$/Watt /year	[35]
Material	€144			[36]
Warranty	25 years	25 years	10-25 years	[35]
Power Output	250 – 450W	240 – 300W	200 – 400W	[37]

Conclusion

In conclusion, the energy systems in buildings encompass a diverse range of technologies with varying efficiencies and costs. Boilers remain a widely used heat generation method, with advancements in hydrogen-fueled boilers offering potential for cleaner energy. Heat pumps show promise in reducing carbon emissions, but their adoption in the UK is still relatively low compared to other European countries. Combined Heat and Power (CHP) systems offer an opportunity to utilize waste heat effectively. Fuel cells, particularly hydrogen-based, present a clean energy option, but their current limitations must be addressed for widespread implementation. Photovoltaics, although widely installed, face challenges related to supply-demand mismatches and limited conversion efficiency.

To achieve a sustainable energy future, a combination of these energy systems, along with energy storage solutions and efficient use, will play a vital role in meeting energy demands while reducing environmental impact. This research specifically focuses on the analysis of those technologies mentioned. While other energy technologies such as heat storages, wind sources, and biomass are intentionally excluded from this study and not discussed in detail. The exclusion of these technologies is in alignment with the research objectives and scope.

3.4 Basic Hydrogen Properties

Hydrogen is the most abundant chemical substances, constituting around 75% of all normal matter in the universe [38]. This element is symbolized as H and has atomic mass of 1.008. It is the lightest element in the world, as it is colourless, odourless, and tasteless. Normally, hydrogen works bounding together with two atoms (H_2). Generally, it is encountered in compounds, bonded with other material on the existing earth; such as water (H_2O), Chlorine (HCl), and Methane (CH4).

To have a better understanding of the basic properties of hydrogen, below is a brief description of the characteristics of hydrogen:

- Hydrogen has a much lighter molecule than methane, with a lower value of British Thermal Unit (BTU) of volume [39].
- Gaseous hydrogen contains a third of the energy of the same volume of Methane [40] however, on a weight basis it contains three times the energy of Methane [40].
- Hydrogen has a higher flame temperature with a peak of 4000°F (2204.4°C) compared to the flame temperature natural gas which is about 3600°F (1982.2 °C)[39].
- Hydrogen has a very low density in the gaseous state [41] liquefying such as an energy consumption process[42]
- Hydrogen has a higher octane level which is rating up to 100, meaning that it has the ability to prevent unwanted auto ignitions in combustion chambers [42].
- Hydrogen can be stored, derived, and converted through various processes [40].

Table 6 presents the basic properties of Hydrogen [42]. It shows that hydrogen has a very low density in the gaseous state. As liquid, the energy content of hydrogen is much higher, liquifying hydrogen has more energy consumption because Hydrogen needs more energy and that makes it less attractive alternative to be used as a fuel.

Table 6. Basic Properties of Hydrogen, retrieved from K. Mazloomi, C. Gomes, 2012.

Property	Value	Unit
Name, symbol, number	Hydrogen, H, 1	-
Category	Non metal	-
Atomic weight	1.008	-
Density (gas)	0.089	g/l
Density (liquid)	0.07	g/cm^3
Liquid to gas expansion ratio	1:848	Atm. conditions
Energy content, Higher Heating Value (HHV)	142	MJ/kg
Energy content, Lower Heating Value (LHV)	120	MJ/kg
Flammability range in air	4-75	°C
Autoignition temperature	585	°C

Table 6 presents the energy density of Hydrogen in compression with other common types of fuels. Hydrogen has general a high energy density than Methane and natural gas. Energy content is the amount of the energy that is released when a fuel reacts with oxygen[43]. It is quantified by a High heating Value (HHV) and Low Heating Value (LHV). These values represent the amount of required energy to vaporize a liquid, and the HHV subtracted with the energy required to a vaporize water.

In the Table 7 explained that hydrogen is an excellent energy carrier with respect to 1 kg of hydrogen contained 33,33 kWh of usable energy, three times larger than natural gas. However, in terms of volumetric energy density, it depends on the pressure how hydrogen stands for. Under ambient conditions, a cubic metre of hydrogen provides some 3 kWh, equivalent to 0.003 kWh per litre. Pressurised hydrogen contains about 0.5 kWh/L at 200 bar, 1.1 kWh per litre at 500 bar, and 1.5 kWh per Litre at 700 bar. While the best energy density is 2.8 kWh/litre with liquified hydrogen pressure[44].

Table 7. Energy density of hydrogen compared to the frequently used fuels. Retrieved from Mazloomi & Gomes, 2012

Material	*Energy per kg*		*Energy per Liter*		*Energy per cubic meter*
	(M.J./kg) [42]	(kWh/kg) [40]	(M.J./L)	(kWh/L)	(kWh/Nm^3)
Hydrogen (liquid)	143	33.3	10.1	2.8	2800
Hydrogen (compressed, 700 bar)	143	33.3	5.6	1.5	1500
Hydrogen (atm. Pressure)	143	33.3	0.0107	0.003	3
Methane (atm. Pressure)	55.6	10.6-13.1	0.0378	0.0105	10.6
Natural Gas (liquid)	53,6	10.6-13.1	22.2	6.16	6160
Natural Gas (compressed 250 bar)	53.6	10,6-13.1	9	2.5	2500
Natural Gas (atm. Pressure)	53.6	10.6-13.1	0.0364	0.0101	10.1

3.4.1 Hydrogen safety

Hydrogen explosive

The threshold for hydrogen is similar to natural gas, at 4.1% hydrogen in air, and better than the 1,2% limit of petroleum in air [40]. Although Hydrogen has a high range, it is not overriding factor in the real situations where dilution and dispersion keep the gas/air ratio low.

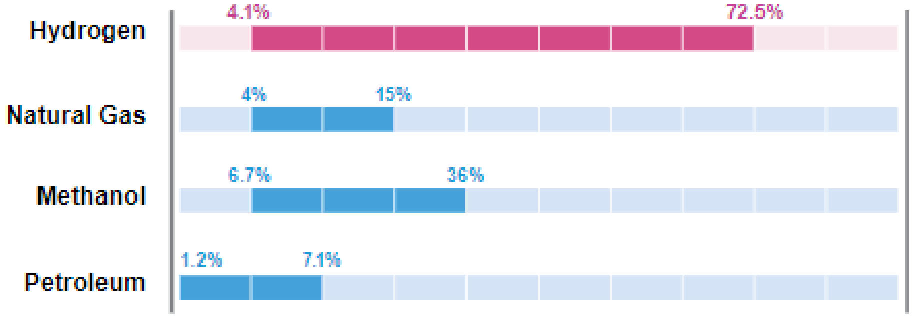


Figure 7. Explosive Limits Comparison in Air. Retrieved from Arup, 2021 (Five minutes guide of hydrogen)

In average conditions, people cannot see, smell, or taste the presence of hydrogen as a gas. However, it is flammable and can self-ignite without an external energy source.

Energy density and leakage

Hydrogen has about one-third of the energy density of methane. However, due to the small molecular size of hydrogen, the risk of a leakage always has a chance of occurrence. Furthermore, the higher pressures to counteract, the higher propensity of hydrogen can be leaked.

However, if a leak does occur, the area should be well ventilated to prevent hydrogen to blow up. A gas detection should be in place to alert operators to the leak before it ignites. If a leak does ignites, there would be a need for detecting the flame quickly and accurately.

Flame visibility and odors

Hydrogen burns with a very pale blue to nearly invisible flame. A hydrogen flame poses special dangers beyond those posed by hydrocarbon flames, because human senses cannot easily detect it. The area ahead of the flame would see a sort of shimmer like a mirage, and even see sparkles when dust particles briefly burning [45]. Figure 8 presents different shots of Hydrogen during the ignition process.

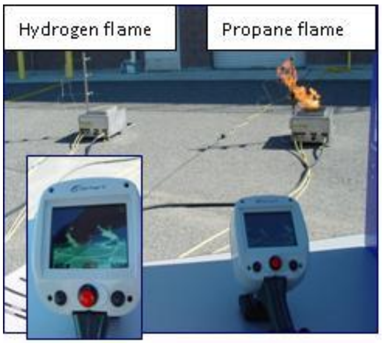


Figure 8. (Left) Hydrogen and Propane flames in day light. Retrieved from https://h2tools.org/, accessed 25 March 2023 (Right) Hydrogen and Propane Flames at Night, retrieved from Image works. Retrieved from https://h2tools.org/, accessed 25 March 2023

From the images shown in Figure 8, clearly showed that hydrogen flames are almost invisible during daylight hours, so ignition are almost impossible to be observed with the naked eye. A pure hydrogen flames will not produce smoke. Therefore, a flame detector is needed such as thermal imaging camera to detect the revealed flame, so it is recommended to install such kind of detectors in storage rooms.

Radiant heat

The heat of the flame is not clearly visible, because the infrared radiation exists in a small amount. Thus, an insight infrared radiation could give the sensation of the heat when standing next to a flame.

Although gas detectors can contribute to prevent any harmful leakage and explosion, flame detection is also needed to detect flame and heat radiations of Hydrogen. Such kind of deductions should incorporate flame detectors that sense the non-visible spectrum of electromagnetic radiation, which includes ultraviolet (U.V.) and Infrared (I.R.) radiation.

3.4.2 Hydrogen storage

As mentioned in the Table 7, hydrogen has much higher energy content in liquid form than in compressed gas state [46]. The main advantage of storage of liquefied hydrogen is its high density in low pressure. These features enable compact and light weight storage and efficient delivery options [46], [47]. Furthermore, the temperature of liquefied hydrogen can reach up to -250°C. Therefore, the process needs more energy to produce this such temperature, adds an excess of 30% to the production power demand. As a result, liquified hydrogen costs 4 until 5 times higher than the compressed gas states [48] this type of production is not commonly used in the market. While in terms of the cost and efficiency, the cost of an energy storage system is 1/30 that of the battery storage, and its efficiency ranges between 95% and 97% [49]

Storing hydrogen in high pressure vessels is an alternative option for the most vehicle manufacture due to the efficiency, design, cost and environmental advantages [50]. Though another cost-effective way to store Hydrogen is with the gas yet compressed to provide an easy to use source for the users. Hence, many professionals anticipate that hydrogen storage in high pressure cylinders is very unlikely to be a popular method in the future [51]. Figure 9 shows hydrogen cylinders that have been used to store hydrogen. In stored Hydrogen in the cylinders can be distributed through pipelines.

Figure 9. Hydrogen cylinders of H21 project by DNVGL. Retrieved from https://www.telegraph.co.uk/business/2021/05/03/hydrogen-heating-homes-pipeline/ accessed 29 March 2023

Regarding to the cylinders which constantly gets a contact of hydrogen, can also have the possibility of hydrogen embrittlement, which can affect metals, even high strength steel to be brittle in the long term [52], [53] This starts with the diffusion of hydrogen itself through the metal. Then, the metal create pressure from the cavity they are trapped in, and thereby, may cause physical damages to the metal.

However, guidelines and safety management procedures should be followed in order to prevent the mentioned issues, the damage and losses.

3.4.3 Hydrogen production process

There is a range of methods used to generate hydrogen from different resources. Unfortunately, the current hydrogen production methods in the U.K. are almost derived from fossil fuels [3]. Currently, an estimated 10-27TWh of hydrogen is produced in the U.K. mostly for use in the petrochemical sector. Further, only a very small amount of electrolytic hydrogen is produced in the U.K. Through hydrogen is one of the most viable solutions for energy transition, it contradicts when the energy source is still being generated from the fossil fuels. It can be outspoken green if it is created from renewable energy in which electrolysis is involved and electricity from Solar power is taking over, even though the production is not massive yet.

Hydrogen from Fossil Fuels

Fossil fuels have a heavy hydro-carbon based molecular structure. It is extracted by breaking the compounds between hydrogen and carbon content [54]. This substance can be extracted from biomass [55] coal [56] gasoline, oil (heavy and light), methanol and methane [57]. It is also known as Grey and Blue Hydrogen. Grey hydrogen is the hydrogen harvested from fossil gas through steam methane reformation. Blue hydrogen is the grey hydrogen that has been paired with carbon capture to reduce CO2 emissions.

Steam Methane Reforming is a process which includes steam that reacts with a hydrocarbon feedstock to produce hydrogen, carbon dioxide, and carbon monoxide [48].

The reaction of this highly endothermic process is given by the equation below:

$$H_2O + CH_4 \rightarrow CO + 3H_2 \quad (9)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (10)$$

Reforming is followed by a water gas shift reaction explained in figure 10.

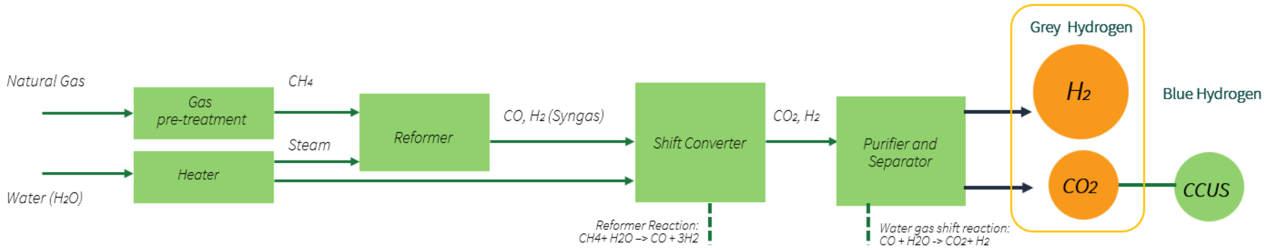


Figure 10 Scheme of Hydrogen from fossil fuels is produced. [illustrated by author]

Figure 10 outlines the processes of producing Hydrogen from fossil fuels. These processes comprise the follows:

- Methane and steam enter the reformer, then the initial steam reforming is reacted and assisted by a catalyst. It is often called syngas when the result was a carbon monoxide and triple hydrogen.
- By doing a shift converter to produce and purify hydrogen, a catalyst assists and create the reaction of $CO+H_2O \rightarrow CO_2 + H_2$
- Hydrogen and carbon dioxide are ultimately separated. Blue hydrogen still continues the process to use CCUS, capturing carbon dioxide in the atmosphere while production is occurring.

Hydrogen is a by-product of other oil refinement [57]. Although the advantages of a reasonable production price and possibility of mass production are high, problems of pollution and limited resources cannot be denied. Therefore, this resources are not renewable [57]. However, steam methane reforming with carbon capture (CCS) or also called blue hydrogen is the most economical production technology as CO2 emissions are minimised [58].

Hydrogen from Water and Electricity

An electric current splits water into hydrogen and oxygen. If the electricity is produced by renewable sources, such as solar and wind, the hydrogen will be called as a green hydrogen or renewable as well [59]

The overall chemical reaction of a water electrolysis process is given by followed equations:

$$H_2O \rightarrow H_2 + (1/2)\ O_2 \quad (11)$$

This method does not have a large share in global production. It spends high production costs [60]. It also has a low conversion efficiency, and electrical power expenses [61] On the other hand water electrolysis has some unique qualities which capable of producing absolutely sustainable and clean hydrogen. This goal can be achieved if the electricity is obtained from an emission-free method such as renewable and green sources. However, the fact that such energy can be generating systems eight times faster than those with oil base fuels [62]

Water electrolysis process requires a minimum energy of 39.4 kWh/kg of hydrogen generation at full conversion efficiency [42]. However, typical electrolyser consumes up to 50 kWh in order to generate 1 kg of hydrogen [63]. Many efforts are made in order to increase the efficiency of water electrolysis, and thus, the higher efficiencies can obtained in extreme pressure and temperature conditions. Table 8 illustrates the details of producing Hydrogen through electrolyser.

Table 8. Hydrogen production detail via electrolyser. Retrieved from Ivy, J. 2006.

Hydrogen Production	1 kg	1 kg
Electricity input needed	53 kWh	39 kWh
Efficiency	75%	100%
Energy Content HHV	39 kWh	39 kWh

Electricity costs	$0.04 and $0.055 kW/h	<0.075 kW/h
Hydrogen cost production	$3.00 / kg	<3.00 / kg

As shown in Table 8, it can be noticed that a low temperature electrolysers cannot be more efficient than the ideal line, and thus, the only way to decrease the amount of electricity needed can be fulfilled by providing another energy system such as heat [64].

There are two common systems of electrolysers, namely: Proton Exchange Membrane (PEM) and Alkaline electrolyser. First, PEM it is a system that uses electrolyte in a solid polymer form (Figure 11). Second, Alkaline electrolyser is the system where, electrolyte is a liquid alkaline solution, usually sodium hydroxide (NaOH) or potassium hydroxide (KOH), with a thin diaphragm (Figure 12).

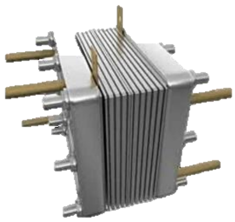


Figure 11. Proton Exchange Membrane (PEM) Electrolyser, retrieved from Broadlef Capital International Pty Ltd. August 2021

Figure 12. Proton Exchange Membrane (PEM) Electrolyser, retrieved from Broadlef Capital International Pty Ltd. August 2021

Biohydrogen from Biomass

There are three methods of hydrogen production from Biomass, at the Figure 13 demonstrates biological processes, electrochemical technique, and thermochemical processes. However, primarily the conversion of Biomass to hydrogen is using thermochemical (gasification, pyrolysis) pathways. And the most majority of Biomass production is using gasification.

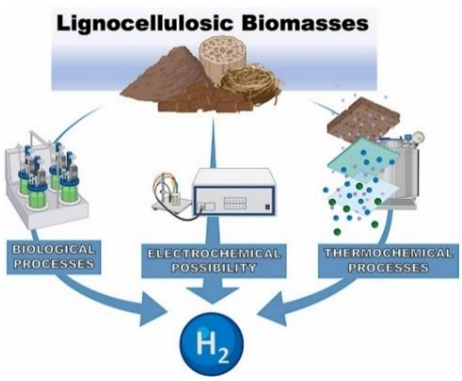


Figure 13. Biomass Hydrogen Production, retrieved from Thibaut, Lepage. 2021

Biomass gasification is a well-established technological approach that converts the organic matters such as household waste, agriculture waste, organic municipal solid waste, animal waste, forest residues, or other special crops grown specifically for energy use. This will produce at a high temperature (>7000 ^{o}C) without combustion and with a controlled amount of oxygen and/or steam into carbon monoxide, hydrogen and carbon dioxide[59], [65].

Thus, the simplified reaction is mentioned below:

$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + Other species

Note: The above reaction is using glucose as a surrogate for cellulose, actual biomass had highly variable composition and complexity with cellulose as one major component.

Another reaction using water-gas reaction is:

CO+ H2O → CO2 + H2 (+ small amount of heat)

Navaro et al. reported that biomass can be carbon neutral due to its maintained natural cycle and the source of materials which is from waste [65]. Besides that promising possibilities of biological hydrogen production, many challenges characterize this technology, including its production which the yields of H_2 are often low.

Currently, the hydrogen production costs from biomass remain quite high, ranging from 1.21 to 2.42 $/kg, which are three times higher than that production using Steam Methane Reforming (SMR) 0.75 $/kg [66]

Biohydrogen from algae and plants

The increase use of hydrogen will impact to the higher production volumes in the next few years. Biohydrogen will be the alternatives which offer some advantages of less emission from renewable sources such as plants and algae. Commonly, microorganisms such as micro-algae and cyanobacteria, produce the enzymes required to synthesise H_2 including nitrogenases and hydrogenases [67]. These different organisms then produce H_2 through some biological reactions in the low temperatures and pressures, between 25 and 80°C. Under these conditions, besides H_2, the gas also produced CO_2, and small amounts of CH_4, CO, and H_2S depending on the converted substrate. Hydrogen is primarily produced from the anaerobic metabolism of pyruvates generated during catabolism of carbohydrates [68]. However, compared with photolysis, the H2 yield in the gaseous product is lower due to the minor gases [69] The H_2 yield also relies on the byproducts of the reaction. Moreover, regarding the regeneration of the algae, microorganisms can be easily regenerated by replication, decreasing the turnover frequency compared with chemical catalysts.

Therefore, this biological process has the potential to integrate waste management into energy production. However, it still requires the development of current technologies to be financially competitive and have the potential for practical application and commercialisation. Generally, two factors are limiting the development and scaling of biological processes. The H_2 yield and production rate are lower (no progressive improvement of the production volumes). Another factor is the variability of the feedstock can affect the H2 yield and the economy of the process.

3.4.4 Hydrogen conversion to electricity

Hydrogen can produce electricity through fuel cells by combining hydrogen and oxygen atoms, as shown in Figure 14. The hydrogen reacts and electrochemical cell, similar to battery, can produce electricity, water, and small amounts of heat [70].

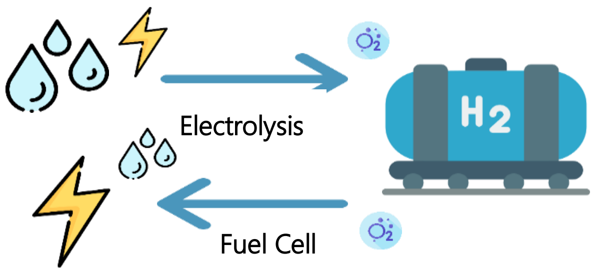


Figure 14. Back and forth process of electrolysis. Electrolyser converts electricity to hydrogen, while fuel cells convert hydrogen back to electricity [Illustrated by the author]

Battery-powered vehicles take nearly 45 minutes to recharge themselves, whereas hydrogen vehicles are refuelled in less than 10 minutes which is an additional benefit in terms of time [71]. Besides, batteries are composed of very hazardous materials like cobalt, lead, and lithium which are non-friendly to the environment as well as the human health. However, PEM FC; one of the fuel cells and easily available materials. This hydrogen fuel cells also considered as environmental friendly technology. It is suitable for stand-alone power supplies for remote location electrification. Hydrogen fuel cells have many different types, which results in a variation in the efficiency, ranging between 40% and 60% [72].

3.4.5 Hydrogen Production and Development in the UK

Current hydrogen production in the UK is estimated of 3 GW [3], [58] with the ambition of 5GW in 2030[3]. The majority of the hydrogen produced in the UK today is made from fossil fuels utilizing Steam Methane Reformation without capturing carbon emissions, or called Grey Hydrogen [3] Only small amount of Green Hydrogen is produced in the UK. However, The UK government expect to scale up the low carbon production through 2020s, with the main production is Blue Hydrogen with carbon capture storage. [25] Since the price of natural gas is increased, the government will use this condition to shift to hydrogen and reducing costs over time from renewable energy based. Including green hydrogen with electricity sources which is dedicated from the offshore wind [3].

By 2030 Green hydrogen will be produced large scale, and the plan of enable over 1 GW electrolytic hydrogen projects is fully developed as early as 2020s [3]. Recently, British Petroleum company (BP) has proposed HyGreen project in Teesside, which targets 60Mwe of green hydrogen production by 2025. Together H2 Teesside project which produced up to 1GW of blue hydrogen will be covered 30% of UK's hydrogen production target by 2030 [73]. Most H2 production is used for industrial cluster, therefore, needs a local storage to produce independently for further area exclude the central area. The UK has committed to a "twin track" approach, to develop together of both hydrogen production between electrolytic and CCS-enabled hydrogen. And in the end, green hydrogen will have a cost-competitive with CCS-enabled methane reformation in the early 2025. The cost feasibility of Hydrogen will be discussed in the further chapter.

Conclusion

Hydrogen, the most abundant element in the universe, has properties that make it a potential clean and efficient energy carrier since it has high energy density compared to natural gas. While hydrogen has high flammability poses safety challenges. Storing hydrogen provides more energy contents though the cost and electricity will be more required. Green hydrogen can be generated through water electrolysis utilizing renewable energy sources. The UK aims to scale up low-carbon hydrogen production, focusing on electrolytic and CCS-enabled hydrogen projects to achieve its hydrogen production targets by 2030. And hydrogen is one of the visible solutions of Carbon neutral free since its emission only a water vapor and can be integrated to the buildings.

3.5 Hydrogen Pilot Projects

It is a debatable question whether hydrogen will be applied in buildings for power or heating appliances. There are many current potential end-uses for hydrogen on a big scale. Hydrogen is often used within the industry cluster as a feedstock for high-temperature processes, shipping, and long-term energy storage for electricity production [49,50,51]. As predicted, in 2050, the global consumption of about 50% of energy sources is approaching electrification [77]. In new-build neighbourhoods with highly insulated homes (low heat demand), all-electric solutions seem to be the most logical solution. Since an electric heat pump offers a very efficient form of heat supply [78].

Hydrogen electrification might play the role of being incorporated with other renewable energy resources. Solar power to produce electricity for the new-build houses and battery storage is feasible to feed the energy stock in summer. Whilst, for old-build houses, the location is concerned with integrating hydrogen into heating building systems. Historical neighbourhoods in the centre for example, which connected to the grid can be a solution of hydrogen sources.

Table 9. Data collection for pilot projects of the existing hydrogen-use in buildings

	Hydrogen Distribution and Pipelines (HyNet UK)	Hydrogen Blend (Rozenburg, Rotterdam)	Hydrogen Grid (H4Heat UK)	Hydrogen Electricity (24 /7 Green Village)
Design System	Desalination Seawater → Power Plant (Electrolyser)→ Renewable energy (Solar generators and wind) → Hydrogen Distribution through pipes in the neighbourhood.	Electricity Supply → Electrolysis → Methanation → Gas grid injection and gas use	Grid pipelines (H_2) → Hydrogen boiler → hydrogen appliances → Hydrogen boiler → heating	Renewable energy → Electrolyser → compressor → hydrogen storage → fuel cell → battery → household
Energy Conversion Efficiency	Not defined	35% (total system efficiency)	90-95% (boiler efficiency)	60% (fuel cell efficiency)
Suitability	Cluster and City	Apartment and Old Grid pipelines	Deprived Neighbourhoods	Independent housings or Neighbourhoods
Capacity	48T Wh/year	8,3kWe		300 kWh/ 2 m^2
Advantages	• Low cost and high efficiency • Low carbon bulk hydrogen production • Safeguards for existing industry	• Can use the old pipelines • Hydrogen can be easily blended to the natural gas unless not exceeding the hydrogen percentage limit	• High efficiency of energy production • Hydrogen can be easily blended to the natural gas	• Highly scalable for long term energy storage to meet the seasonal balance • Hydrogen is used only when its needed • Using electricity to power the house • Has a year complete independent energy source
Disadvantages	• Suitable for a big cluster • Dependent on hydrogen supply	• A large energy loss during the production process • Releasing carbon emission of methanation. • Long production process which caused less efficiency • Risk of methanation is higher	• Dependent on the hydrogen supply • Dependent on the price range of hydrogen, since hydrogen is supplied from the central (in this case are private companies)	• High costs for hydrogen equipment • Long process to produce energy • A system scheme should have been more simplified

Not only some researchers who have been concerned with the hydrogen study but various companies also develop a technology of the application in buildings since the government is supporting to move forward to the hydrogen economy. Pilot projects allow to study synergies between different technologies. In the table 4 lists the advantages and disadvantages of using hydrogen in many pilot projects that have been developing in the recent years.

3.5.1 Hydrogen Distribution and Pipelines (HyNet UK)

The project is located in the U.K., and has been considered as a first large scale project to distribute hydrogen energy to the city or even the cluster area (Figure 15). HyNet is a complete system of hydrogen production, hydrogen supply, hydrogen utilization, carbon capture and transportation.

In terms of cost, on this basis, the plant delivers a levelized cost of hydrogen of £43.46/MWh (HHV basis). The estimated equivalent cost for a 5x unit is £35.62/MWh. By way of comparison, this is lower than the equivalent cost of natural gas. It accounted for the cost of carbon in 2035, which is assumed to be £37.16/MWh, in line with BEIS data, with a rising trajectory beyond this due to increasing carbon price.

The specification for the hydrogen and the acceptable ranges thereof has been defined by the approach to place the same concentration limits on certain types of hydrogen. There is a place for natural gas, ensuring that any mixed stream will remain within the natural gas specification.

The current hydrogen blend contained 10 ppm and it would be possible to guarantee to be within the HSE guidance level. Assuming blend level 20% vol means that the hydrogen contain up to 50 ppmv CO. This project will use conservative limit of 50 ppmv.

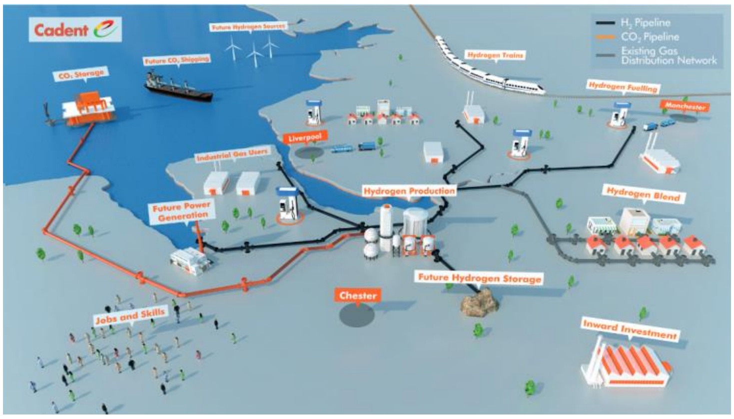


Figure 15. HyNet infographic of pipeline distribution planning in the UK. Retrieved from Cadent, HyNet. 2023.

The plan of distributing 100% Hydrogen is still on rising, since the project of 50ppmv is promising and succeed. The team is working to find the best way to achieve that in the system. Though assuming one cluster builds out a single unit of bulk hydrogen production, a lot of households will be independent on energy and save the energy cost of the grid.

3.5.2 Hydrogen Blend (Power-to-Gas Project Rozenburg Rotterdam)

The power-to-gas production chain consists of two technologies, namely: being electrolysis and methanation as illustrated at Figure 16. Electrolysis refers to the conversion of electricity into hydrogen, whereas methanation is the synthetic conversion of hydrogen and carbon dioxide into methane.

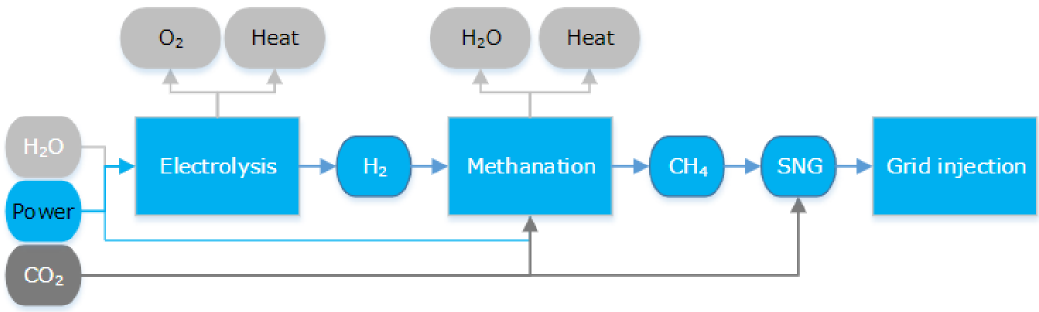


Figure 16 Power-to-gas production chain. Retrieved from DNV.GL. P2G Project Rozenburg. 2015

In the Figure 16, contains a flow diagram that describes the flows on a proportional basis. It visualizes the material flows and the mass efficiency of the process can be estimated. The flow diagram demonstrates that only part of the electricity is converted into hydrogen and only part of the hydrogen is converted into methane.

The Methanation

Methane is needed to mix with a small flow of carbon dioxide in order to comply with the gas-quality parameters before it can be injected into the gas grid. Yet, the risks of methanation are more diverse. The pressure and temperature may become higher than those for which the system is specified. The methanation process is operated in the temperature ranging from 200 °C to 500°C, whereby the temperature in the catalyst may run up locally to 700°C.

The injection into gas grid

The specified parameters of the gas composition must be measured continuously . The system must be equipped with a provision that makes it stop immediately if one or more parameters are not within the adjusted threshold values. Pressure monitoring is also needed in order to prevent exceeding the maximum pressure in the pipes of the network.

Energy Balance and Conclusion

The conversion of the electricity to hydrogen and oxygen was performed with an efficiency of 47%. The energy efficiency of this methanation process was set at 73%. However, it has been found that the energy balance of the entire system of Power-to-Gas system was very low, which was only 35% as illustrated in Figure 17.

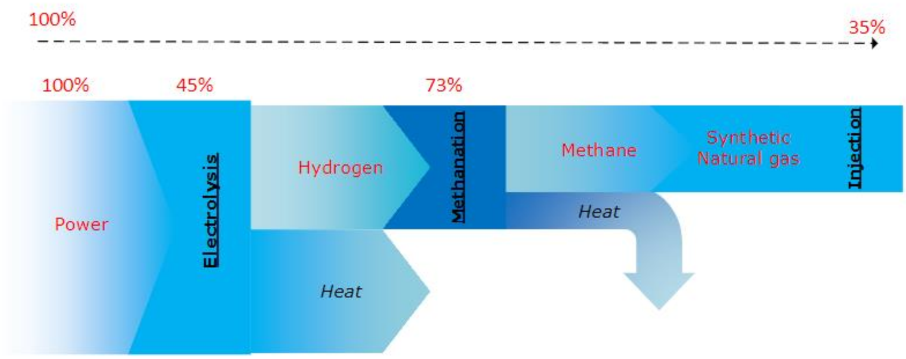


Figure 17. Energy Balance of Power-to-Gas system, retrieved from DNV report

Although this system has an advantage of the possibility to blend hydrogen with natural gas and enables for not changing the grid of the existing pipelines, the system of using methane is not green and still has a side product of emissions. These emissions contain carbon monoxide, higher hydrocarbons, and nickel carbonyl. Yet, this formation of those components may lead to blockage of the reactors and hazardous situation during the exposure. Other than that, methanation also uses high electrical power which must be connected in accordance with the guidelines.

3.5.3 Hydrogen Grid (Hy4Heat UK)

Hy4Heat is a program which is led by Department of BEIS (Business, Energy, and Industrial Strategy). BEIS a collaboration between some companies in the U.K., including: Arup, Kiwa Gastec, and Yo Energy. The mission of this program is to establish a technically possible, safe, and convenient energy packages by replacing natural gas (methane) with hydrogen in residential and commercial buildings as depicts on Figure 18. This also will enable government to determine whether to proceed this packages to a community trial in the U.K.

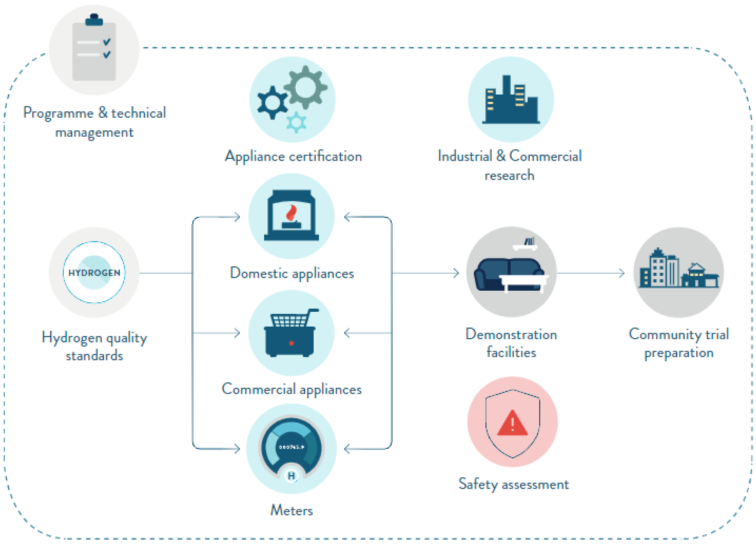


Figure 18. The program package of Hy4Heat, in the U.K. Retrieved from BEIS Hy4Heat report. Demonstrating hydrogen for heat. 2023

The programme consisted of ten distinct but interconnected work packages. These packages would operate in different timescales. All the programmes are designed to achieve the work package in a safe manner, other duties of work package is explained respectively as follows:

- Delivering the program and duties
- Managing delivery contract
- Conducting research into variety of commercial appliances and the issues
- Assessing the safe use of hydrogen gas in domestic properties, also the ventilation of gas
- Demonstrating the prototype appliances
- Conducting investigation and recommendation into hydrogen quality standards, the safety risk management; hydrogen purity, odorant, and colourant repots,
- Carrying out maintenance of hydrogen use in building and appliances.

The system is basically has the highest efficiency of hydrogen, since it uses gas distributed from the central and using hydrogen gas boiler to produce the heating as demonstrates on Figure 19.

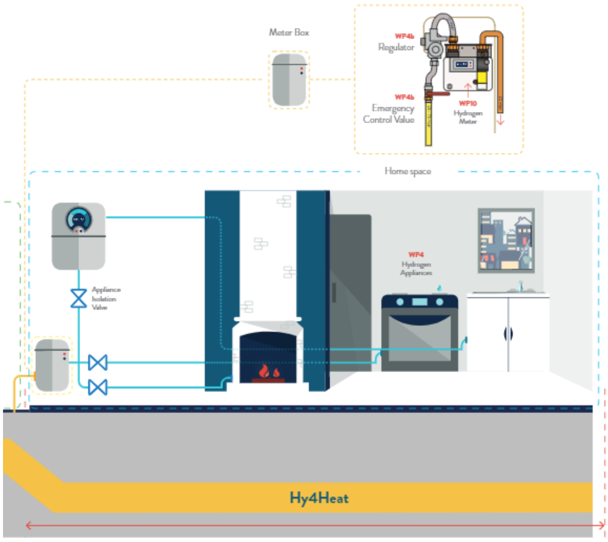


Figure 19. System scheme of Hy4Heat in the UK. Retrieved from Hy4Heat. BEIS. Demonstrating hydrogen for heat. 2023

3.5.4 Hydrogen Storage (24/7 Green Village)

A local, CO2-free energy system for the built environment. 24/7 Energy Lab is one of the examples and pilot projects for being locally producer of hydrogen without any emission and being the real sustainable solution as presented at Figure 20. It runs autonomously, and locally setup, so it can run when it is needed. Currently, the development of the system is now in progress. The installed with the generation of green electrons by the sun and wind, then energy storage in batteries and conversion of hydrogen into electrons take place.

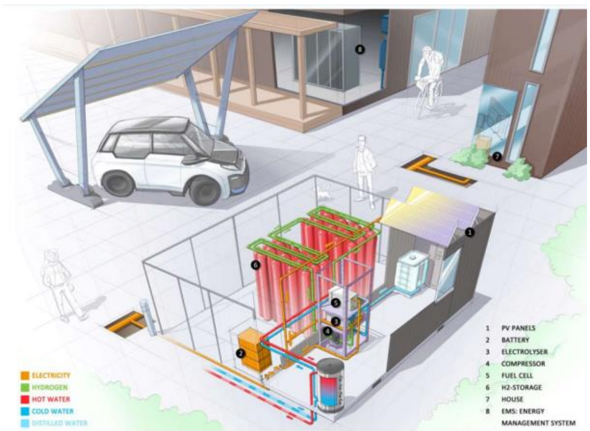


Figure 20. Hydrogen energy system in 24/7 Energy Lab. Retrieved from Green Village documentary (interview with Lidewij van Trigt)

This project was started when there is a doubt of energy fulfilment in the winter season, locally and independently energy households also becoming increasingly popular nowadays. Further, hydrogen can be a solution to store energy and to use it in a long-term storage.

By making combination of solar panels, a battery, an electrolyser to produce hydrogen, hydrogen cylinders store hydrogen and a fuel cell generates electricity with a stored hydrogen (Figure 21). By generating electricity to houses from the hydrogen storage through fuel cells, the house on the figure is locally self-produced. Heating is produced through heat pump by the electricity is provided from the hydrogen storage. In the summer, electricity can be generated from the solar panels and the stored in batteries. In the winter season, all the energy is generated by the hydrogen storage.

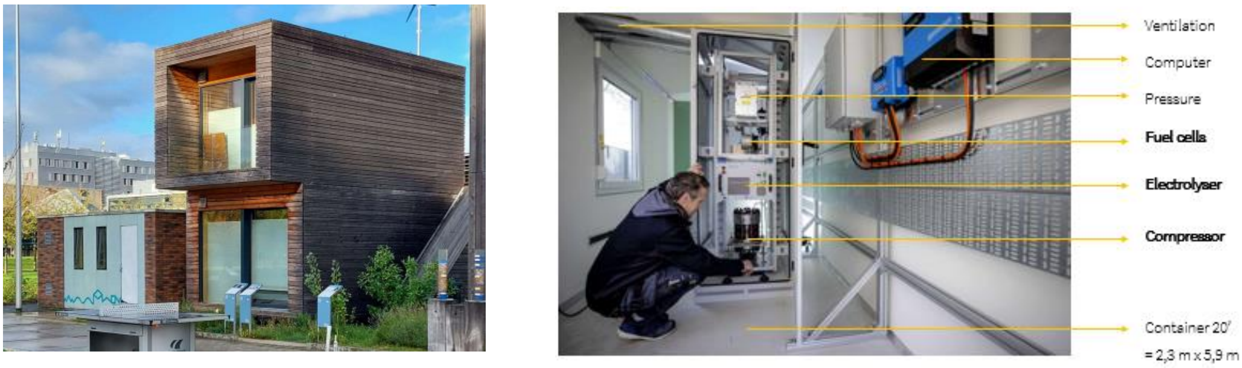
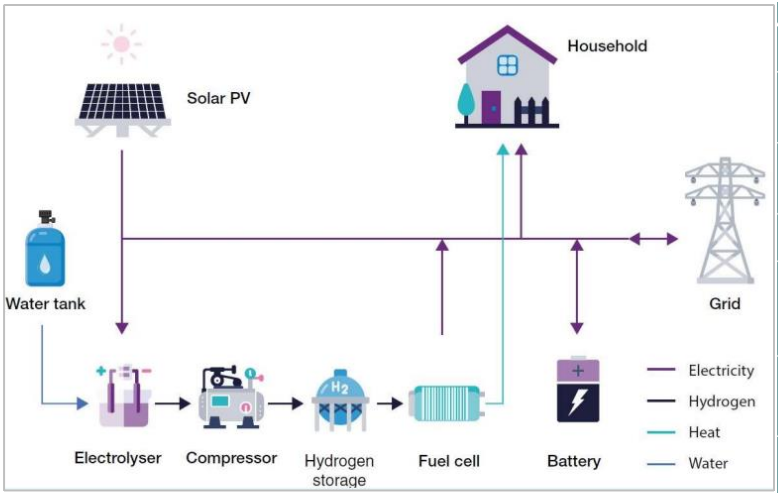


Figure 21. Self-autonomy Housing for 24/7 Energy Lab, Green Village. Retrieved from personal documentary



Household energy consumption	2.200 kWh/year
Solar PV power capacity Annual production	6 kWp ~5400 kWh
Electrolyser (Enapter) power and capacity	2.4 kW (input) 1kg H2 / 24hrs = 57.6 kWh
Compressor (HyEt) power and capacity	600 W (input) 2 kg H2/ 24hrs
Fuel cell (Nedstack) Power	2.3 kW (el) 13.3 kWh/kg H2 2.5 kW (th) 14.5 kWh/kg H2
Hydrogen storage Capacity, volume, maximum pressure	60 kg 2700 L (54 * 50 L) 300 bar
Lithium battery Capacity and power	15 kWh 5 kW

Figure 22. Hydrogen energy system in 24/7 Energy Lab.
Retrieved from Green Village docummentary. (interview with Lidewij van Trigt)

Hydrogen with the capacity of 300 bar pressure in the cylinders are being stored to keep it for the winter use. These cylinders are about 54 cylinders, in which each of them weights 60 per cylinder. These cylinders adequate to supply electricity for 1 person, 28 m^2 household in the winter. During the summer, battery and solar arrays are used, whereas they are placed at the top of the roofs of the houses. The hydrogen system scheme is explained in Figure 22. This system needs a compressor to create a pressure before storing it in the storage.

Conclusion

There have already been numerous projects have already demonstrated the diverse applications and benefits of hydrogen, for instance, HyNet UK is actively spreading hydrogen energy to urban clusters, while the Power-to-Gas project in Rozenburg, Rotterdam project is investigating the conversion of power to hydrogen and methane, blending them into the existing gas system. In addition, the Hy4Heat initiative in the UK is aiming to replace methane with hydrogen in both residential and commercial structures. Meanwhile, the 24/7 Green Village project is showcasing how locally-generated hydrogen can be utilized for energy storage and distribution.

However, each project possesses its own advantages and disadvantages, underscoring the need for careful consideration and integration of hydrogen technologies with existing energy systems for efficient and sustainable applications in the future.

3.6 Cost Effective Literature Review

3.6.1 Capital Expenditure (CAPEX)

Capital Expenditure are the expenses used in energy systems to undertake the upfront or investments by the system. This capital expenditures on fixed assets can include the purchasing of equipment, building the infrastructures; the installation of new pipes, or an upgrade of the building renovations in order to develop the prior systems.

The CAPEX will include the costs associated with purchasing, distributing and control systems, in the common-used system, Table 10 explains the parameters of the prominent factors to utilize for the further analysis [79]. While, there are key components of CAPEX to consider incorporated with hydrogen system costs. Hydrogen production using renewable energy used in the system, this case is PV also valued in the calculation.

In this research, green hydrogen is generated by utilizing electrolysis technologies. Three main types of electrolysers are potential to use; Alkaline, Proton Exchange Membrane, and Solid Oxide Electrolysis. However, PEM method is considered rapidly developed which sustain at least twice the current density than Alkaline Electrolysers, which can increase energy efficiency and decrease the total system footprint and capital cost [79]

Table 10. Key parameters of CAPEX in hydrogen energy systems

Widely-used energy system [79]	Hydrogen-based energy system [79]
Application installation costs; include energy convertors (boilers, heat pumps)	Application installation costs; (hydrogen boilers, fuel cells, hydrogen production CAPEX; through electrolysers generated by PV source)
Ancillary Equipment installations costs; radiators, control system, valves	Ancillary Equipment installations costs; radiators, control system, compressor, valves
Infrastructure and grid upgrade system	Infrastructures
Labor expenses for installation	Labor expenses for installation
Additional costs (vertical flue costs, administration, ductworks)	Additional costs (administration,)

Table 11 delve down deeply into the key parameters on various reports providing information of Electrolysers hydrogen production using PEM technologies, these values use in the further analysis of subsequent levelized cost calculation of hydrogen production.

Table 11. Key parameters of PEM electrolyser from difference literatures.

Parameters	BEIS, 2021 [80]	IEA, 2014[81]	Dept. of Energy US, 2017[82]	European Union, 2015[83]
Capital Cost (current) /kW	£1,200	US$1,500-3,800	US$900	€1,200-€1940
Capital Cost (2030) /kW	£600	US$800	US$400	€250-€1270
Energy Consumption (current)	55 kWh/kg H_2	51-61 kWh/kg H_2	54.3 kWh/kg H_2	47-73 kWh/kg H_2
Energy Consumption (2030)	46 kWh/kg H^2	48 kWh/kg H^2	50.3 kWh/kg H^2	44-53 kWh/kg H^2
Stack Lifetime (current)	60,000 hrs	20,000-60,000 hrs	53,000 hrs	20,000-90,000 hrs
Stack Lifetime (2030)	96,500 hrs (11 yrs)	75,000 hrs	85,000 hrs	60,000-90,000 hrs
Installation Cost (current)	11%	Not mentioned	12%	Specifically excluded
Operational & Maintenance cost	5%	5%	5%	5%
Stack Replacement cost, % of total installed capacity	60%	Not mentioned	40%	Not mentioned

3.6.2 Variable and fixed Operational Expenditure (OPEX)

Operational expenditure refers to the ongoing costs incurred to operate and maintain an energy system and hydrogen systems in buildings during its lifetime. Unlike CAPEX, which represents the initial investment, OPEX encompasses the day-to-day expenses and operational costs associated with running the system efficiently and safely. For the energy systems and hydrogen systems, OPEX include various elements below.

OPEX in this research includes maintenance and repairs, this will cover the costs of regular maintenance, inspections, and any necessary repairs to keep the system running smoothly and ensure its longevity.

Labor and workforce, OPEX includes expenditures related to staffing, include salaries, benefits, or the skilled operators and technicians which required to monitor the system effectively.

Utilities, these costs include expenses for electricity, water, and other utilities used while in the operation of the system.

System monitoring and control; OPEX covers expenses for monitoring equipment, sensors, and control systems used to optimize the system's performance and ensure safety.

It is imperative to acknowledge that when calculating OPEX, fuel expenditures should be segregated in order to accurately determine the individual worth of each energy source.

The operational expenditures (OPEX) associated with hydrogen production will be computed independently. These expenses will be incorporated into the overall hydrogen production cost, which will be determined using the Levelized Cost of Hydrogen methodology. It is important to note that the attribute of hydrogen generation is already accounted for in these costs, including the operational expenditures of photovoltaic systems.

3.6.3 Fuel Costs

Fuel costs refer to expenses incurred in acquiring the primary energy source that is consumed to generate electricity or provide energy in various sectors. The fuel costs represents the price paid to obtain the fuel needed generate electricity and heat behind the energy system. Renewable energy sources such as solar power source there is no direct fuel cost, as it is harnessing the energy from natural resources. Moreover if the electricity is produced locally in the rooftop in buildings. A separated analysis is needed to understand the method of the electricity produced. Additionally, fuel costs of hydrogen due to its locally produced by local PV, another different analysis of hydrogen production costs over lifetime utilizing LCOH is computed.

3.6.4 Levelized Costs of Energy (LCOE)

Levelized costs of Energy (LCOE) represents the costs of generating energy for a particular system. It is an economic assessment of the cost of the energy-generating system including capital Expenditure (CAPEX), operation and maintenance (OPEX), cost of fuel, cost of capital over its lifetime. LCOE is the average revenue per unit of electricity generated or discharged that would be required to recover the costs of building and operating the local generating plant [84]. LCOE is often cited as a convenient summary measure of the overall competitiveness of different generating technologies dependent on the source of the electricity production.

The model is based on a straightforward calculation in which the various system costs are evaluated then divided by the amount of electricity or energy production. Equation 12 shows LCOE is division between the present value of total costs over lifetime by the present value of electricity produce in a lifetime.

$$\text{Levelized Cost of Energy (LCOE)} = \frac{\text{Net Present Value of Total Costs}}{\text{Net Present Value of Energy Generation}} \quad [\$/kWh] \quad (12)$$

$$\text{Net Present Value (NPV) of Total Cost} = \sum_n \frac{\text{Total Capex and Opex Costs and Fuel Costs n}}{(1+\text{discount rate})^n} \quad [\$] \quad (13)$$

$$\text{Net Present Value (NPV) of Energy Generation} = \sum_n \frac{\text{Cost of net heat /electricity generation n}}{(1+\text{discount rate})^n} \quad [kWh] \quad (14)$$

Levelized cost metric is used to provide a transparent method of comparison between different scenarios of generating technologies. However, the simplicity of this metric means some relevant issues are not considered. Data from market, from BEIS, and other research related are gathered to find the LCOE value of each scenario.

In addition to this, Payback Time (PBT) is calculated, a period of time in when energy investment costs is returned. A PBT formula is described in the Equation 15.

$$\text{Payback Time (PBT) of each scenario} = \frac{\text{Capital Investment Scenario} - \text{Capital Investment Base case}}{\text{Annual Energy Costs Base Case} - \text{Annual energy costs Scenario}} \quad [year] \quad (15)$$

Conclusion

The Levelized Cost of Energy is considered a powerful tool to measure the cost-effectiveness of comparing energy systems due to various reasons. LCOE provides a common metric comparing the cost of different energy sources or technologies on an equalized basis. It is also incorporated both the upfront capital expenditure (CAPEX) and the ongoing operational expenditure (OPEX) over the lifetime of energy system. The next essential factor also because of its adaptability to context, which can be tailored to different scenarios considering variations of system, technology, or fuels. LCOE is also valuable since adaptable to evaluate emerging technologies for instance hydrogen against established ones. It helps to count the basic costs information when in market it has not publicly announced yet. It aids to determine the cost trajectory of new solutions and can guide investment decisions and policy making.

3.7 Carbon Emissions Measurement

The carbon emission measurement refer to the amount of carbon dioxide (CO_2) and other greenhouse gas (GHG) emitted as a result of the energy and activities associated in the energy system. The larger the carbon footprint is, the more negative the impact on the climate. Calculating carbon emissions associated with the energy consumption of the buildings, it is essential to consider the carbon intensity of the energy sourced used. Different energy sources varying carbon intensities, depending on how they are generated or extracted.

3.7.1 Coal

Coal-fired power plants, in particular, are known for their high carbon intensity. Coal is carbon rich fossil fuel, when it burns, combustion also emits other pollutants like sulphur dioxide (SO2), nitrogen oxides (N2O), or even methane and particular matter effects to the environment. For coal, for domestic needs, total emissions from the combustion is 0.34 kg/kWh [85].

3.7.2 Natural Gas

The majority of contemporary gas meter quantify gas consumption in cubic meters. In the case of natural gas, this value is specifically determined to be 10.6 kWh per cubic meter as also mentioned in the comparison energy content at Table 7.

The carbon dioxide (CO2) emissions resulting from the combustion of natural gas amount to 0.18 kg/kWh[86]. In the year 2006, the aggregate gas supply in the United Kingdom amounted to 1,047,000 GWh. However, a portion of this supply, namely 79,400 GWh, was allocated for 'Energy industry usage', while an additional 12,000 GWh was designated as 'Losses'. The cumulative inefficiencies amounted to 91,400 GWh, equivalent to 8.7% of the total energy generated. Consequently, the corresponding adjustment in CO2 emissions is required, increasing the value from 0.185 to 0.203 kg/kWh[87].

The average yearly petrol consumption in the United Kingdom for households is reported to be 16,000 kWh[87]. A greater quantity, as not every family have a natural gas supply. For the sake of this analysis, a smaller than average home is defined as consuming 12,000 kWh, which corresponds to around two-thirds of the average meter. Conversely, a bigger than average household is considered to consume 27,000 kWh, indicating a 50% increase in consumption compared to the average. A consumption rate of 5000 kilowatt-hours (kWh) per individual annually is allocated for student housing in a residential facility.

3.7.3 Electricity Grid

The carbon dioxide (CO2) emission factor employed in this study is 0.19 kge of CO2 emitted per kilowatt-hour (kWh) of electricity generated [86]. This emission factor is sourced from the Department for Business, Energy and Industrial Strategy (BEIS) in 2012, in which this data does not include the generation, transmissions, and distribution system. This include a provision for the 7.8% of losses incurred in the transmission and distribution processes within the national grid. And there is a decrease in the UK electricity CO2e factor compared to the previous year. Which compared to 2019 it decreased by 9% of that year. The above decrease in coal use in electricity generation and an increase in renewable generation.

According to a study conducted, the mean electricity usage per home is reported to be 4,800 kilowatt-hours (kWh) [87]. A household that is smaller than the average is defined arbitrarily as consuming 3,000 kWh, which is approximately two-thirds of the average consumption. Conversely, a family that is larger than the average is defined as consuming 7,000 kWh, which is around 50% more than the average consumption. Solar Panel Energy Electricity

The amount of carbon emissions produced by solar panels can vary depending on several factors, such as manufacturing process of the solar panels, the energy mix during the manufacture, and also installations. As reference, data from IPCC at Table 18 mentioned that the carbon footprint of infrastructure and supply chain of PV rooftop is about 42 grams per kilowatt hour of energy, while, for the utility PV solar emits up to 66 grams per kilowatt hour of energy. Despite these emissions in the manufacturing and installation stages, over the typical lifespan of a solar panel usually is around 25 to 30 years and the clean electricity it generates offsets the initial carbon emissions several over time.

3.7.4 Hydrogen

Carbon emissions produced by hydrogen can vary significantly based on the method used to produce the hydrogen. Hydrogen is not an energy source by itself, but rather directly hydrogen did not emit the carbon emissions, however, the carbon emissions associated with hydrogen production whether produced by low-carbon or high-carbon method, or even renewable energy.

Green hydrogen is produced by using electrolysis, when the electricity used in the process comes from renewable energy source such as solar, wind, therefore, due to its green production energy source, there is no virtually direct carbon emissions associated with its production. However, to be considered of the infrastructure and supply chain emissions of each renewable energy production method.

Blue hydrogen which is considered has low carbon production, using fossil fuels and combining carbon capture storage (CCS) to generate lower emissions, than the amount of emissions will be associated with the CCS process.

Conclusion

Upon doing a comprehensive literature analysis pertaining to carbon emissions linked to different fuel sources, it becomes apparent that each fuel type demonstrates unique attributes in relation to its environmental consequences. Table 12 presents a concise overview of the primary observations of carbon emissions associated with various fuel sources.

Table 12. Carbon emissions values from different literatures.

Parameters	Direct Emissions (BEIS, 2022) [88]	Direct Emissions (IPCC, 2014) [89]	Infrastructure & supply chain emissions (IPCC, 2014) [89]	Life cycle emissions (IPCC, 2014) [89]
Coal (Domestic)	0.36 kg/kWh	0.670-0.870 kg/kWh	0.0096 kg/kWh	0.74-0.91 kg/kWh
Natural Gas	0.18 kg/kWh	0.350 – 0.490 kg/kWh	0.0016 kg/kWh	0.41-0.65 kg/kWh
Electricity Grid (specific in the UK for average)	0.19 kg/kWh	Not mentioned specifically	Not mentioned specifically	Not mentioned specifically
Biomass	0.01-0.0129 kg/kWh	(depends on the power plant efficiency, not mentioned specifically)	0.210 kg/kWh	0.13-0.42 kg/kWh
Geothermal	0	0	0.045 kg/kWh	0.006 – 0.079 kg/kWh
Solar PV (Rooftop)	0	0	0.042 kg/kWh	0.026-0.060 kg/kWh
Solar PV (utility)	0	0	0.066 kg/kWh	0.018- 0.18 kg/kWh
CCS – Coal / oxyfuel	Not mentioned	0.0140.0.11 kg/kWh	0.017 kg/kWh	0.1-0.2 kg/kWh
CCS – Coal / PC	Not mentioned	0.095-0.14 kg/kWh	0.0.28 kg/kWh	0.19 – 0.25 kg/kWh
CCS – Natural Gas	Not mentioned	0.03-0.098 kg/kWh	0.0089 kg/kWh	0.94-0.34 kg/kW h
Hydrogen	0	0	Depends on the production process	Depends on the production process

This literature review elucidates the varied carbon emission profiles associated with different fuel types. Table 12 explains that based on the latest reference updated by BEIS, 2022, data for infrastructures and supply chain emissions unfortunately is not available. So the two data mentioned in the table for direct emissions and infrastructure and supply chain emissions will be calculated. The latest data by BEIS for direct emission will be taken into account.

PEM Electrolyser Energy Storage

[ITM-power.com | UK]

4. ENERGY SYSTEMS - DESIGN DEVELOPMENTS

4.1 Background

Sustainable pathways in renewable energy systems highlight hydrogen as a pivotal element in the transition. Hydrogen offers the potential to address intermittent energy supply challenges by functioning as a storage medium for excess energy sources. Moreover, it has the capacity to enhance the flexibility and overall resilience of energy system [90]. To fully comprehend the comparative efficiencies, performances, and compatibility of energy systems, a comprehensive investigation is imperative. This examination serves as a foundation for decision-making. Aiding in the assessment of opportunities within existing energy system designs and the prospective integration of hydrogen-based energy systems.

This research encompasses an exploration of design solutions of energy systems that incorporating hydrogen. It is essential to acknowledge the existence of design limitations as a prerequisite before advancing to the subsequent stage of design development. The design development phase of this study involves the exploration of various design solutions which are widely accepted in the present and or incorporated hydrogen in the future. These designs are drawn from a comprehensive literature reviews and real-world pilot projects to be implemented within a residential neighbourhood. Notably, six distinct approaches as explained in Table 13 offer unique insights of energy system design and potential contributions to the field.

Table 13. Segmentation of energy system alternatives in two different systems.

Widely-accepted System	*Hydrogen System*
System 1: Natural Gas Grid System	*System 3*: Natural Gas and Hydrogen Blend System
System 2: All-electric Heat Pump System	*System 4*: Microgrid Hydrogen Boiler system
	System 5: Cogeneration Hydrogen Fuel Cell System
	System 6: Hybrid Hydrogen Heat Pump System

4.2 Design Limitations

This study is utilizing a bottom-up model. The building energy systems model investigated in this study is based on renewable electricity as energy carriers, as well as the energy conversion and storage components displayed in each potential system in which considers the local context of the building and the neighbourhood. The study will assume that in the future year of 2030, green hydrogen will be constantly supplied, so the next cost analysis will be conducted in that year. This study assumes that the hydrogen network is part of the city. Below are listed the limitations of this project:

1. *The systems under exploration in this study are confined to local operation and are limited solely to the boundaries of the neighbourhoods*, one block of the neighbourhood is utilized at the beginning and in the final chapter will be implemented to a larger scale. The depicted system in the diagram does not pertain to large-scale distribution systems intended for regional or national deployment.
2. *Green hydrogen is locally produced using solar power as an energy source*. The system employed local components and utilized local grid to subsequently supply green hydrogen within the neighbourhood.
3. *The neighbourhood's energy system operates as a stand-alone setup*, due to its local production capabilities of the neighbourhood.

4. The electricity grid served as a backup system, only accessed when necessary. Therefore, *the study ignores the contribution of electricity off the grid or back to the grid* in order to simplify calculations and analysis.
5. In this chapter, focused on the design system levels, building renovation levels will be performed in the next chapter considering two parameters of light and ambitious renovation. Though, *building renovation levels have not played a major role in the study yet.*

4.3 Design Developments

The data is gathered in literature reviews, five of plenty data were collected and narrowed down to two hydrogen systems; microgrid hydrogen boilers, and hydrogen fuel cell. Although hydrogen offers promising advantages of its emission, there are other two additional energy systems that are frequently used compared to the hydrogen energy system; heat pumps, and natural gas, which are widely utilized in the market. Therefore, six different systems and combinations are studied in this research: natural gas boiler systems, all-electric heat pump systems, natural gas and hydrogen blended systems, microgrid boiler hydrogen systems, waste-heat hydrogen fuel cell systems, and hybrid hydrogen heat pump systems.

Table 14 presents an overview of key data points that are considered for the development of energy systems. This table shows the way of decision formulation behind the design development.

Table 14. Design formulation of energy systems alternatives derived from the Pilot Projects

Pilot Projects	*Appliances*	*System*	*Scale*	*Description*
Basic energy system (Base Case)				*Natural gas boiler system*
Widely-accepted alternative				*All-electric heat pump system*
HyDeploy UK	*Blend 20% hydrogen*	*Hydrogen blend*	*Neighbourhood*	*Natural gas and hydrogen blended system*
PurifHy Projects (Rozenburg, NL)	*(methanation) Power2Gas, hydrogen blend*	*Hydrogen blend*	*Apartment*	
HyNet UK	*Boiler*	*Hydrogen grid*	*City*	*Microgrid hydrogen boiler System*
Hy4heat UK	*Boiler*	*Hydrogen grid*	*Neighbourhood*	
Green Village, NL	*Fuel Cell +Heat Pump*	*Hydrogen hybrid*	*Building*	*Hybrid Hydrogen heat pump system*
Cogeneration hydrogen fuel cell system; to understand the basic fuel cell production system without any intervention with other heating systems (waste-heat deployment)				*Cogeneration hydrogen fuel cell system*

Scenario 1. Natural Gas Grid System

Electricity source : Photovoltaic on rooftop, Electricity grid (support)

Heat Source : Natural gas with gas boiler

> Space Heating : Gas boiler

> Domestic Hot Water : Gas boiler

Electrical Storage : Batteries

The common heating system described here for households relies on natural gas as the primary energy source, with boilers being the main appliances to support this system. Boilers are widely used 80 % of households in the UK for heating purposes [91].

The system is designed utilizing natural gas into the grid. The photovoltaic rooftop system generates electricity from sunlight and stores it in battery. The natural gas boiler provides a reliable source of heat, employing an individual condensing combi boiler each house for both uses of domestic hot water and space heating. Typically, up to 40 to 60 degrees Celsius, is utilized for room heating, while higher temperature water, reaching to 60 degrees Celsius circulated for hot water needs. Natural gas is supplied to the boiler through pipelines from suppliers, the boiler ignites natural gas which heats a heat exchanger, water circulates through the heat exchanger, and is heated by the combustion of natural gas. Then the heated water is distributed to the home through those pipeline systems.

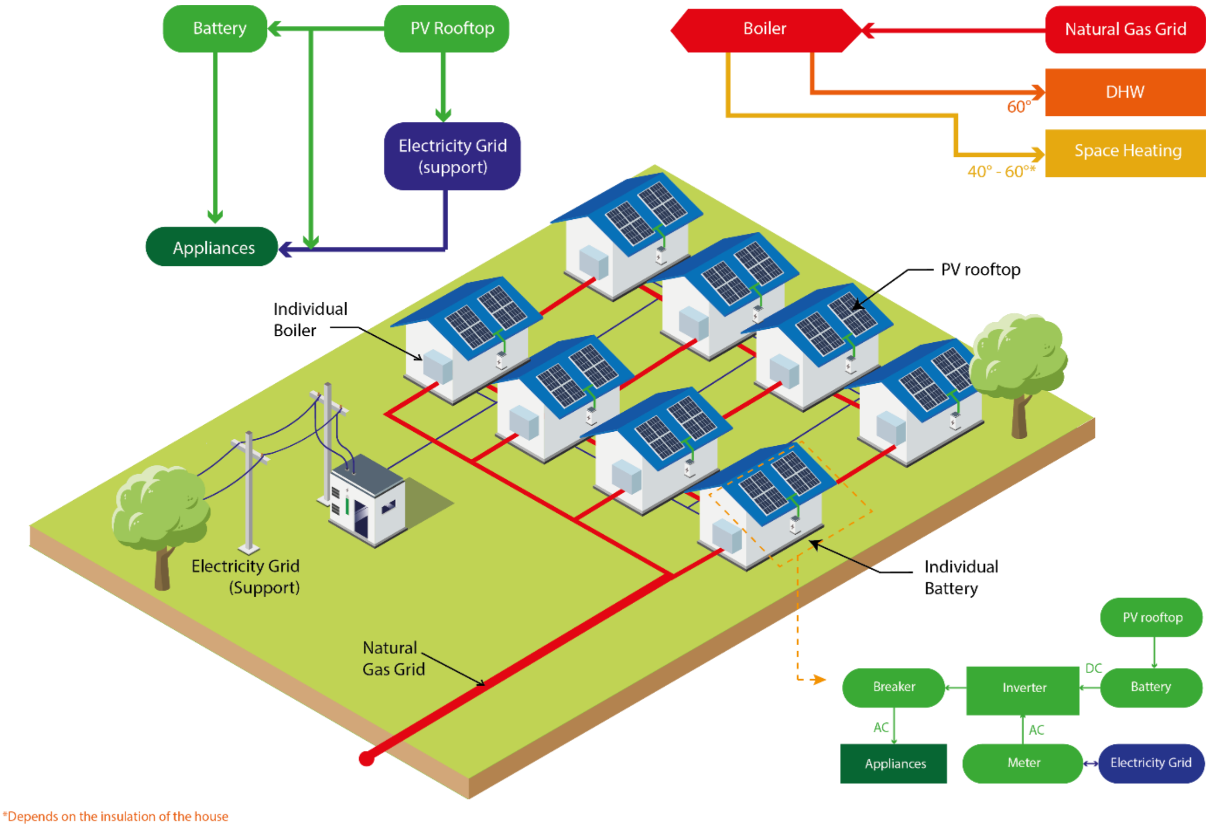


Figure 23. An illustration of energy system design in scenario 1; natural gas grid system (Author illustration)

To complement the energy supply of electricity, this system is equipped with photovoltaics (PV) and battery systems. The electricity generated by PV then be stored in batteries which enable users to reduce their energy consumption and their reliance on electricity grid. This helps to reduce the need on fossil fuel sources. The batteries in the system can also power homes when the sun is not shining and it can also provide the additional electricity that is required. Overall, this common heating system combines the convenience and efficiency of natural gas boilers with the benefits of rooftop solar panels.

Table 15 shows the analysis of capabilities and limitations of the system which employing boilers in the system.

Table 15. Potentials and limitations of natural gas grid system

Potentials	Limitations
• The most common and widely recognized heating system, which is known for its <u>simplicity</u> and durability. Due to boilers which more reliable and long-lasting compared to other heating systems. [92] • In terms of <u>energy efficiency</u>, boilers can be very efficient at heating buildings [92] • <u>The costs</u> associated with boilers as the main appliance of this system are reasonably at price [93] • This boiler system works well even in the poorly insulated houses	• Needs a regular <u>maintenance</u> to ensure the operation and safety [92]. • <u>Infrastructure readiness</u> for this system of connecting gas grid should be taken into account [94] • In terms of the <u>future development</u>, British government plan to phase out Carbon-fueled central heating systems around after 2025 [95] • In terms of <u>carbon emission</u>, as mentioned in literature reviews, natural gas produces 0.65 kWh/kg life cycle emissions when the gas is starting combusted [89].

Scenario 2. All Electric Heat Pump System

In this system, the neighbourhood is operating a centralize energy system, accommodating appliances such as;

Electricity source : Photovoltaic rooftop and electricity grid (support)

Heating source : Electricity from PV central (through heat pump central + booster (additional)

> Space Heating : Heat pump

> Domestic Hot Water : Heat pump

Electrical storage : Batteries

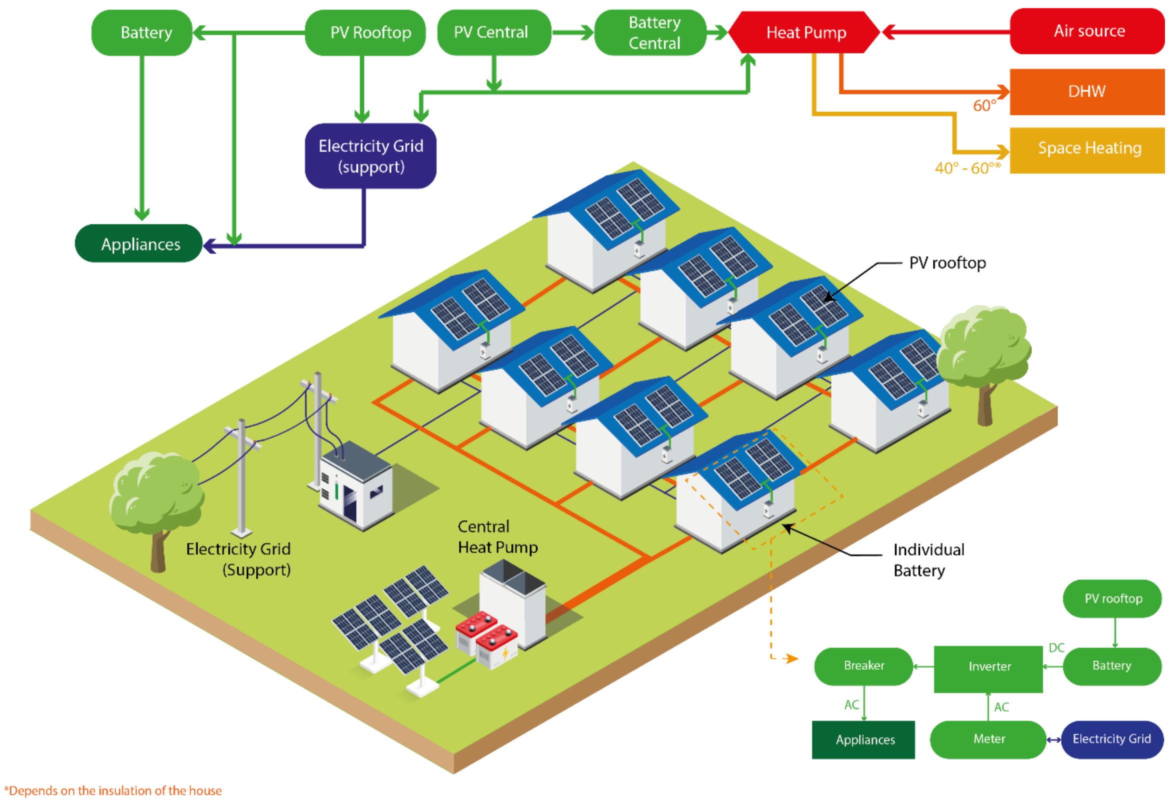


Figure 24. An illustration of energy system design in scenario 2; All electric heat pump system (Author illustration)

In this scenario, the neighbourhood relies entirely on its electrical application. An air source heat pump is utilized in the neighbourhood to provide heating and cooling. The selection of an air-based heat pump has been encouraged by its lower energy consumption in comparison with ground-based heat pumps. Air source heat pumps are frequently more used and easier to install, generally cost-effective, and has low operational costs than ground source heat pump systems. In this system, centralized heat pump is applied, as it is more efficient, and less costs whether in operational or in capital costs. Moreover, the community sense of the area is visible regarding its maintenance and operation in the community.

The production of domestic hot water is facilitated by heat pump which may be supplemented by an additional booster in cases where the desired temperature cannot be achieved.

The system also incorporates batteries, which offer advantage in terms of electricity storage when buildings experience power depletion. Table 16 provides an examination of the benefits and the drawbacks associated with the utilization of an all-electric heat pump with centralized scale system.

Table 16. Potentials and limitations of all-electric heat pump system

Potentials	Limitations
• In terms of energy efficiency, heat pumps are three-to-five times more energy efficient than regular boiler systems [7] • Regarding cost-effective, monthly expenses of heating can be saver, however this dependent on the source of electricity • In terms of versatility and simplicity, in summer, heat pump can be functioned as a cooling, which eliminates a separate appliances [96] • Centralized heat pump systems require less space and less materials then it will reduce carbon footprint and can free up valuable space in the neighbourhood, its carbon emission of heat pumps also less, depends on where the electricity source come from. • Regarding maintenance, centralized heat pump system will be easily maintained and reducing the cost of operation and maintenance, caused its multiple central system not scattered across the neighbourhood • In terms of future development, the HM government in the UK, supports the development of heat pumps which aims to increase 55,000 number a year in 2021 to 600,000 a year by 2028[97] The government also implements the "Boiler Upgrade Scheme" that provides grants of £5,000 to £6,000 for heat pumps.	• Regarding the needs a well-insulated house to reach a desire temperature output and efficient energy [96] • Regarding the capital cost investment, heat pumps have the high upfront installation costs [25]

Scenario 3. Natural Gas and hydrogen blended System

Electricity source	: Photovoltaic, electricity grid (support)
Heating source	: Hydrogen gas 30% and natural gas 70% (blended)
> Space heating	: Regular boiler
> Domestic hot water	: Regular boiler
Electrical Storage	: Batteries
Energy Storage	: Local hydrogen storage

This proposed alternative as illustrated in Figure 25 involves the combination of two energy sources: natural gas comprising 70% and hydrogen comprising 30%. This particular blend does not differ significantly from other common variants. The proposed approach involves the blending of hydrogen natural gas within the existing pipes located in the surrounding area. Where the production of hydrogen in the area is significantly supplied or initiating supplied within the neighbourhood. Green solar-powered hydrogen utilizing photovoltaics and batteries with centralized system is implemented within the production of green hydrogen. The implementation of this system has the potential to significantly decrease the local production costs of hydrogen, as it enables large-scale production in the downstream phase. The regular version of boilers are utilized and the upgrade of pipelines is not required due to the low hydrogen content in the pipes, thus, the capital expenditures of the system can be reduced.

There are number of challenges that need to be addressed before blending hydrogen and natural gas can be widely deployed. One of the challenges is the smaller molecule of hydrogen than a methane, the main component of natural gas. This means that it can leak more easily through existing pipelines and seals. Another challenge is that hydrogen can embrittle some metals, which can weaken pipelines and other equipment. However, research is ongoing developed on new materials and technologies that can overcome these challenges. In the meantime, a number of pilot projects are underway to test the blending of hydrogen with natural gas.

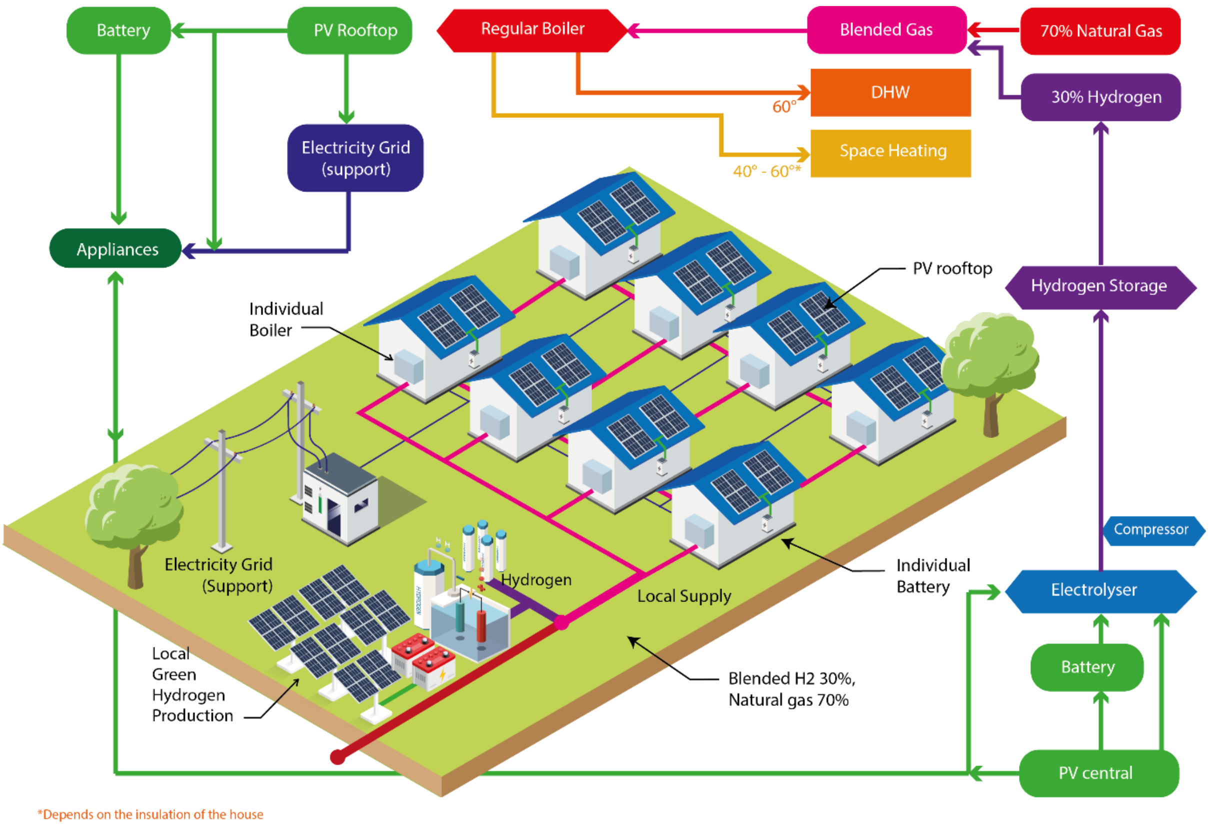


Figure 25. An illustration of energy system design in scenario 3; natural gas and hydrogen blend system (Author illustration)

Nonetheless, it is imperative to acknowledge the impending necessity for hydrogen, which over the year hydrogen demand will increased and the cost of hydrogen will be decreased, thus, gas source will eventually phase out, resulted in the anticipation of escalation in the cost of traditional gas sources. The consideration of locally produced green hydrogen utilizing solar powered in the neighbourhood is supplied and taking into consideration. Therefore, with this incorporation of localized green hydrogen production at the neighbourhood level emerges as a pragmatic response to the imminent hydrogen demand and the pressing need to circumvent the economic challenges tied to grey or other hydrogen sources. This strategic shift toward decentralized, eco-friendly hydrogen generation represents the forward-looking nature of energy system planning within the contemporary discourse on sustainable energy transitions.

Table 17. Potentials and limitations of natural gas and hydrogen blend system

Potentials	Limitations
• In terms of energy efficiency, hydrogen natural gas blended has the same efficiency of the first system caused using the same boiler system. • Regarding cost-effective, it is observed that boilers and gas grids utilizing same components as conventional boilers exhibit reduced capital expenses. • Regarding carbon emissions and footprint, 20% of hydrogen blended could reduce up to 6 million tonnes of carbon emissions every year ([98] • Regarding energy seasonal availability, hydrogen has potential to use in the cold weather, using storages with the high pressure.	• Regarding the operational or a fuel costs, hydrogen which is locally produced within the neighbourhood may have a higher fuel costs in this current development and will be lower with the discount rate of 5% in 2050. • Regarding Independency, the way system still dependent on the grid poses challenges on shifting to the independent energy system • In terms of future scenario, hydrogen blend will be shifted to fully 100% hydrogen source. Therefore, this move will be continuously upgrade.

System 4. Microgrid Hydrogen Boiler System

In this particular variant, the system operates exclusively on 100% hydrogen, which is collectively stored within the neighbourhood. The local electricity supply is sourced primarily from photovoltaic panels, with the electricity grid serving as a backup support.

Electricity source : Photovoltaic, electricity grid (support)
Heating Source : Hydrogen gas
> Space Heating : Hydrogen boiler
> Domestic Hot Water : Hydrogen boiler
Electrical Storage : Batteries
Energy Storage : Hydrogen Storage

In this system as demonstrated in the Figure 26, hydrogen is produced locally through electrolysis, a process that allows electricity to split water into hydrogen and oxygen. The system works as follows: Solar panels generate electricity to power the electrolyser, then the electrolyser splits water into hydrogen and oxygen, the hydrogen is stored in the hydrogen storage tank. When a demand of hydrogen arises, the hydrogen is transported through pipelines and produced heats by boilers. Then the heat is utilized for space heating and domestic hot water needs. The use of high temperature water, reaching up to 60°C, is suitable for providing hot water for domestical uses. Additionally, lower temperature ranging from 40-60°C can be effectively employed for space heating purposes.

Green hydrogen production in the neighbourhood was centralized in local area, including photovoltaics, batteries, and hydrogen storages. However, the electricity use for appliances for each residential building was generated by the PV rooftop along with individual battery. The boilers in this system employed the new technology of hydrogen boilers where the gas source is 100% employed hydrogen thus the upgrade of the pipelines is require, anticipated to the character of hydrogen which the pipes are still vulnerable to hydrogen-induced embrittlement – meaning that cracks will appear and grow – the tests found by the American Society of Mechanical Engineers (AMSE) mentioned that although cracks did occur, the steel was sufficiently tough to comply with standard for hydrogen pipelines, which specifies a minimum fracture toughness threshold [99].

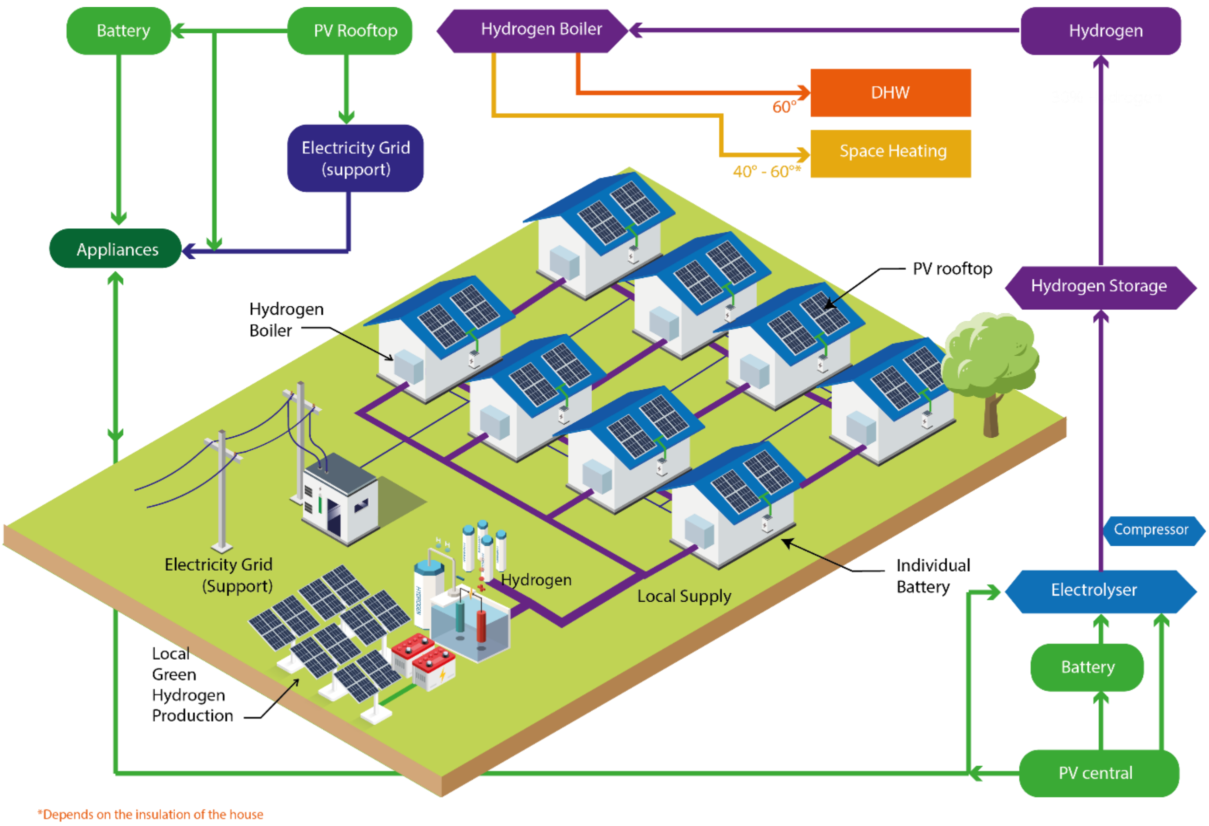


Figure 26. An illustration of energy system design in scenario 4; microgrid hydrogen boiler system (Author illustration)

However, in this potential scenario, the upgrade of existing pipelines or an option of changing the whole new hydrogen-specific pipelines is considered. Upgrading the existing natural gas pipelines can potentially be cost-effective than dedicated new pipelines from scratch. The leakage inspection of hydrogen embrittlement cracking with magnetic particle testing (MPT) and ultrasonic testing (UT) is required to identify the particular cracks in the surface of the pipes [100]. Table 18 presents the potential and limitations of hydrogen microgrid boiler heating system.

Table 18. Potentials and limitations of hydrogen microgrid boiler system

Potentials	Limitations
• In terms of energy efficiency, the efficiency of hydrogen boilers will be similar as the regular boiler, thus efficiency of energy consumption will be low. • Regarding carbon emissions and footprint, producing green hydrogen using photovoltaics, significantly reduce carbon emissions compared to conventional fossil fuel-bases heating systems. • Regarding energy seasonal availability, hydrogen has potential to use in the cold weather and times when the peak demand is needed • Regarding its future scenario, the system benefits to be efficiently integrated with the grid, making an energy transition from the old grid of natural gas grid.	• In terms of infrastructure readiness. The grid should have upgraded due its safety that should be taken into account, thus, some of the grid will be upgraded due to the standardize of the system. • Cause its production and infrastructure cost, the capital cost and operational costs may relative higher than the natural gas boiler system.

Scenario 5: Cogeneration Hydrogen Fuel Cell System

Power source	: Photovoltaic, electricity grid (support) and Electricity surplus from fuel cell
Energy Source	: Hydrogen gas
> Space Heating	: Waste-heat from fuel cell
> Domestic Hot Water	: Waste-heat from fuel cell
Storage	: Hydrogen storage and batteries

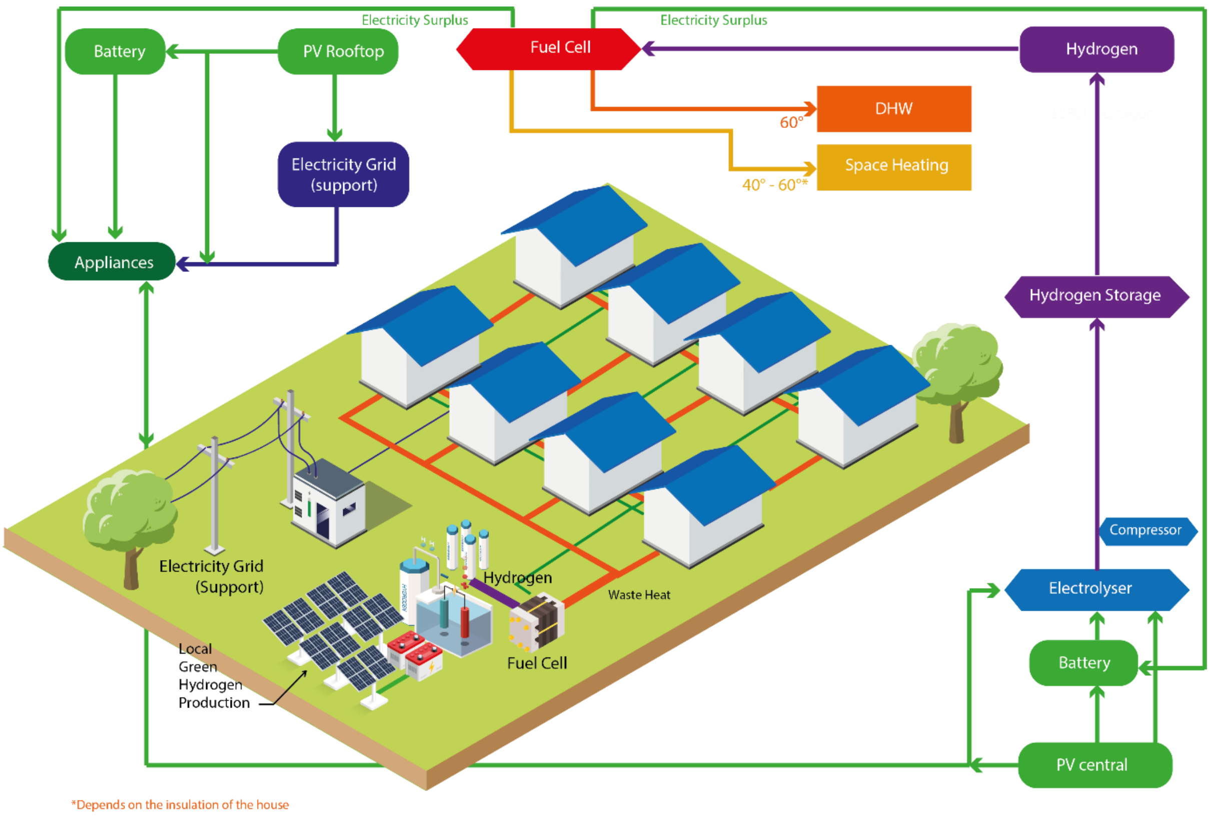


Figure 27. An illustration of energy system design in scenario 5; cogeneration hydrogen fuel cell system (Author illustration)

Hydrogen fuel cell waste-heat system is a system that utilizes waste-heat as a heat source. This system is designed utilizing solar powered to generate electricity from sunlight similar with other scenarios of energy systems. The electricity is then used to power the hydrogen production process through electrolysis. The primary energy conversion device in this system is hydrogen fuel cell. Hydrogen gas is fed into the fuel cell, where it reacts with oxygen from the air to produce electricity, heat, and water vapor. While fuel cells are highly efficient in converting hydrogen into electricity, fuel cells also generate waste heat as by product. According to W.A.N.W. Mohamed et al, who designed a test of fuel cell stack, explained that waste-heat produced by fuel cell can reach up to 40 to 60 degree Celsius [101]. Therefore, this system is investigated whether the waste heat produced by fuel cell can meet the heating demand or could not result significantly in this system.

In this specific configuration, a heat pump is not employe to capture and utilize waste heat efficiently. All the heating source was generated by the waste-heat of Fuel cell. Heat pumps are commonly used to extract heat from various sources, including the waste heat generated by fuel cells, and to provide additional heating to a building or for other purposes. By omitting a heat pump, the system misses an opportunity to improve the overall energy efficiency.

Another challenges may appear in this system is the efficiency may very seasonal and with weather conditions, as solar electricity generation depends on sunlight availability. During periods of low solar irradiance, the system may rely more on the hydrogen fuel cell for electricity generation, leading to higher production of electricity than of its waste heat, to meet the heating demand of residentials. Therefore, with the excess production of electricity, the electricity demand for appliances of each dwelling could be meet only by the surplus energy of the fuel cell.

In result, this system may inefficiency and exhibits lower overall energy efficiency compared to more integrated systems. This is affected by the long process of producing heat and low production of heat which generated only by waste heat. Table 20 explains the advantages and disadvantages of hydrogen microgrid boiler heating system.

Table 19. Potentials and limitations of hydrogen microgrid boiler heating system

Potentials	Limitations
• Regarding carbon emissions and footprint, this system is totally generated by solar powers, which offers no direct emissions contributing carbon footprints. • In terms of complementary energy generation, this two combination benefits to complement electricity generation characteristics. PV generate electricity during daylight, and fuel cell can ensure the demand during the night.	• In terms of simplicity and efficiency, this system is not efficient since may use a high amount of hydrogen once the heat is needed. • Regarding the cost-effectiveness, both technologies have high initial costs, which also added the high operational costs • In terms of efficiency, it involves some energy losses, which the efficiency of fuel cell is 40%, more hydrogen is consumed to generate the heat.

Scenario 6. Hydrogen Hybrid Heat Pump System

Power source : Photovoltaic, Electricity Grid

Energy Source : Hydrogen gas grid with Hydrogen boiler, and fuel cell

> Space Heating : Heat Pump, Fuel Cell

> Domestic Hot Water : Hydrogen gas grid with hydrogen boiler

Storage : Hydrogen Storage and Battery

The Committee on Climate Change (CCC) in 2018 in United Kingdom have advised that hydrogen could contribute to heat decarbonization in buildings, mainly via hybrid heat pump systems incorporating a current technology, a heat pump [102]. A hydrogen fuel cell is integrated into the system. Green hydrogen through electrolysis utilizing local generation is used to fuel the fuel cell thus no emissions are produced only water vapor as by product. While the efficiency to generate electricity of the fuel cell is around 60%, then this electricity can power the heat pump and meet other electrical needs in building. The heat pump effectively absorbs thermal energy from the surrounding environment and transfers it to the building for the purposes of space heating and hot water provision. Therefore, through this process heat pump is functioned as a heat booster. The electricity provided by the fuel cell has the potential to enhance the thermal output by the heat pump. This is particularly valuable in extremely low temperature when the efficiency of the heat pump might decrease in ambient temperatures. In addition to its primary function of generating electricity, a hydrogen fuel cell contributes further by providing waste heat as a valuable supplementary source of thermal energy. This waste heat, often regarded as byproduct in fuel cell operation that meets the required heat temperature which can be harnessed and utilized within the building's heating system.

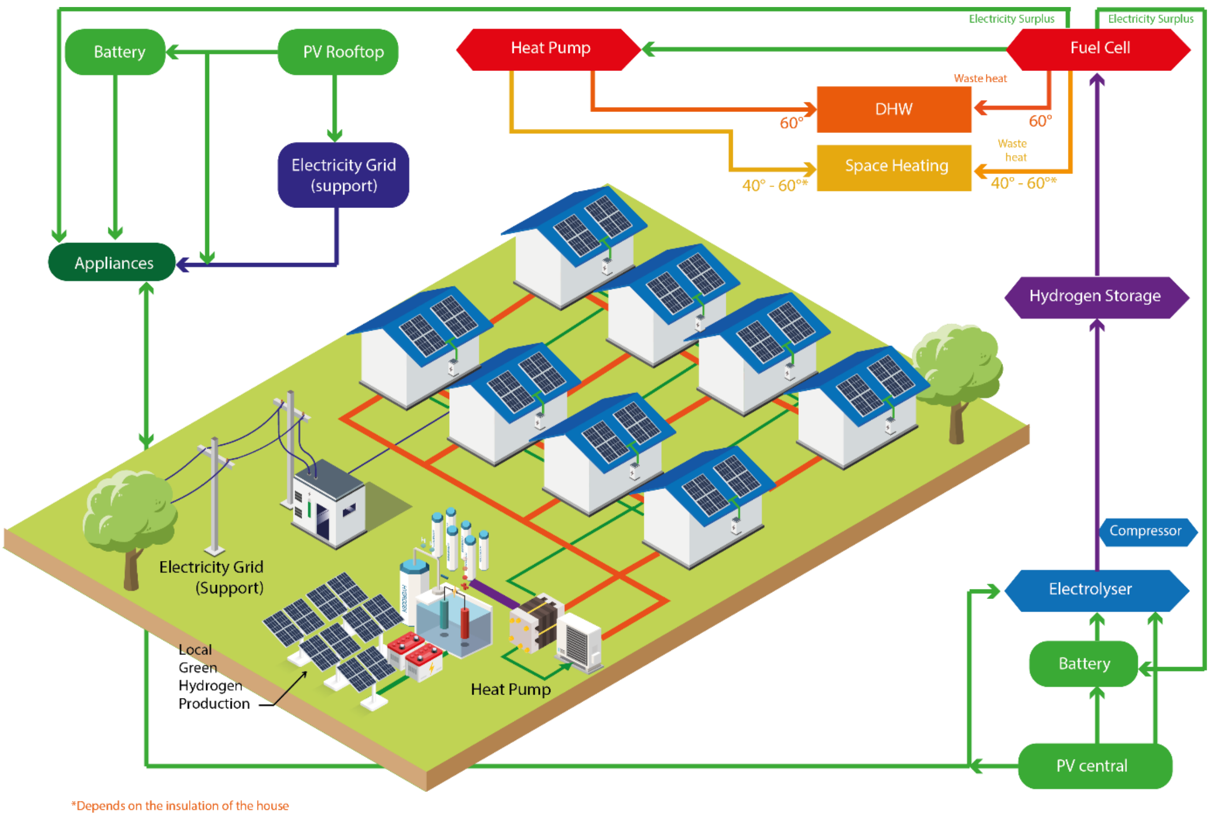


Figure 28. An illustration of energy system design in scenario 6; hydrogen hybrid heat pump system (Author illustration)

By uniting the capabilities of the heat pump and the hydrogen fuel cell in this manner, a harmonious synergy is achieved, creating a system that maximizes energy efficiency and environmental sustainability. The heat pump efficiently provides heat from the environment, while the hydrogen fuel cell generates electricity to support the heat pump.

The Hydrogen Heat Pump Fuel Cell System exhibits significant potential as an environmentally friendly and low-carbon heating alternative. However, due to its complexity of combining fuel cell and heat pump with green hydrogen local production utilizing electrolyser in the neighbourhood, a consideration of cost effectiveness would be taken into account, along with the investment costs of the technology and infrastructure enhancement. Table 20 shows the analysis of potential and limitation of Hydrogen hybrid heat pump system.

Table 20. Potentials and limitation of hydrogen hybrid heat pump system

Potentials	Limitations
• In terms of energy efficiency, the combination of a heat pump and a fuel cell allows for efficient utilization of energy. After the fuel cell works to convert hydrogen to electricity which has only 60% efficiency, heat pump used the electricity from fuel cell and from the environment gaining more heating to heat the buildings. • Regarding carbon emissions and footprint, The system use hydrogen as a fuel source, and when the hydrogen is derived from PV, it can yield little carbon emissions, so rendering it an ecologically sustainable heating option. • Regarding energy seasonal availability, hydrogen has potential to use in the cold weather and times when the peak demand is needed, this also allows of being stand-alone system.	• Regarding the cost-effectiveness, both technologies have high initial costs, which also added the high operational costs of hydrogen production costs. • In terms of safety, the management and preservation of hydrogen necessitate strict attention to rigorous safety protocols owing to its highly flammable nature and low ignition energy, hence introducing intricacy to the overall system.

5. CASE STUDY AND RENOVATION RECOMENDATION

5.1 Case Study and Building Typology

The neighbourhood is conveniently located at Ashbourner Grove 19, west of Central Forest Park, Stoke-On-Trent, in the United Kingdom. This area was considered a yellow belt neighbourhood with high heating demand, resulting in elevated levels of carbon emissions of approximately 49 kg CO_2 [103].

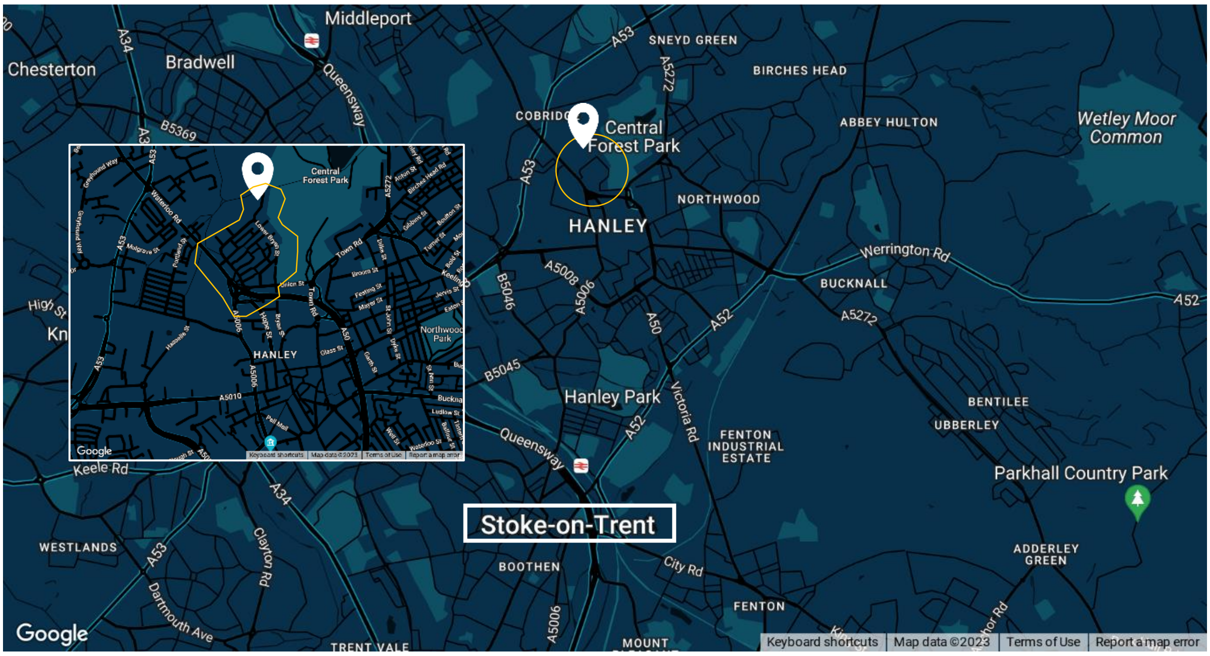


Figure 29. A case study site located in Hanley, Stoke-On-Trent, United Kingdom. Retrieved from maps.google.com

With strong ambitions to implement the UK Hydrogen Strategy, Stoke-On-Trent City Council and companies from the private sector are working together to achieve the goals of hydrogen economy. The United Kingdom is one of the 30 countries and regions to include hydrogen in the government's decarbonisation plans. According to the UK government analysis, 20-35% of the UK's energy consumption will be hydrogen-based by 2050. Further support from the UK government is contributed to various hydrogen projects, including the £240 million Net Zero Hydrogen Fund, with Stoke-On-Trent involved to develop pilot projects within the city area.

Hanley is selected for this case study due to its parameters as one of the neighbourhoods requiring advance development to reduce heating demand. Several case studies were conducted on different housing typologies in the UK. Parameters for a set of typical buildings in the United Kingdom used to represent wider housing stock in Hanley, Stoke-On-Trent, were derived from the comprehensive TABULA database, last updated in 2014. The dataset from Tabula was compiled through a combination of household interviews and inspections carried out by surveyors, ensuring an accurate representation of the surveyed properties. Then five distinct typical buildings with varying building ages and construction materials were identified. With these data, then narrowed down to a total of 25 houses within a single block in the structured region.

The location depicted in Figure 29 serves as a foundational reference point of dwelling characteristics in the United Kingdom. TABULA data is utilised to encompass crucial information about the dwellings' age and material conditions, insulation types, and heating devices. Subsequently, this data was processed to model, calculating the energy demands for each dwelling, in order to determine energy consumption patterns for space heating, domestic hot water, and electricity usage. The Excel model from the Climate Design Course was employed as.

The energy efficient characteristics of these building typologies are defined in relation to examples of unmodernised properties in the UK, i.e., those that have not undergone any renovations since the same year as their initial construction. Light renovations, often entailing insulation improvements, were carried out in most English houses by 2012, although some dwellings still lacked comprehensive insulation. Therefore, renovation recommendations, both light and ambitious ones, can be a valuable tool for estimating the potential for improved energy performance after appropriate restorations.

Figure 30. Building typology classification in the neighbourhood. Retrieved from maps.google.com

The thermal performance mentioned in the building elements is based upon the age of the dwellings. This reflects unimproved and inefficient system in relatively unmodernised dwellings, assuming that as the oldest version on the verge of being replaced by more efficient systems in both light and ambitious renovations, taking into account condensing boilers in the heating system.

Table 21. Building typologies employed in the research within the Stoke-On-Trent and TABULA database

Building Models in Real (Stoke-On-Trent)				
Type A	Type B	Type C	Type D	Type E
				
Building Models in Tabula (English Houses database)				
Type A	Type B	Type C	Type D	Type E
				
1945-1964	1965-1980	1981-1990	1965-1980	1945-1964
4 people	4 people	5 people	4 people	3 people
2 floors	1 floor	2 floors	2 floors	1 floors
10 units	3 units	6 units	3 units	3 units
25 housings | 1 block				

Table 21 displays the selected buildings in the neighbourhood to show the differences between real-world data and the TABULA dataset, ranging from the oldest age of 1945 to 1990. These five distinct building typologies, as illustrated in Figure 30, has a specific number of dwellings, contributing to one housing stock in Hanley, Stoke-On-Trent.

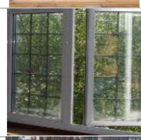
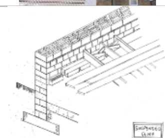
Meanwhile, Table 22 is presented the condition of each type with poor insulation materials and without any renovation until 1996 or before 2012. In this data, 87% of all dwellings have loft and 79% of them have cavity walls. Meanwhile, the heating system varies from no boilers to using standard boilers, combi boilers, or back boilers.

Table 22. U-values of the Base Case scenario for various building materials of English dwellings

Base Case (Non-renovated houses)										
Refurbishment measures	Type A		Type B		Type C		Type D		Type E	
	Insulation	U-value	Insulation	U-value	Insulation	U-value	Insulation	U-value	Insulation	U-value
Windows (single glazing)	None	4.8	None	4.8	None	3.1	None	3.1	None	4.8
Solid wall	None	1.6	None	1.6	None	1.6	None	1.6	None	1.6
Floor	None	0.59	None	0.72	None	0.5	None	0.59	None	0.72
Pitched Roof	None	2.3	None	1.5	Yes	0.4	None	1.5	None	2.3
Door	n/a	3	n/a	2	n/a	2	n/a	2	n/a	3

To understand building construction materials on the Base Case of English dwellings, the insulation types are described in Table 23.

Table 23. Building insulation materials on the Base Case scenario of English dwellings

Building Element	Brief description	Image
Cavity wall	Cavity wall construction, separated by a narrow cavity. These wall can be insulated through filling the cavity.	
Non cavity wall	These walls are not filled with a cavity – principally solid wall masonry construction. External insulation applied in externally or internally, for instance Plasterboard.	
Loft insulation	Insulation can be found between joists above the ceiling of the top floor or between the rafters of the roof.	
Glazing	Old houses without undergone any refurbishment only with single glazed windows.	
Roof types	Some dwellings with pitched or flat, some also use the slanted roof with the underneath is being functioned.	
Floor types	Floors are typically solid or suspended timber, which mentioned that floor insulation is very rare in the UK.	
Door	Doors are usually wooden, metal, or PVC with frames or similar materials.	

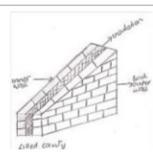
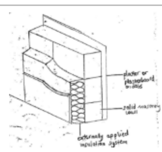
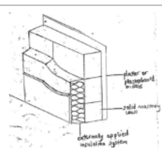
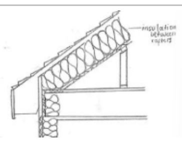
5.2 Renovation Recommendation

To decrease the energy demand of the buildings, combinations of measures are used for the renovation scenarios, which include improving the insulation by using low u-values in the building components. As mentioned earlier, although light renovations were predicted to occur in 2012 and beyond, it is possible that not all houses have undergone complete renovations. On the other hand, ambitious renovations are expected to play a crucial role in the future scenario of highly energy-efficient buildings from now to 2030. In the light renovation scenario, insulation is added to the walls and roof of the dwellings. Meanwhile, the modification of the window frames and glazing is part of the ambitious renovation scenario. Recommendations for possible renovations for each building type and improvements of each material can be seen in Table 24 and Table 25, respectively.

Table 24. Various alterations of improved U-values of building materials in light and ambitious renovations

Refurbishment measures	Type A		Type B		Type C		Type D		Type E	
	Insulation	U-value	Insulation	U-value	Insulation	U-value	Insulation	U-value	Insulation	U-value
Light Renovation (W/m^{2}K)										
Window change	Yes	2.2	No	4.8	No	3.1	No	3.1	No	2.2
Wall insulation	Yes	0.6	Yes	0.6	Yes	0.6	Yes	0.6	Yes	0.6
Roof insulation	Yes	0.13	Yes	0.13	No	0.4	Yes	0.13	Yes	0.13
Floor Insulation	No	0.59	No	0.72	No	0.5	No	0.59	Yes	0.72
Ambitious Renovation (W/m^{2}K)										
Window change	Yes	1.6	Yes	1.6	Yes	1.6	Yes	1.6	Yes	1.6
Wall insulation	No	0.6	No	0.6	No	0.6	No	0.6	No	0.6
Roof insulation	No	0.13	No	0.13	No	0.4	No	0.13	No	0.13
Floor Insulation	No	0.59	No	0.72	No	0.5	No	0.59	No	0.72

Table 25. Improvement values on building materials in light and ambitious renovations

Building Element	Measure	U-Value	Picture
Window	uPVC double glazing	2.2	
Window	uPVC double glazing	1.6	
Wall	Cavity filled wall insulation	0.6	
Wall	Solid wall insulation	0.3	
Roof	Loft Insulation between rafters	0.13	
Door	PVC Board	1.8	

5.3 Energy Demand Modelling

This study adopted a specific approach involving energy demand modelling to achieve a full comprehension of the cumulative energy used within the observed neighbourhood. To obtain a precise estimation of energy consumption, it is essential to conduct a comparative analysis of various existing energy systems. Furthermore, the adjustment for weather data in the UK is highly needed for energy demand modelling computations as the United Kingdom has notable climate variations throughout the annual cycle. Therefore, this aspect becomes critical for the accurate determination of the building climate used for the calculation of each hour of energy simulation. Based on the UK's hourly static energy balance, and by employing the model obtained from the Climate Design Course, each recommendation provides a different value depending on the level of renovation. Significant differences may stand out in several key parameters, such as total square metre per area, U-values of each material construction, Air Changes per Hour (ACH) rate, heat recovery efficiency, and solar gain from window facades. Total energy for domestic hot water is generated based on the total number of occupants in one house, which typically differs for each house. Table 26 shows the input parameters of the ambitious renovation in every building type and their respective values. These inputs are based on the upgraded insulation values discussed in previous chapter. It is crucial to note that the values vary from one renovation case to another, depending on the level of renovation. For instance, regarding the Air Changes per Hour (ACH) rate, the Base Case of English dwellings has 0.8 exchanges per hour, while the ACH rates for light and ambitious renovation scenarios are 0.7 exchanges per hour and 0.5 exchanges per hour, respectively. According to ASHRAE 62.2, a minimum ventilation rate of 0.35-0.5 exchanges per hour is recommended for residential buildings in order to ensure acceptable indoor air quality [104].

Table 26. Input parameters for Energy Demand Modelling in the context of an 'Ambitious Renovation'

Building Input Parameters	**Type A**	**Type B**	**Type C**	**Type D**	**Type E**
Dimensions					
Width	6 m	6 m	7,5 m	6 m	8 m
Length	9,5 m	9 m	8 m	10 m	12 m
Floor height	3 m	3 m	3 m	3 m	3 m
Total floors	2	1	2	2	1
Total façade area (incl. glass) North	33.6 m2	25.2 m2	42 m2	33.6 m2	33.6 m2
Total façade area (incl. glass) East	67.2 m2	16.8 m2	22.4 m2	56m2	22.4 m2
Total façade area (incl. glass) South	33.6 m2	25.2 m2	21.0 m2	33.6 m2	33.6 m2
Total façade area (incl. glass) West	67.2 m2	16.8 m2	22.40 m2	56 m2	22.4 m2
Total roof area (incl. glass)	72 m2	54 m2	60 m2	60 m2	96 m2
Total ground floor area	72 m2	54 m2	60 m2	60 m2	96 m2
Total floor surface area	114 m2	54 m2	120 m2	120 m2	96 m2
Transmissionss					
Rc Window	0.45 m2K/W	0.45 m2K/W	0.45 m2K/W	0.45 m2K/W	0.45 m2K/W
Rc façade walls	1.49 m2K/W	1.49 m2K/W	1.49 m2K/W	1.49 m2K/W	1.49 m2K/W
Rc roof	7.52 m2K/W	7.52 m2K/W	2.33 m2K/W	7.52 m2K/W	7.52 m2K/W
Rc floor	1.52 m2K/W	1.22 m2K/W	1.83 m2K/W	1.52 m2K/W	1.22 m2K/W
U-value window	1.6 W/m2K	1.6 W/m2K	1.6 W/m2K	1.6 W/m2K	1.6 W/m2K
U-value facade wall	0.6 W/m2K	0.6 W/m2K	0.6 W/m2K	0.6 W/m2K	0.6 W/m2K
U-value roof	0.13 W/m2K	0.13 W/m2K	0.4 W/m2K	0.13 W/m2K	0.13 W/m2K
U-value floor	0.59 W/m2K	0.72 W/m2K	0.5 W/m2K	0.59 W/m2K	0.72 W/m2K
Infiltration					
Air Change Hour (ACH)	0.50/ h	0.50/ h	0.50/ h	0.50/ h	0.50/ h
Flow rate infiltration	171 m^3/h	81 m^3/h	168 m^3/h	168 m^3/h	134.4 m^3/h
Ventilations					
Heat Recovery efficiency	0.9	0.9	0.9	0.9	0.9
Ventilation flow rate per person	25 m^3/h/prsn	25 m^3/h/prsn	25 m^3/h/prsn	25 m^3/h/prsn	25m^3/h/prsn
Total Surface of Windows					
Window area (East)	20.16 m^2	5.04 m^2	6.72 m^2	16.8 m^2	6.72 m^2
Wndow area (West)	6.72 m^2	1.68 m^2	2.24 m^2	5.6 m^2	2.24 m^2
Internal Heat Gain					
Heat gain per person	117 W/person	117 W/person	117 W/person	117 W/person	117 W/person
Light power per square meter	3 W/m^2	3 W/m^2	3 W/m^2	3 W/m^2	3 W/m^2
Appliances power per m^2	3 W/m^2	3 W/m^2	3 W/m^2	3 W/m^2	3 W/m^2

As mentioned previously, the calculation of energy demand modelling was performed by utilising a building model in Excel, with data collected on an hourly basis for a period of 8765 hours a year. This hourly data was then added up yearly to obtain the energy demand per year. However, this modelling does not consider the dynamic effects of building mass and the dynamic control per hour, including controls for the cases of summer or winter. Table 27 shows one of the calculation profiles of how the energy demand is observed, along with the explanation of the calculations.

Table 27. Heating demand modelling profile for hour 10 in a Type A dwelling

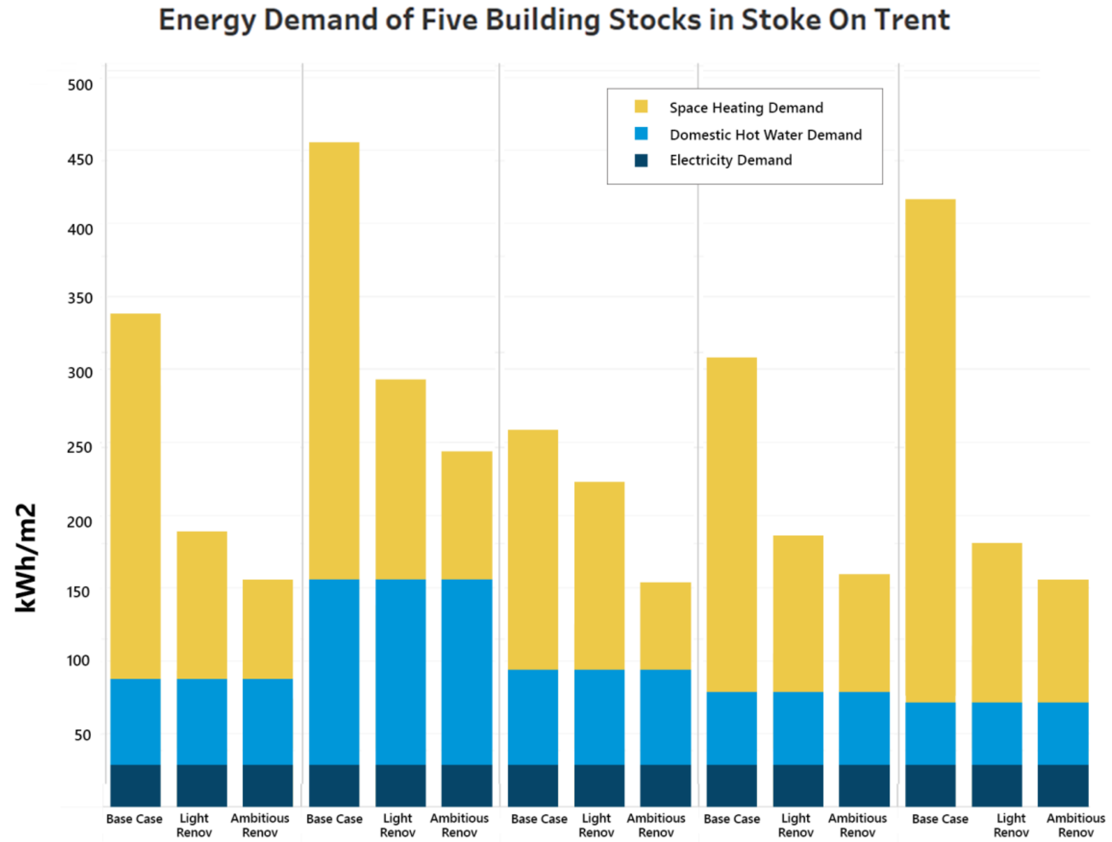
Description	Formula	Values
Transmission	$Q_{trans} = \sum U \cdot A \cdot \Delta T$	2323.7 Wh
Infiltration	$Q_{infiltration} = \rho \cdot c \cdot n \cdot V/3600 \cdot \Delta T$	829.9 Wh
Ventilation	$Q_{ventilation} = (1-\eta) \cdot m_{vent} \cdot c \cdot \Delta T$	41.2 Wh
Solar Gain	$Q_{solar} = g \cdot A_{window} \cdot E_{sun\ load}$	229.8 Wh
Internal Gain	$Q_{internal} = Q_{int,\ people} + Q_{int,\ lighting} + Q_{int,\ appliance}$	1332.0 Wh
Total Heat Demand	$Q_{tot} = Q_{trans} + Q_{inf} + Q_{vent} - Q_{sol} - Q_{int}$	1633.0 Wh

The results of energy demand calculations for the five typical buildings are presented in Table 28 containing specific data from three cases, namely: non-renovation (Base Case), light renovation, and ambitious renovation. Each case has three energy demand calculations for space heating, domestic hot water, and electricity. In this regard, the amount of space heating demand varies depending on the levels of insulation, whereas that of domestic hot water shows a consistent pattern across different renovation cases, depending on the number of occupants in the buildings. Meanwhile, the electricity demand has similar outcomes across different levels because the calculation model does not clearly specify on which appliances are used in each dwelling. Then, to verify the accuracy of the modelling outcomes, the final values were cross-referenced with the data presented in the Tabula database. However, due to its limited data provision, only the values of space heating demand are available in this database. Therefore, only this comparison can be used to validate the data.

Table 28. Energy demand calculations for five representative dwellings in Hanley neighbourhood

Surface Area of Houses (m2)	**Number of houses**	**A (Base Case)**				**B (Light Renovation)**				**C (Ambitious Renovation)**			
		Tabula	**Calculation/ Modelling**			**Tabula**	**Calculation/ Modelling**			**Tabula**	**Calculation/ Modelling**		
		Space Heating (kWh)	**Space Heating (kWh)**	**DHW (kWh)**	**Electricity (kWh)**	**Space Heating (kWh)**	**Space Heating (kWh)**	**DHW (kWh)**	**Electricity (kWh)**	**Space Heating (kWh)**	**Space Heating (kWh)**	**DHW (kWh)**	**Electricity (kWh)**
A (144 m²)	10	40,493 kWh	41,687 kWh	8,490 kWh	3,781 kWh	15,538 kWh	13,412 kWh	8,490 kWh	3,781 kWh	13,810 kWh	10,642 kWh	8,490 kWh	3,781 kWh
B (54 m²)	3	12,312 kWh	17,791 kWh	6,792 kWh	1,418 kWh	7,479 kWh	7,450 kWh	6,792 kWh	1,418 kWh	5,060 kWh	4,736 kWh	6,792 kWh	1,418 kWh
C (120 m²)	6	17,184 kWh	23,557 kWh	8,790 kWh	3,151 kWh	12,432 kWh	15,052 kWh	8,490 kWh	3,151 kWh	9,948 kWh	6,490 kWh	8,490 kWh	3,151 kWh
D (120 m²)	3	26,568 kWh	29,609 kWh	6,792 kWh	3,150 kWh	13,740 kWh	12,596 kWh	6,792 kWh	3,150 kWh	11,280 kWh	9,275 kWh	6,792 kWh	3,150 kWh
E (96 m²)	3	24,941 kWh	35,261 kWh	5,094 kWh	2,521 kWh	9,888 kWh	10,572 kWh	5,094 kWh	2,521 kWh	8,832 kWh	8,954 kWh	5,094 kWh	2,521 kWh

From the data validation above, the similarity between the values from the modelling and the Tabula database is less than 30%, indicating that the calculations can be processed further. A total of 25 houses within the five typical buildings were examined in this study. The representative data of these 25 houses were further used in each energy system scenario by comparing three different criteria, i.e., energy consumption, cost effectiveness, and carbon emissions. The collective data is shown in the next graph in Figure 31Figure 25.



	A			B			C			D			E		
Building Year	1945-1964			1965-1980			1981-1990			1965-1980			1945-1964		
Total Area	144 m2			54 m2			120 m2			120 m2			96 m2		
Inhabitants	4 people			4 people			5 people			4 people			3 people		
Total Houses	10 houses			3 houses			6 houses			3 houses			3 houses		
(kWh/m2)	Base Case	Light Renov	Ambitious Renov	Base Case	Light Renov	Ambitious Renov	Base Case	Light Renov	Ambitious Renov	Base Case	Light Renov	Ambitious Renov	Base Case	Light Renov	Ambitious Renov
Electricity Demand	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
DHW Demand	59	59	59	126	126	126	71	71	71	57	57	57	53	53	53
Space Heating Demand	289	93	74	329	138	89	196	125	54	247	105	77	367	110	93
TOTAL	**375**	**178**	**159**	**482**	**290**	**240**	**293**	**222**	**151**	**330**	**188**	**160**	**447**	**189**	**173**

Figure 31. Total heating demand for five dwellings in Stoke-on-Trent's building stock across three different levels of renovation with different surfaces.

The energy demand for domestic hot water varies upon the total number of occupants per house; as the number of individuals residing in one house increases, it is anticipated that there will be a corresponding increase in the energy demand for domestic hot water. Meanwhile, electricity demand is not the main focus of this study because there is no detailed data regarding specific equipment or appliances used in the given scenario. Overall, there in a significant increase in energy demand from the Base Case scenarios to the completion of the renovation process, both light and ambitious renovations, with the total values for ambitious renovation scenarios on the five typical houses ranging from 150 to 200 kWh per square metre.

6. COMPARISON OF PRIMARY ENERGY CONSUMPTION

6.1 Energy Efficiency Comparison

The development of energy performance in building sector should proceed in parallel with energy production and energy consumption, primarily due to the constraints imposed by the finite nature of the energy resources [105]. Numerous studies have been conducted to investigate the holistic energy consumption in buildings. Therefore, This practical assessment aims to compare the energy efficiency for various scenarios of building energy systems.

Energy performance refers to the effectiveness of the energy system converts its primary energy source into energy outputs such as electricity, heat, or cooling; the more energy consumed in the conversion process to the output, the lower the system performance. A system with good energy performance will efficiently convert its primary energy source into valuable and useful energy outputs, resulting in lower energy losses and waste.

Accurate estimation of energy consumption in a building is a vital strategy to reduce energy demand and improve energy efficiency which plays an important role in controlling energy usage, as well as reducing costs and maintaining comfortable environment in the buildings [106]

In this chapter, the results of various energy performance scenarios in buildings are presented, where the performances of different energy systems designed in Chapter 4 are compared. The energy in each scenario is produced locally by solar power. Table 29 presents the total values of energy demand in one block comprising 25 dwellings.

Table 29. Annual energy demand in one block or 25 dwellings in the neighbourhood

Annual Energy demand for 1 block (25 houses)	Base Case	Light Renov	Ambitious Renov
Space heating demand	806.19 MWh	316.28 MWh	214.25 MWh
Domestic hot water demand	191.88 MWh	191.88 MWh	191.88 MWh
Electricity demand	77.98 MWh	77.98 MWh	77.98 MWh
Total amount of Energy Demand	1,075.05 MWh	586.14 MWh	484.11 MWh

Scenario 1. Natural Gas Grid Heating System

The primary focus in this scenario is the utilisation of a boiler system fuelled by natural gas. In this method, the efficiency of the boiler is the main factor that influences the overall efficiency of the domestic energy system. The heating system operates within a temperature range of 40 to 60 degrees Celsius and caters to domestic hot water demand as it approaches 60 degrees Celsius. To respond to the temperature setpoint, a condensing 'Combi Boiler' is employed which effectively provides energy for both domestic hot water and space heating in one controlled unit. The thermostatic radiator valves, managed by controllers, optimise start/stop during the cycles.

Conventional boilers account for approximately 85% of energy consumption and contribute to 67% of CO_2 emissions. While energy efficiency of outdated gas-fired boiler systems is estimated at 85% [107], [108], condensing boilers can increase this efficiency by about 10%. This model incorporates two heat exchangers, which efficiently capture and recycle heat from exhaust gases before release [107]. Consequently, condensing boilers achieve a thermal efficiency of 95% when utilised for space heating within the temperature range of 40 to 60 degrees Celsius. However, this efficiency decreases slightly to 85% when a higher temperature of 60 degrees Celsius is required. In addition, the technology in this system also results in a 5% reduction in energy loss due to grid transmission. The energy performance of this system can be determined by considering the overall energy demand, as presented in Table 30 which also presents a comprehensive overview of the calculations performed within the system.

Table 30. The estimation of energy consumption for Scenario 1- Natural gas grid system

Energy consumption	Unit	Base Case	Light Renov	Ambitious Renov
Space heating demand	MWh	806.19	316.28	214.25
Efficiency (40°-60°C) of boiler	%	95	95	95
Energy consumption for boiler	MWh	848. 82	332.93	225.53
Efficiency of grid transmission	%	95	95	95
Total natural gas for space heating	MWh	893.29	350.45	237.40
Domestic Hot Water (DHW) demand	MWh	191.88	191.88	191.88
Efficiency (≥60°c) of boiler	%	85	85	85
Energy consumption for boiler	MWh	225.74	225.74	225.74
Efficiency grid transmission	%	95	95	95
Total natural gas for DHW	MWh	237.62	237.62	237.62
Electricity demand for appliances	MWh	77.98	77.98	77.98
Efficiency of local grid transmission	%	95	95	95
Energy consumption for grid transmission	MWh	82.08	82.08	82.08
Efficiency of DC/AC conversion	%	95	95	95
Total electricity (PV rooftop) for Appliances	MWh	86.40	86.40	86.40
Total natural gas consumption (Space Heating + DHW)	MWh MWh	893.29 + 237.62 1,130.91	350.45 + 237.62 588.07	237.40 + 237.62 475.02

In this system, approximately 588 MWh of natural gas is consumed to heat 25 dwellings with a total energy demand of around 508 MWh for both space heating and domestic hot water. Therefore, the total efficiency during system operation is calculated to reach 86.4 %, with heat loss contributing to this percentage. The efficiency of gas boilers plays a significant role in overall system efficiency, underscoring the importance of having high-performance boilers. Furthermore, other factors such as heat loss during distribution and the quality of the insulation may also have an impact on the efficiency of the overall system. Thus, the commendable 85% of efficiency signifies that the system is working well.

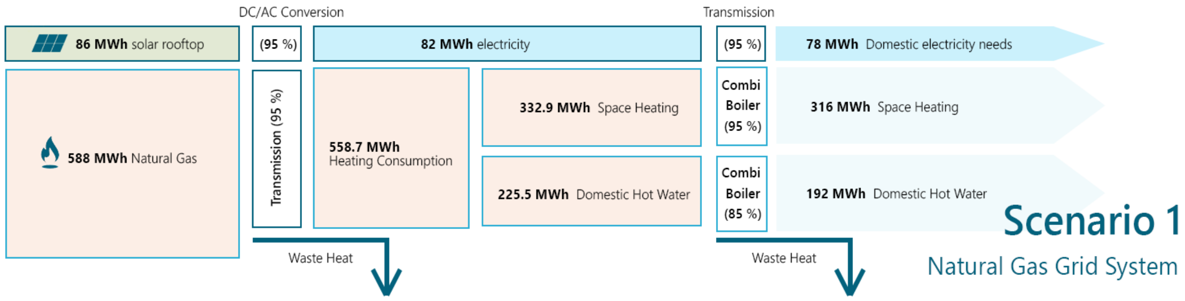


Figure 32. Energy consumption diagram of Scenario 1 – Natural gas grid system, utilizing light renovation (graphic illustrated by author)

In this system, the crucial role of well-insulated houses in optimising the performance of a heat pump system becomes apparent. The Base Case scenario highlights the inapplicability of this system due to the absence of proper insulations. Insulation is pivotal for efficient building operations, ensuring consistent indoor temperatures, and ultimately reducing energy consumption. For this reason, this system achieves its optimal performance in dwellings with medium to high insulation levels Table 31 provides a comprehensive overview of the calculations within this system.

Table 31 presents a diagram illustrating the energy consumption and heat output of the natural gas grid system in light renovation scenario, which offers an intriguing case for the analysis. This analysis takes into account yearly usage, regardless of weather, by utilising photovoltaic technology to power various appliances. Additionally, the electrical grid serves as a supplementary power source during periods of insufficient solar yield, with a capacity considered sufficient to meet the energy consumption of 86 MWh annually. However, specific details regarding system coverage during winter or summer are not clearly delineated, causing the seasonal storage in this scenario not yet being applied. In winter, the electrical grid continues to act as a significant contingency plan, with great potential for backup power supplies including batteries.

Scenario 2. All Electric Heat Pump System

In this system, the crucial role of well-insulated houses in optimising the performance of a heat pump system becomes apparent. The Base Case scenario highlights the inapplicability of this system due to the absence of proper insulations. Insulation is pivotal for efficient building operations, ensuring consistent indoor temperatures, and ultimately reducing energy consumption. For this reason, this system achieves its optimal performance in dwellings with medium to high insulation levels Table 31 provides a comprehensive overview of the calculations within this system.

Table 31. The estimation of energy consumption for Scenario 2 - All-electric heat pump system

Energy Consumption	Unit	Base Case	Light Renov	Ambitious Renov
Space heating demand	MWh	-	316.28	214.25
Efficiency (40°C) of heat pump	%	-	4.30	4.30
Energy consumption for heat pump	MWh	-	73.55	49.83
Efficiency of grid transmission	%	-	95	95
Total Space Heating Consumption	MWh	-	77.42	52.45
Domestic Hot Water (DHW)	MWh	-	191.88	191.88
Efficiency (60°C) of heat pump	%	-	3.50	3.50
Energy consumption for heat pump	MWh	-	54.82	54.82
Efficiency of grid transmission	%	-	95	95
Total DHW Consumption	MWh	-	57.70	57.70
Electricity demand for appliances	MWh	-	77.98	77.98
Efficiency of local grid transmission	%	-	95	95
Energy consumption for grid trasmission	MWh	-	82.08	82.08
Efficiency of DC/AC conversion	%	-	95	95
Total electricity (PV rooftop) for appliances	MWh	-	86.40	86.40
Total electricity (PV central) for heating	MWh		77.42 + 57.70	52.45 + 57.70
	MWh		135.134	110.157

It is evident that an outstanding level of energy efficiency can be achieved with this system. In result, a substantially lower energy source is achieved by the same level of energy demand. The energy consumption in this scenario is required only one fourth of the energy demand. As clearly illustrated in Table 31 only 135 MWh of electricity is needed to meet the total heating demand of 508 MWh in light renovation scenario. Compared to the natural gas grid system in the previous scenario that produces an energy source of 588 MWh, it becomes apparent that this system can achieve approximately five times more energy efficiency with a system efficiency of more than 350%, demonstrating its remarkable potential for resource conservation.

Furthermore, energy production is distinguished based on its usage. The electricity generated by individual PV rooftops is utilised to cover the electricity demand for appliances. As for the heating system, the electricity produced by the central PV is used to operate the centralised heat pump system which not only serves multiple building units to facilitate large-scale development but also provides easy access and scalability of transitioning into local renewable energy sources. This eventually leads to more streamlined maintenance and more affordable service costs. In addition, synergy between the centralised energy production and the central PV can enhance the independence of the electrical grid. However, it should be noted that additional investment costs for discrete PV production may be incurred due to the need for more equipment and installations.

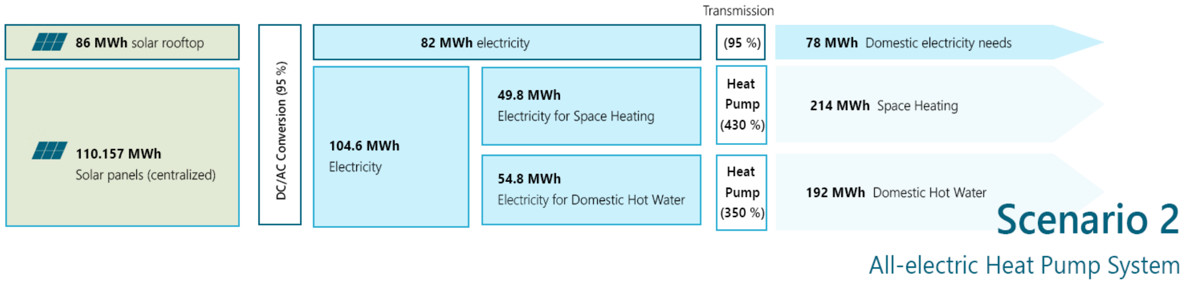


Figure 33. Energy consumption diagram of Scenario 2 – All-electric heat pump system, utilizing ambitious renovation (graphic illustrated by author)

Scenario 3. Natural Gas and Hydrogen Blended System

In this system, a notable 30% proportion of hydrogen is integrated into the existing natural gas pipelines. The production of hydrogen is carried out efficiently through the utilisation of photovoltaic panels which generate hydrogen on an annual basis. However, the energy efficiency of this system does not differ significantly from the first scenario where a conventional boiler is employed in a system that uses 100% natural gas. In addition, it is essential to note that the incorporation of additional appliances in the hydrogen production process necessitates a greater investment and electricity expenditure.

Table 32. The estimation of energy consumption for Scenario 3 – Natural gas and hydrogen blended system

Energy Consumption	Unit	Base Case	Light Renov	Ambitious Renov
Space heating demand Efficiency (40°-60°C) of Boiler Energy consumption for boiler	MWh % MWh	806.19 95 848.62	316.28 95 332. 93	214.25 95 225.52
Heating demand for 70% Natural gas Efficiency of grid transmission	MWh %	594.03 95	233.05 95	157.86 95
Total natural gas consumption for space heating	MWh	625.30	245.32	166.17
Heating demand for 30% Hydrogen Efficiency of Hydrogen storage Energy consumption for hydrogen storage Efficiency of (Electrolyser + compressor)** Energy consumption (Electrolyser + compressor) Efficiency of DC/DC conversion	MWh % MWh % MWh %	254.59 99 257.15 70 367.37 95	99.88 99 100.89 70 144.12 95	67.66 99 68.34 70 97.63 95
PV central to produce hydrogen (for space heating)	MWh	386.70	151.71	102.77
Domestic Hot Water (DHW) demand Efficiency (≥60°C) of Boiler Energy consumption for boiler	MWh % MWh	191.88 85 225,742	191.88 85 225,742	191.88 85 225,742
70% Natural gas consumption Efficiency of grid transmission	MWh %	158.02 95	158.02 95	158.02 95
Total natural gas consumption for DHW	MWh	166.336	166.336	166.336
30% Hydrogen Efficiency of Hydrogen storage Energy consumption for hydrogen storage Efficiency of (electrolyser + compressor)** Energy consumption (Electrolyser + compressor) Efficiency of DC/DC conversion	MWh % MWh % MWh %	67.72 99 68.4 70 97.72 95	67.72 99 68.4 70 97.72 95	67.72 99 68.4 70 97.72 95
PV central to produce hydrogen (for DHW)	MWh	102.867	102.867	102.867
Electricity Demand for Appliances Efficiency of local grid transmission	MWh %	77.98 95	77.98 95	77.98 95

Energy consumption for grid transmission Efficiency of DC/AC conversion	MWh %	82.08 95	82.08 95	82.08 95
Total electricity (PV rooftop) for appliances	MWh	86.40	86.40	86.40
Total natural gas consumption for heating	MWh MWh	625.30 + 166.34 791.64	245.32 + 166.34 411.66	166.17 + 166.34 332.51
Total electricity (PV central) for hydrogen production	MWh MWh	386.70+ 102.87 489.57	151.71 + 102.87 254.58	102.77 + 102.87 205.64

**Compressor efficiency is explained in the following table:

In all cases it is assumed that H2 gas is initially generated at a pressure of 20 bar (290 psia). A study conducted by Maria (2023) on modelling electrolysis at different pressures reveals that 1.05 to 1.5 kWh/kg of hydrogen is required to compress from 20 bar to 350 bar. From the model of 10 MW PEM electrolyses, with a total production of 181.3 kg, about 7,149 kW of compressed hydrogen is produced with the resulting pressure output of 20 bar. An additional 202 kW of electricity is needed to increase the pressure by 200 bar and 273 kW to 350 bar. Therefore, with 7,149 kW of compressed hydrogen and 10.000 kW+273 kW of input electricity, the efficiency of 350 bar compression is 69.59%, which is rounded to 70%. It should be put in mind that this process is a combination of electrolysis and compressing process.

Despite the additional costs, the significant reduction in carbon emissions is a noteworthy advantage achieved through the utilisation of a 30% hydrogen blended into the natural gas system. Figure 34 presents a comprehensive illustration of this system and reveals that approximately 508 MWh of heating demand consumes about 666,14 MWh of energy, with 411 MWh generated from natural gas and 254 MWh hydrogen from Local photovoltaics. This indicates that even though 30% of the energy is covered by hydrogen, a significant amount of energy is still needed, most likely due to the energy-intensive process of electrolysis and other processes in hydrogen production.

On the other hand, the system's total efficiency of 76%, accounting for total energy consumption of 666 MWh and the output or heating demand of 406 MWh, is still commendable. Furthermore, by taking into account 411 MWh of natural gas resource and approximately 10.6 kWh/kg of its energy content, the annual energy production from natural gas is 57,110 cubic metres per year for one block or 25 houses.

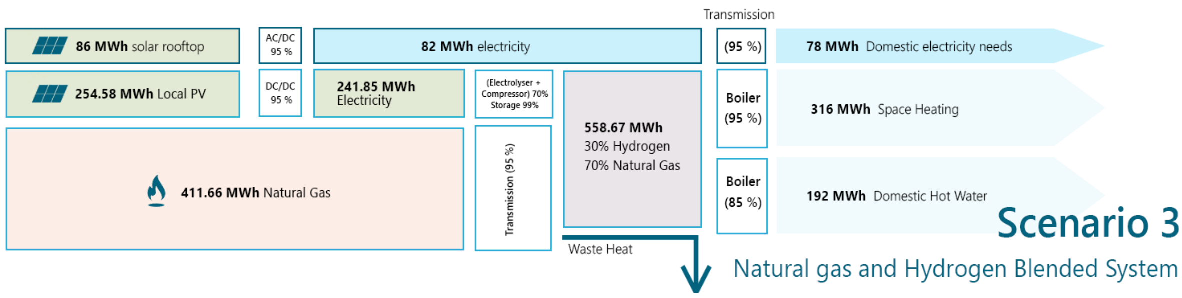


Figure 34. Energy consumption diagram of Scenario 3 – Natural gas and hydrogen blended system, utilizing light renovation (graphic illustrated by author)

Scenario 4. Hydrogen Microgrid Boiler System

In this system, a localised energy infrastructure using 100% hydrogen as the primary fuel source is built within the neighbourhood. A self-production of hydrogen with photovoltaic-based is utilized. The generated hydrogen gas is then distributed into a small-scale grid designed to provide heating in the neighbourhood of Stoke-On-Trent. As it fully disperses hydrogen, the pipeline network requires upgrades to ensure the safety of hydrogen distribution. Nevertheless, the use of hydrogen boilers to replace the regular boilers also needs to be taken into consideration to achieve a complete and good performance system. While the new technology of hydrogen boilers does have an effect on increasing capital costs, this scenario excludes the projection of hydrogen demand which specifies on the decrease of total cost of hydrogen production.

Table 33. The estimation of energy consumption for Scenario 4 – Microgrid hydrogen boiler system

Energy Consumption	Unit	Base Case	Light Renov	Ambitious Renov
Space Heating Consumption Efficiency (40°-60°C) of Hydrogen Boiler Energy consumption for Hydrogen Boiler	MWh % MWh	806.19 95 848. 82	316.28 95 332.93	214.25 95 225.53
Efficiency of hydrogen storage Energy consumption for hydrogen storage Efficiency of electrolyser + compressor Energy consumption electrolyser + compressor Efficiency of DC/DC conversion	% MWh % MWh %	99 857.39 70 1,224.84 95	99 336.29 70 480.42 95	99 227.80 70 325.43 95
PV central to produce hydrogen (for space heating)	MWh	1,289	505.70	342.56
Domestic Hot Water (DHW) Efficiency (≥60°C) of Hydrogen Boiler Energy consumption for Hydrogen boiler	MWh % MWh	191.88 85 225.74	191.88 85 225.74	191.88 85 225.74
Efficiency of hydrogen storage Hydrogen storage consumption Efficiency of electrolyser + compressor Energy consumption electrolyser + compressor Efficiency of DC/DC conversion	% MWh % MWh %	99 228.02 70 325.74 95	99 228.02 70 325.74 95	99 228.02 70 325.74 95
PV central to produce hydrogen (for DHW)	MWh	342.89	342.89	342.89
Electricity Demand for Appliances Efficiency of local grid transmission Energy consumption for grid transmission Efficiency of DC/AC Conversion	MWh % MWh %	77.98 95 82.08 95	77.98 95 82.08 95	77.98 95 82.08 95
Total electricity (PV rooftop) for appliances	MWh	86.40	86.40	86.40
Total electricity (PV central) for hydrogen production	MWh MWh	1,289 + 342.89 1,631.89	505.69 + 342.89 848.59	342.56 + 342.89 685.45

Table 33 provides a comprehensive overview of the energy consumption calculations within the system. To fulfil the heating demand of 508 MWh for both space heating and domestic hot water, hydrogen consumption of up to 848.6 MWh is needed. As a result, the total efficiency of this system is found to almost reach 60%, encompassing the entire process from the initial stages to the hydrogen production phase.

The production of hydrogen at a high pressure of 350 bar requires a substantial amount of electricity. The more energy needed to cover the hydrogen conversion process; the more photovoltaics required to accommodate this need. Thus, to enhance further utilisation, a photovoltaic system generating direct currents (DC) will adapt to the current electrolyser rate. An electrolyser may have such a high direct current (DC) that it requires another DC/DC conversion, which is calculated with 95% effectiveness in the system.

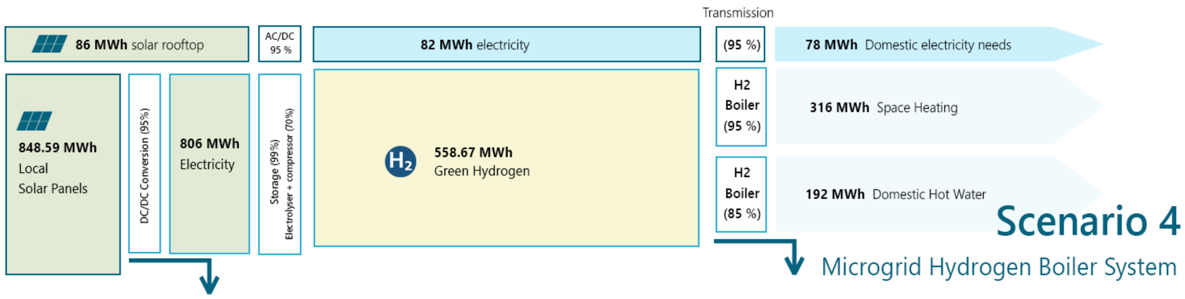


Figure 35. Energy consumption diagram of Scenario 4 – Microgrid hydrogen boiler system, utilizing light renovation (graphic illustrated by author)

Scenario 5. Cogeneration Hydrogen Fuel Cell System

In this scenario, waste heat from the fuel cell plays a pivotal role in the system. In addition to the electricity generated by the system, the waste heat which can reach a temperature range of 40 to 60 degrees Celsius is utilised for fulfilling the heating demand for both space heating and domestic hot water. However, in result, this system is categorized as inefficient system, falls under classification of an energy-efficient system yet provide a complex set up. Which utilizes only waste heat from the fuel cell, in result, it is requiring more heat to cover the demands. Therefore, more energy is needed and the system is becoming inefficient. However, despite producing waste heat, fuel cell also produces electricity which has its efficiency of almost 60%. Its production of electricity surpasses the demand and allowing its surplus electricity to be reused into the production of green hydrogen. Consequently, with electricity generated through fuel cells, installations of photovoltaic rooftops are no longer needed, as the electricity produced can aptly satisfy the energy demand for various appliances.

Table 34. The estimation of energy consumption for Scenario 5 – Cogeneration hydrogen fuel cell system

Energy Consumption	Unit	Base Case	Light Renov	Ambitious Renov
Space Heating Consumption	MWh	806.19	316.28	214.25
Efficiency (40°-60°C) of Fuel cell (heat)	%	37	37	37
Fuel Cell Energy Consumption	MWh	2,178.90	854.82	579.06
Efficiency of hydrogen storage	%	99	99	99
Energy consumption for hydrogen storage	MWh	2,200	863.45	584.91
Efficiency of (Electrolyser + compressor)	%	70	70	70
Energy consumption (Electrolyser + compressor)	MWh	3,144	1,233	835.58
Efficiency of DC/DC conversion	%	95	95	95
PV central to produce hydrogen (for space heating)	MWh	3,309	1,298	879.6
Domestic Hot Water (DHW)	MWh	191.88	191.88	191.88
Efficiency (≥60°C) of Fuel Cell	%	37	37	37
Fuel cell Energy Consumption	MWh	518.6	518.6	518.6
Efficiency of hydrogen storage	%	99	99	99
Energy consumption for hydrogen storage	MWh	523.83	523.83	523.83
Efficiency of (Electrolyser + compressor)	%	70	70	70
Energy consumption (Electrolyser + compressor)	MWh	748.34	748.34	748.34
Efficiency of DC/DC conversion	%	95	95	95
PV central to produce hydrogen (for DHW)	MWh	787.72	787.72	787.72
Electricity generated by Fuel Cell (Space Heating)	MWh	2,015.47	790.7	535.625
Efficiency of Fuel cell (electricity)	%	57	57	57
Electricity surplus by fuel cell	MWh	1148.82	450.7	305.3
Electricity generated by Fuel Cell (DHW)	MWh	518.6	518.6	518.6
Efficiency of Fuel cell (electricity)	%	57	57	57
Electricity surplus by fuel cell	MWh	295.60	295.60	295.60
Electricity Demand for appliances	MWh	77.98	77.98	77.98

Efficiency of local grid transmission Energy consumption for grid transmission	% MWh	95 82.08	95 82.08	95 82.08
Total Electricity Surplus (deviation)	MWh	1,361.5 (+)	664.22 (+)	518.82 (+)
Total electricity (PV central) for hydrogen production	MWh MWh	3,309 + 787.72 4,097.36	1,298 + 787.72 2,085.72	879.6 + 787.72 1,667.32

However, there is room for improvement, considering the high energy consumption of approximately 2,086 MWh required for green hydrogen production, far exceeding the heating demand of 406 MWh. Consistent operation of the fuel cells to meet the heating demand results in an overall system efficiency of only 24%, highlighting the need for further enhancements, as elucidated in Table 34.

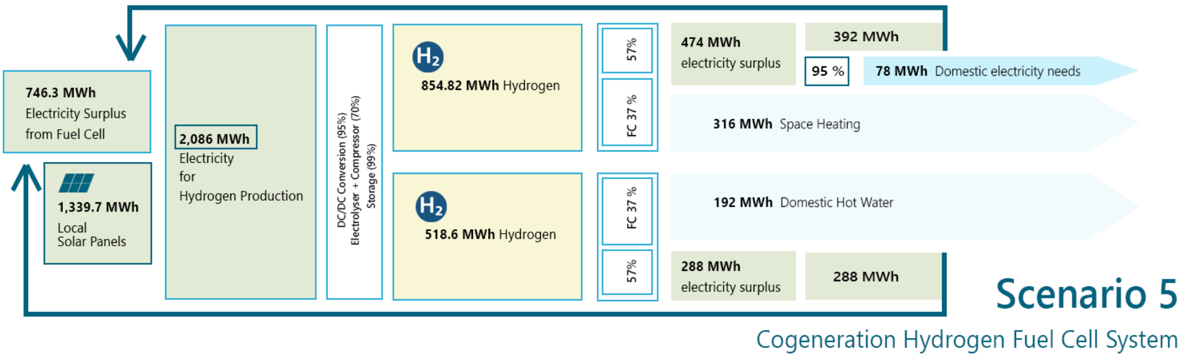


Figure 36. Energy consumption diagram of Scenario 5 – Cogeneration hydrogen fuel cell system, utilizing light renovation (graphic illustrated by author)

This innovative system harnesses the potential of waste heat as a valuable energy source. By efficiently repurposing the waste heat from the fuel cells to meet the heating demand, this system is committed to sustainable energy solutions. Nevertheless, the inherent complexity of this setup underlines the need for strategic improvements, particularly in light of the high energy consumption required for green hydrogen production. Figure 36 depicts a visual representation of the energy system's cyclical process, emphasising the pivotal role of fuel cells in this multifaceted energy ecosystem.

Scenario 6. Hydrogen Hybrid Heat Pump System

This innovative system needs a reduced amount of hydrogen to fulfil the heating demand. The hydrogen is green as it is generated from solar-powered energy source. In this scenario, an air-source heat pump is introduced to complement the utilisation of hydrogen fuel cells. This heat pump will further optimise system efficiency by recovering heat from the air source for heating purposes. This scenario does have promising outcomes, with the heat pump contributing 248.8 MWh of the total heating demand of 406 MWh. This reflects a relatively efficient system, boasting an impressive overall efficiency of 163%. Nonetheless, this system can still be further improved, since the heat pump operates continuously and relies heavily on electricity from the fuel cells. To maximize energy efficiency, it is highly advised to implement a control system that enables the heat pump to work directly from the solar panels especially during sunny weather. This enhancement can lead to reduced energy consumption, thereby improving system sustainability.

In this context, the heat pump contributes significantly to reducing the heating demand as it works synergistically with the fuel cells to produce electricity. The electricity demand for the heat pump is not only channelled through direct solar power source. This means that this renewable energy source can minimise the system's dependency on fuel or electrical grid. Additionally, seasonal storage for peak demand can also be achieved by utilising this hydrogen source. This explains how this system has an outstanding efficiency of 163%.

However, there is compelling potential for further improvements of this system to address the heat pump's continuous operation and refining-tune its control system to prioritise solar-generated electricity during sunny periods. This strategic adjustment not only benefits its energy efficiency but also strengthens the resilience and sustainability of this system, aligning it closely with environmentally conscious goals.

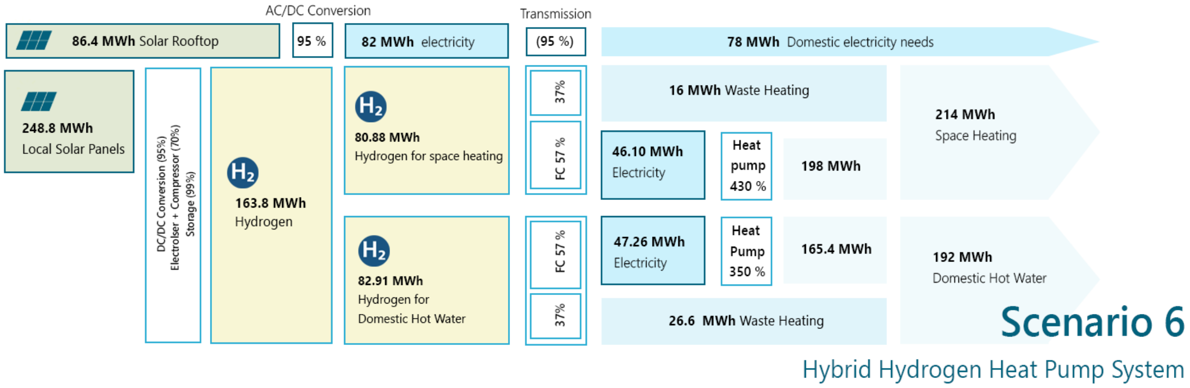
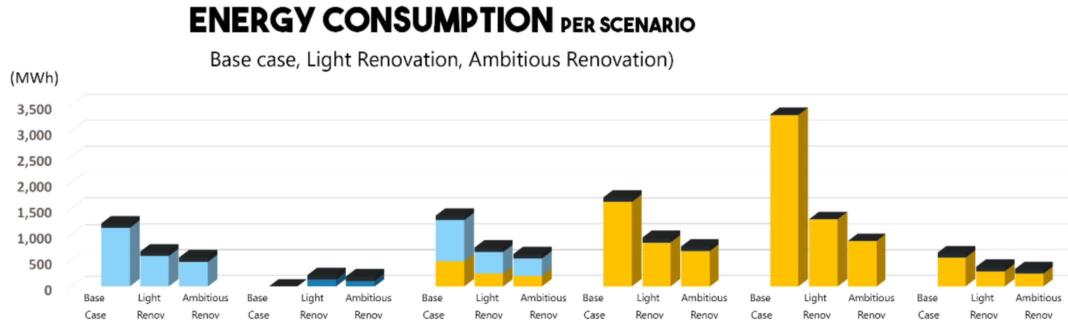


Figure 37. Energy consumption diagram of Scenario 6- Hybrid hydrogen heat pump system, utilizing ambitious renovation (graphic illustrated by author)

Conclusion of Energy Consumption Analysis



(MWh)	Scenario 1 Natural gas grid system			Scenario 2 All-electric heat pump system			Scenario 3 Blending hydrogen and natural gas system			Scenario 4 Microgrid hydrogen boiler system			Scenario 5 Cogeneration hydrogen fuel cell system			Scenario 6 Hybrid hydrogen and heat pump system		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Electricity (PV rooftop) for appliances	86	86	86	0	86	86	86	86	86	86	86	86	0	0	0	86	86	86
Electricity (PV central) for heating	0	0	0	0	134	109	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas consumption for heating	1,131	588	475	0	0	0	792	412	333	0	0	0	0	0	0	0	0	0
Electricity (PV central) for HYDROGEN production	0	0	0	0	0	0	490	255	206	1,632	849	685	3,310	1,298	880	556	295	249

Figure 38. Analysis of Energy Consumption in six different scenarios of energy systems (illustrated by the author)

This study sets out a comparison of promising prospects of various integrated hydrogen systems for buildings within the area of the Stoke-On-Trent neighbourhood as demonstrated in Figure 38. All Electric Heat Pump System in Scenario 2 is considered the most efficient system with the lowest energy consumption, compared to the other alternatives. However, among other hydrogen solutions, the Hydrogen Hybrid Heat Pump System in Scenario 6 exhibits an outstanding result as the most efficient system, with the outcome of nearly half that of the Base Case scenario (Scenario 1: Natural Gas Grid System), with the effective use of fuel cell products due to its complete functionality. The waste heat generated by the fuel cells can still be utilised to meet the low temperature heating demand for space heating purposes. Therefore, the electricity produced is intended for domestic appliances. Eventually, there is no unused waste produced by the fuel cells, and the heat pump can help save the energy consumption in this system. In result, the overall efficiency of this system reaches 163%. Nevertheless, Scenario 2 which relies solely on heat pump still produces twice the system efficiency of about 360%.

On the other hand, the lowest performance is demonstrated in Scenario 5, Cogeneration Hydrogen Fuel Cell System, which is considered inefficient because it only contributes 24% of the overall system efficiency. This may be because the energy used in this system is generated solely by the waste heat from fuel cells, which may not be able to meet the heating demand of the buildings, thus requiring more energy to be generated to fulfil the heating demand in this system.

The other scenarios of hydrogen systems, e.g., Scenario 4 (Hydrogen Microgrid Boiler System) and Scenario 3 (Natural Gas and Hydrogen Blended System), have moderate energy consumption, with total efficiencies reaching 60% and 76%, respectively. However, it cannot be concluded that these specific systems lead to other hydrogen systems. So, it is crucial to consider how hydrogen is utilised and/or prioritised. This always depends on the context, region, and possible availability of hydrogen sources. If the city has sufficient supply of hydrogen, the use of hydrogen grid in the system is preferable.

From these findings of system efficiency, Scenario 5 which relies solely on fuel cells may not be feasible for application in buildings due to the limited effectiveness and complexity of the system. These limitations lead to a high primary energy demand, which results in increased energy consumption and low energy performance. Hence, an increase in capital costs may also occur. Furthermore, it is important to note that the conventional natural gas infrastructure in Scenario 3 will be phased out over several years as a result of current governmental policies. Therefore, Scenario 3 can only be implemented during the transition period and will be replaced gradually to Scenario 4.

6.2 Components Sizing of Energy Systems

Once the energy consumption of each system has been determined, it becomes feasible to identify the utilities that can be seamlessly integrated into a unified system. Figure 31 visually outlines the process of determining the optimal component dimensions that align with the specific configuration criteria of each system.

 PV Monocyrstalline (Rooftop) Flat type PV | 25 years 600 Watt peak 19.5x0.99x0.04 m^3 https://thesolarbrother.co.uk/products/high-power-solar-panel-600w	 Battery 300 Ah 48 Volt (Individual House) 15 kWh 0.6x1.1x0.23 m^3 https://www.meritsunpower.com/	 PV Monocyrstalline (Centralized) Flat type PV | 25 years 600 Watt peak 19.5x0.99x0.04 m^3 https://voltaconsolar.com/12v-complete-off grid-solar-kit-1000w.html	 Modular Battery (Centralized) 10 years 500 kWh, 1 MWh 10ft | 2.9x2.44x3 m^3 20 ft | 2.9x2.44x6.1 m^3 https://www.voltaienergy.com/bess_container/show-98.html
 Electrolyser - Nel C Series 350 Bars | 10-20 years 1.4x1.5x1.3 m^3 https://nelhydrogen.com/product/c10-c20-c30/	 Hydrogen Storage - Nel 350 bar 350 Bars | 25 years 1.2x2.4x0.6-3m^3 https://nelhydrogen.com/product/hydrogen-fueling-storage/	 Compressor Bauercomp 10-20 years 1.4x1.5x1.3m^3 H-SERIES 1 | Bauer Compressors https://www.bauercomp.com/products/hydrogen/h-series-1	 Hydrogen Fuel Cell stack – Ballard PEM fuel cell stack | 25 years 0.484x0.555x0.195m^3 https://www.ballard.com/about-ballard/publication_library/product-specification-sheets/fcvelocity-9ssl-spec-sheet
	Boiler 18 kW - Bosch Combi Condensed | 10-15 years 18 kW per house 0.28x0.33x0.72 m^3 Bosch elektrische cv ketel		Heat Pump 92 kW - Sprsun Centralized heat pump | 20 years 92 kW 418.75 kW | 25 houses 2.0x1.1x0.2m^3 https://sprsunheatpump.com/52KW-92KW-25-EVI-Air-to-Water-Low-Temp-Heat-Pump-Heating-w-Copeland-Compressor-pd6086665.html

Figure 39. Components sizing of energy systems (illustrated by author)

A careful sizing is determined which considered centralized system on the production of hydrogen, utilizing solar powered as the energy sources. This centralized system is highly efficient since the conversion of solar energy into hydrogen can be optimized, for instance, the sun exposure of solar panels could potentially be adjusted so it can capture more energy. Moreover, centralized system can often take advantage of economies of scale, which means that larger installations tend to have lower unit costs. The cost of resource and maintenance also can be reduced, since the system will be more straightforward and helps to ensure the equipment operation at peak efficiency and reduces downtime. Centralized energy system also can minimize the transmission losses as the electricity generated, which then easier to scale up as demand grows.

The following paragraphs, a detail exposition of component sizing will be presented. Firstly, the initial component under consideration is the photovoltaics (PV) rooftop system, which serves as a primary electricity source for households appliances. In order to ascertain the requisite sizing, a production calculation method is utilizing Excel through the framework of Zero Energy Design course. Considering efficiency of solar panels which sets out at 20% and the coverage area of 50% of the rooftop surface within the neighbourhood. These parameters are multiplied and will obtain the total square meter required for the PV panels. The determination of the kilowatt -peak rating of PVs is derived through the division of output by the Kk factor. This factor accounts for the solar radiation incident on a specific area, taking into consideration factors of the angle of incidence and the pitch of the roof. For instance, in the context of this research case study, Hanley in the UK, the Kk stands at 935 value. These calculations are crucial to establish the appropriate sizing to optimize the energy. One of PV sizing is described in equation 15.

$$\begin{aligned} \text{Energy Output} &= \text{Kk factor} \times \text{kWp} \\ 86{,}405 \text{ kWh} &= 935 \times \text{kWp} \\ \text{kWp} &= 92 \text{ kilowattpeak} \end{aligned} \tag{15}$$

Subsequently, battery size is determined by assessing the peak capacity when the appliances are operated. The expected duration during which a backup power is required must also be considered. Generally, the peak capacity of heating can be obtained through energy demand modelling, conducted by utilizing Excel sheet of the Climate Design course. For instance, in scenario 1, which involves natural gas grid system, the peak capacity of the boiler across five typological dwellings during a specific hour ranges from 0.32 to 0.86 kW. Over the subsequent 24 hours, this system will generate the energy from 8 to 21 kWh per day. From this number, the average energy backup is 15.36 kWh per day. Consequently, a 15 kWh battery is selected, providing a backup duration of 23.4 hours. In other scenarios, additional components within hydrogen system must be considered, for example, electrolyser, compressor, and fuel cell capacity, as each component significantly influences the determination of battery size.

The electrolysis sizing is developed by the nominal rate production per hour by the electrolyser. In this study, a product of electrolyser from Nel is deployed. Nel hydrogen is releasing type C electrolyser as illustrated on Figure 40, providing various production of hydrogen ranges from 10 Nm^3/h to 30 Nm^3/h. In this component, a pressure of 1 bar is applied in 0°C temperature.

Figure 40. PEM electrolyser C type by NEL hydrogen

To calculate the size of electrolysers, it is essential to determine the required hydrogen mass. For instance, considering scenario 3, which involves a blend of 30% hydrogen and 70% natural gas. To produced 406,132 kWh of heating; this scenario requires 205,637 kWh of hydrogen and 411,652 kWh of natural gas annually. Given that the energy content of hydrogen is around 33.3 kWh/kg, therefore, the mass of hydrogen can be calculated at 7,645 kilograms per year. The output electrolyser pressure is set at 1 bar (0.1 MPa) with the temperature of 0°C, which based on National Institute of Standards and Technology, correlating with a hydrogen density of 0.0887 kg/m^3. Consequently, an annual volume of 86,189 cubic meters of hydrogen is produced. This is equivalent to a daily production rate of 236 cubic meters or 9.8 m^3 per hour. Therefore, the use of one piece of electrolyser C10 by Nel hydrogen with 10 Nm^3/hour is recommended.

In addition to the sizing of the electrolysers, it is crucial to consider complementary appliances, such as compressor. Which is sized based on the product requirements specified by a particular compressor brand. Table 35 explains the detail information of the compressor sizing.

Table 35. Sizing of compressors based on the production rate on each scenario of the energy systems

No.	Type	Model	Motor Power	Final pressure	Flow Capacity	Production rate in the study
1.	A	H120-5	4 kW	350	5.4-7.1 m^3/h	-
2.	B	H120-7.5	5.5 kW	350	7.5-10.1 m^3/h	Scenario 3 (9.8 m^3/h), Scenario 6 (9.62 m^3/h)
3.	C	H15.4-20	16 kW	350	21-35 m^3/h	Scenario 4 (32.8 m^3/h)
4.	D	H15.4-20	16(x2)	350	42-70 m^3/h	Scenario 5 (81 m^3/h; Type C+D)

Ultimately, the capacity of fuel Cell can be determined by applying Equation 16. By calculating the hydrogen mass for each scenario, where the energy content per kilogram is 33.3 kWh/kg, and the Lower Heating Value (LHV) of hydrogen is 120,000 kJ/kg, the required fuel cell capacity can be ascertained.

$$hydrogen\ amount\ (kg) = \frac{P\ (kW)\ x\ t\ (h) x\ 3600s}{\eta\ (\%)\ x\ LHV\ (kJ/kg)} \tag{16}$$

In order to a comprehensive understanding of the appliances sizing, this research delves deeper into each scenario by elucidating the intricacies of their respective dimensions, power requirements, and operational considerations. The detailed breakdown of these parameters is explained explicitly in Table 36.

Table 36. Sizing of each component in every scenario of energy system

Scenario 1	Scenario 2	Scenario 3
Natural Gas Grid System	All-electric Heat Pump System	Natural Gas and Hydrogen Blended System
• *PV rooftop* 92 kWp 330 m^2 • *Individual battery* 15 kWh • *Individual regular boilers:* 16.75 kW per dwelling / 418.75 dwellings	• *PV rooftop* 92 kWp 330 m^2 • *Individual battery* 15 kWh • *PVs (centralized)* 116.3 kWp 413 m^2 • *Battery (centralized)* 500 kWh 5 hrs • *Heat pump (centralized)* 418.75 kW 5 units of 92 kW heat pumps	• *PV rooftop* 92 kWp 330 m^2 • *Individual battery* 15 kWh • *PVs (centralized)* 272 kWp 966 m^2 • *Battery (centralized)* 1 MWh 7 hrs • *Electrolyser* 1 unit C10 Nel 10 Nm^3/hrs • *Compressor* 5.5 kW • *Hydrogen Storages* 55 cylinders 327 m^3 • *Individual regular boilers* 16.75 kW per dwelling / 418.75 dwellings
Total Area of Scenario 1 appliances: 335 m^2	Total Area of Scenario 2 appliances: 759 m^2	Total Area of Scenario 3 appliances: 1,647 m^2

Scenario 4	Scenario 5.	Scenario 6
Microgrid Hydrogen Boiler System	Cogeneration Hydrogen Fuel Cell System	Hybrid Hydrogen and Heat Pump System
• *PV rooftop* 92 kWp, 330 m^2 • *Individual batteries* 15 kWh • *PV central* 908 kWp 3,220 m^2 • *Battery central* 2 MWh, 10 hours • *Electrolyser* 1 unit C30 Nel 30 Nm^3/hrs 1 unit C10 Nel 10 Nm^3/hrs • *Compressor* 16 kW • *Hydrogen Storages* 182 cylinders 1,090 m^3 • *Hydrogen Boilers* 16.75 kW per dwelling / 418.75 dwellings	• *PVs (centralized)* 2,231 kWp 7,920 m^2 • *Battery (centralized)* 3 MWh, 7 hrs • *Electrolyser* 3 units C30 Nel 30 Nm^3/hrs • *Compressors* 48 kW • *Hydrogen Storages* 454 cylinders 2,680 m^2 • *Fuel Cell* 135 kW	• *PVs rooftop* 92 kWp, 330 m^2 • *Individual batteries* 15 kWh • *PVs (centralized)* 266 kWp, 950 m^2 • *Battery (centralized)* 1 MWh, 7 hrs • *Electrolyser* 1 unit C10 Nel 10 Nm^3/hrs • *Compressors* 5.5 kW • *Hydrogen Storages* 54 cylinders, 320 m^3 • *Fuel Cells* 16 kW • *Heat Pumps* 418.75 kW 5 units of 92 kW heat pumps
Total Area of Scenario 4 appliances: 4,677 m^2	Total Area of Scenario 5 appliances: 10,655 m^2	Total Area of Scenario 6 appliances: 1,621 m^2

In the first scenario, the system involves the implementation of an individual boiler in each house, with a capacity of 18 kWh per boiler. This arrangement is designed to fulfil the requirements for domestic hot water and space heating. The utilization of a 300 Ah battery can be implemented in conjunction with around seven photovoltaic (PV) panels per household. In the second situation, a centralized heat pump is utilized. A central local PV is also built with different configuration for the electricity demand per house supplied by rooftop PV. Another utility of 500 kWh battery size battery will be applied in this system. Five centralized heat pump has the capacity of 92 kW for this system.

In the third scenario, hydrogen is utilised within the system. The production of green hydrogen is achieved through the use of solar power. Additionally, local production is centralised, employing solar panels with a capacity of 272 kWp and battery stacks with a capacity of 1 MWh per unit. This setup enables the generation of 7,645 kilogrammes of hydrogen, which is subsequently compressed using a 5.5 kW capacity and stored in 55 cylinders. Furthermore, scenario 4, which involves a microgrid hydrogen boiler, exhibits distinct variations in the sizing of its components. Notably, this configuration necessitates the incorporation of solar panels with a total capacity of 904 kWp, accompanied by the utilisation of a battery of 2 MWh, and with 1 unit of C30 and 1 unit of C10 electrolyser from Nel Hydrogen are employed, to produce the required hydrogen approximately to fulfil 32.80 Nm^3 per hour. In scenario 5, the subsequent system involves the integration of a fuel cell. This particular fuel cell system, possesses a capacity of 140 kW HPS FC and is comprised of two stacked units manufactured by Ballard. The production of hydrogen for this system is substantial due to the significant need for energy consumption. A system is equipped with an electrolyser appliance that has a significant capacity of 81 Nm3/h in total, consist of 3 units electrolyser with the large size of 30 Nm3/h. The final system in scenario 6 exhibits a relatively low hydrogen consumption of 7,471 kilogrammes, so this scenario is considered the most efficient among other alternative hydrogen system. This is achieved by employing a single unit of C10 Nel series electrolyser, which is subsequently compressed using a 21 kW FC 9SSL compressor. The compressed hydrogen is then stored in 54 hydrogen storage cylinders. This setup enables the distribution of hydrogen for the neighbourhood consumption.

Hydrogen Transportation

[DNV_Energy Transition Outlook 2022]

7. COST EFFECTIVE ANALYSIS

Market forecasts underline that H_2 production will increase significantly over the next few years, with a growth of 5 – 10% per year from 50 to 82 Mt by 2050 [110]. Currently, more than 98% of the H_2 production is ensured from the fossil resources include either natural gas and Steam Methane Reforming (SMR) and 76% through only by SMR [111]. A research by Parthasarathy et al. (2014) predicted that cost of hydrogen production from Steam Methane Reforming is approximately 0.75$/kg [112], this prediction cost is low than hydrogen from biomass which remains high ranging from 1.21 to 2.42 $/kg for gasification process and another process of pyrolysis ranges from 1.21 to 2.19 $/kg [112]. This current low-carbon alternatives will not be cost competitive since a derivative of natural gas will shift. Blue hydrogen is naturally more costly without incentives toward the abatement. An estimation of another resource from European Commission at 2020 predicted that costs of hydrogen production from fossil-based range from 1.50 Euro per kg, and including the Carbon Capture and Storage is about 2.00 Euro per kg [113]. Hence, an increase in the H_2 costs from coal gasification is expected from $1 to 2.7 $/kg H_2 in China by 2030 due to taxation [114].

Green Hydrogen Production Costs

On the other hand, the costs for green hydrogen production has the highest range from 2.5 to 5.5 Euro per kg based on the European Commission at 2020. This data is strengthen by the report US Department of Energy report mentioned that existing PEM hydrogen production costs range between 2.50$ and 6.50$ per kg, as shown in table 36 which includes electricity cost, capacity factor, stack efficiency, and capital cost. While based on the study from the International Energy Agency (2019) mentioned that the costs of hydrogen from water electrolysis using renewable energy would be reached to 3-2.8 $/kg H_2, and from 5.3 to 4.8 $/kg using the electricity grid by 2030[114].

Table 37. Hydrogen costs production from various external analysis and associated assumptions

Description	Costs	Source
Green hydrogen production	2.5$ - 5.5$ (/kg)	European Commission (2020)
H_2 Cost Solar PV-based in LA, USA	6.09$ (/kg)	NREL ATB (2020)
H_2 Cost Solar PV-based in Daggett, USA	5.54$ (/kg)	NREL ATB (2020)
PEM hydrogen Production Costs	4.0$ – 6$ (/kg)	H2 Council (2020)
	2.8$ – 5.2$ (/kg)	E3 (2020)
	2.8$ – 6.8$ (/kg)	IRENA (2020)
	2.5$ – 6.8$ (/kg)	BNEF (2020)
Hydrogen production (with 34%-61% electricity grid)	0.14-0.18 (/kWh)	Kevin Knosala et al (2022)

Therefore, from the cost prediction mentioned above, green hydrogen faces several obstacles that must be addressed before it can be considered as a feasible substitute for grey hydrogen and achieve widespread implementation. These challenges include significant manufacturing costs and substantial energy losses. The major expenditure in green hydrogen production is the cost of renewable electricity required to operate electrolyser, followed by the capital cost of the electrolyser component itself [115]

According to a report by International Renewable Energy (IRENA, 2020), the cost of producing green hydrogen in the year 2019 was found to be two or three times higher than that of grey hydrogen. Thus this potential result may lead to elevate in high end-user costs, as it needs to be cost competitive with both fossil fuels and different shades of hydrogen. In contrast, a recent study conducted by Longden et al. (2022) suggests that there is a possibility of green hydrogen production to reduce the costs through scaling up and deployment of renewables and electrolysers in comparison to fossil fuel productions. This raises questions as to whether renewables will be able to progress the necessary rate to support increasing electrification and advancement of green hydrogen [7]. Hence, it is possible that the local production of hydrogen may deviate from the prevailing cost trend, despite the fact that it entails greater capital expenditures and a longer payback period within the vicinity.

7.1 Levelized Cost of Energy

The estimates outlined in this report are intended to provide parameters of the economic approach, utilizing mathematical models on the different systems of six scenarios of cost analysis. Data from literatures such as industrial reports and case studies informed that financial and technical parameters are calculating these key cost parameters; capital investments (CAPEX), operational and maintenance expenses (OPEX) and the fuel costs consumed by each scenario.

Levelized cost of energy calculates a present value of the total costs, including the upfront costs, operating costs and the fuel costs of the energy systems over an assumed lifetime. LCOE can be utilized to supplement the scenario prediction with the simplified methodology. As a result, a number of assumption must be made to standardize the various parameters of an otherwise complex analysis. Levelized Cost of Energy formula is described in the Equation 16 to 18.

$$\textit{Levelized Cost of Energy (LCOE)} = \frac{\textit{Net Present Value (NPV)of Total Costs}}{\textit{Net Present Value (NPV) of Energy Generation}} [\$/kWh] \quad (16)$$

$$\textit{Net Present Value (NPV) of Total Cost} = \sum_n \frac{\textit{Total Capex and Opex Costs and Fuel Costs}\ \mathrm{n}}{(1+\textit{discount rate})^n} [\$] \quad (17)$$

$$\textit{Net Present Value (NPV) of Energy Generation} = \sum_n \frac{\textit{Cost of net heat /electricity generation}\ \mathrm{n}}{(1+\textit{discount rate})^n} [kWh] \quad (18)$$

In operational and maintenance expenses (OPEX), consist of variable and fixed costs. Variable costs are the costs that changed based on the amount of output produced, may include labors, commissions, and raw materials. In the other hand, fixed costs remain the same regardless of the production costs.

Levelized cost of energy allows the users to analyze the scenarios based on different technologies on equalized basis, which has different amount of energy consumptions as well as appliances which considered the energy production, the limit year, and discount rate of each scenario. This methodology benefits to evaluate those different scenarios in constant manner. The LCOE is also clear and straightforward metric that can be easily communicate to stakeholders, policy makers, and public. It facilitates discussions on energy choices and helps to form a shared understanding of the financial aspects of the energy projects. Its adaptability to the context also can be tailored to different scenarios, thus enables localized assessments and customized energy strategies. This multi-dimensional approach supports to a more holistic and comprehensive decision-making process. A summary of the costs and performance parameters used in the levelized cost analysis is shown in Table 36. Based on the literature, given the value of Capital module cost, operational and maintenance costs to be presented in the next analysis of each scenario.

Table 38. Summary of cost data prediction in 2030 based on ARENA report, assumed at 2016.

Description	2030 (CSiro Energy, ARENA) [80]
PV Capital Expenditure (CAPEX) - modul cost	390 $/kWp
PV Capital Expenditure (CAPEX - installation and indirect cost	380 $/kWp
PV Operational &Maintenance cost (OPEX) – variable cost	2.8 % CAPEX
Li-ion Battery Capital Expenditure (CAPEX) – modul cost	200 $/kWh
Battery Capital Expenditure (CAPEX) – Installation cost	10 % CAPEX
Li-ion battery Operational &Maintenance cost (OPEX) – fixed cost	2.02% CAPEX
Li-ion battery Operational & Maintenance cost (OPEX) – variable cost	3.1 $/MWh
PEM electrolyser Capital Expenditure (CAPEX) – modul cost	3 $/kg
PEM electrolyser Capital Expenditure (CAPEX) – installation cost	10 % CAPEX
PEM electrolyser Operational & Maintenance cost (OPEX) – fixed costs	5 % CAPEX
PEM electrolyser Operational & Maintenance cost (OPEX) – variable costs	10% CAPEX

In this study, each scenario is presented with its corresponding analysis and subsequent explanation. In the explanation below, the value of light renovation resulted from the previous energy consumption is utilized since it is applicable in this recent year with some improvements on insulations; on the wall, floor, and roof application, while the ambitious renovation allows a renovation in the glazing replacements. Thus, for scenarios which required desired insulations for well-renovated buildings, then it will apply the ambitious renovations. Therefore, scenario 2 and 6 , which applying heat pumps, will consider deployed the ambitious renovation. In result, the renovation costs will be included in the calculation. The detailed information on how cost analysis is compared is given in the Table 39.

Table 39. The utilization of renovation recommendations of cost-effectiveness analysis in different scenarios

Scenario	Base Case/ Without Renovation	Light Renovation	Ambitious Renovation
Scenario 1. Natural gas grid heating system	X	√	X
Scenario 2. All-electric heat pump system	X	X	√ (+ renovation costs of glazing)
Scenario 3. Natural gas and hydrogen blended system	X	√	X
Scenario 4. Microgrid hydrogen boiler system	X	√ (+ upgrading pipeline costs)	X
Scenario 5. Cogeneration hydrogen fuel cell system	X	√ (+ upgrading pipeline costs)	X
Scenario 6. Hybrid hydrogen heat pump system	X	X	√ (+ renovation costs of glazing + upgrading pipeline costs)

This study conducted a comprehensive analysis, which included an assessment of the Payback Time (PBT) period, to determine the specific year in which an investment cost is expected to be recouped. The payback period for each scenario was compared to the Base Case, as illustrated in Equation 19, which, in this context, is represented by Scenario 1 - Natural gas grid system. This scenario serves as a benchmark, reflecting the prevailing choice found in roughly 80% of homes across the United Kingdom. Additionally, the study considered carious factors influencing the payback period and sought to enhance our understanding of the investment's economic viability over time.

$$\textit{Payback Time (PBT) of each scenario} = \frac{\textit{Capital Investment Scenario} - \textit{Capital Investment Base case}}{\textit{Annual Energy Costs Base Case} - \textit{Annual energy costs Scenario}} \text{ [year]} \quad (19)$$

Scenario 1. Natural Gas Grid Boiler Heating System

In this scenario analysis, the optimal electricity production can be achieved through solar rooftop systems, effective meeting the electricity demand and households. Specifically, it was found that installing approximately seven panels of polycrystalline silicon photovoltaics, each with a 600 Watt-peak capacity, is sufficient to fulfill the electricity requirements per house.

Table 40 outlines the system costs associated with constructing a residential block comprising 25 houses, with the expenses broken down comprehensively. To enhance energy reliability, a 15 kWh lithium-ion battery is integrated to store surplus solar power. On average, each house consumes 0.64 kW of electricity, allowing the battery to provide backup power for roughly 23 hours during outages or peak electricity demand periods. It is important to note that this calculation excludes high power appliances, which were not considered in this study.

Additionally, each house is equipped with an individual heat converter appliance, boasting a 16.75 kWh capacity. The moderate module capital cost for each of these appliances is estimated at approximately $1,200. These boilers are optimized at round 65 liters in size and operate on natural gas, with cost of 0.07 pounds, or 0.088 dollars, or 0,081 Euros per kilowatt-hour.

For more details breakdown of energy costs, it refers to Table 40. This comprehensive assessment allows for a better understanding of the economic feasibility and long-term energy costs implications in this scenario.

Table 40. Levelized cost of energy in 2030 for scenario 1- Natural gas grid system (system approach is in chapter 4)

Parameter	PV Rooftop	Battery	Boiler	Total
Capacity	92** kWp (6 kWp/house)	15 kWh (per house 23 hrs)	418.75 kW (16.75 kW per house)	
Modul Cost	390[1] $/kW$_{(p)}$	200[2] $/kWh	1200[2] $/house/year	
Installation Cost (include piping)	380[2] $/kWp	10[2] % of CAPEX/yr	1,700[3] $/house/year	
Admin & Auxiliary costs	-	-	490[4] $/house/year	
Fuel Costs	-	-	0.088[5] $/kWh	
Natural gas demand	-	-	588,074 kWyear	
Discount rate	3.5%[6]	3.5%[5]	3.5%[5]	
Economic Life	25[2] Years	10[7] Years	15[8] Years	20 Years
Fixed O&M Costs	-	2.02 % CAPEX/yr	4[9] % CAPEX/yr	
Variable O&M Costs	2.8% % CAPEX/yr	3.1[2] $/MWh	6[9] % CAPEX/yr	
Annual production /year				588,074 kWh/year
Capital Cost	36,040$/year	150,000$/year	60,150$/year	
Installation Cost	35,116$/year	30,000$/year	85,000$/year	
Admin + Auxiliary costs	-	-	24,500$/year	
CAPEX /year	71,157$/year	180,000$/year	169,650$/year	420,807 $/year
Fixed O&M Costs	-	3,030 $/year	2,406$/year	
Variable O&M Costs	1,009$/year	414 $/year	3,609$/year	
OPEX /year	1,009$/year	3,444$/year	6,015$/year	10,469 $/year
Fuel Costs /year	-	-	51,751$/year	
NPV CAPEX (20 years)	68,751$/20 years	173,913$/20 years	163,913$/20 years	406,577 $/20 years
NPV OPEX (20 years)	13,857$/20 years	47,297$/20 years	82,597$/20 years	143,751$/20 years
NPV Fuel Cost (5% fiscal policy) (20 years)	-	-	1,111,535$/20 years	1,111,535$/20 years
NPV Production (20 years)				11,363,759 kWh/20years
LCOE				0.13 $/kWh

$$\begin{aligned} \text{**Energy Output} &= \text{Kk factor x kWp} \\ 86{,}405 \text{ kWh} &= 935 \text{ x kWp} \\ \text{kWp} &= 92 \end{aligned} \qquad (16)$$

Which Kk factor is essentially the amount of solar radiation in which depends on the location of the dwelling, the angle, and pitch of the roof.

A factor of kWh/kWp is called Kk factor, which can be utilized to count the amount of solar panels in kWp generated per year. In Stoke-On-trent Kk factor roughly estimates as 935 (Exoenergy, 2016) which displayed in Equation 15.

1 ARENA. 2016. Prediction 2030.

2 Bosch Boiler. Electraboiler.nl (Accessed 14 August 2023)

3 Which? 2023. How much does a new boiler costs? Which.co.uk (Accessed 14 August 2023)

4 Heatable. 2023. How much does the average boiler service cost in 2023? (UK)

5 Ofgem. 2023. Ofgem.gov.uk (Accessed 04 September 2023)

6 HM government. 2021. Environmental Discount Rate Review.

7 Etronixcenter. 2016

8 Zvingilaite. 2015. Heat savings and heat generation technologies

9 Xu, Gang. 2013. Techno economic analysis and optimization of the heat recovery of utility boiler gas

In response to the government's initiative to phase out natural gas, an inflation rate of 5% is applied when evaluating the costs of the boiler system, considering the expected costs escalation over the coming years. Simultaneously, a discount rate of 3.5% has been applied to the net present value (NPV), ensuring a balanced financial perspective.

It is important to note that our cost assessment for this system does not include expenses associated with potential restoration projects. Consequently, the levelized cost of energy (LCOE) is estimated at 0.15 dollars per kilowatt-hour over a 20-year period, specifically for the year 2030. This LCOE calculation emphasizes on all relevant factors, including capital costs for appliances, operational expenses, and fuel costs. When comparing this LCOE, it becomes evident that the LCOE is a reasonable and cost-effective alternative, taking into account the long-term financial sustainability and environmental considerations.

Scenario 2. All Electric Heat Pump System

In scenario 2, a centralized system has been implemented, whereas a heat pump central is powered by centrally installed photovoltaic technology. Similar to the previous system, the electricity required to operate household appliances is generated through photovoltaic (PV) rooftop installations.

However, it is important to note that this system operates at lower temperatures compared to traditional heating systems, necessitating well-renovated dwellings with a robust insulation system. To achieve these lower heating temperatures in the neighbourhood, an upgrade from light renovation to ambitious renovation is required. In this renovation in scenario 2 focuses on glazing improvements where the insulation improvements have been defined completely in light renovation. Therefore, the dwellings have passed renovation criteria on light to increase the level of ambitious renovation, the guide of renovation recommendation is explained in the Chapter 5.2.

Table 41 provides a breakdown of the glazing improvement costs, estimating around 200 Euros per square meter of window. Resulting in a reduction of the U-value from 4.8 to 1.6 W/m^2K. This cost estimate applies to high-level glazing improvements, while the mid-level glazing changes are estimated at 180 Euros with the improvement from 3.1 to 1.6 W/m^2K. These insulation enhancements are a key component in achieving the desired temperature to efficient the energy performance, specifically in this Scenario 2.

Table 41. A glazing improvement of the ambitious renovation in Scenario 2. All-electric heat pump system

Typical Building	Area of glazing (m^2)	Base Case U-Value W/m^2K)	Ambitious renov U-Value (W/m^2K)	Costs (€)	Total Costs (€)	Total buildings	Total Costs (€)
A	27	4.8	1.6	200	5,380	10	53,800
B	7	4.8	1.6	200	1,340	3	4,020
C	9	3.1	1.6	180	1,620	6	9,720
D	22	3.1	1.6	180	4,032	3	12,096
E	9	4.8	1.6	200	1,800	3	5,400
Grand Total							85,036

Additionally, within this system, central solar panels with a total capacity of 116.63 kWp is strategically deployed, requiring approximately 207 units of 600 Watt-peak capacity for each individual panel. The integration of batteries assumes a pivotal role in ensuring uninterrupted energy supply, particularly when solar yields are compromised. Notably, across 25 houses in 1 block, utilizes the incorporation of 500 kWh battery system capable of providing five hours power backup during outages. It is essential to acknowledge that the expected lifetimes of these batteries and heat pumps are stayed no longer than 10 and 15 years respectively. Thus, to encompass the full 20 year analysis period, the quantity of appliances must be appropriately adjusted.

A discount rate of 3.5% is applied to calculate the net present value (NPV) over the 20 years of duration. For a comprehensive breakdown of the financial aspects of the Scenario2, all-electric heat pump system, including the levelized cost of energy can be referred to Table 42.

The findings in Table 42 clearly indicate that the levelized cost of energy within the system stands at 0.64 dollars per kilowatt-hour. This cost assessment underscores the system's viability, particularly when contrasted with the prevailing electricity rates of 0.34 dollars per kilowatt-hour. However, it is crucial to emphasize that these costs encompass a comprehensive scope, including capital expenditures, operational outlays, and renovation-related expenses. Nevertheless, the capital costs associated with generating solar energy in the system is worth an investment of approximately 37,333 dollars per household. Or roughly 4,783 per MWh. This factor warrants a through consideration of the economic implications and long-term benefits associated with adopting this renewable energy approach.

Table 42. Levelized cost of energy in 2030 for scenario 2- All-electric heat pump system (system approach is in chapter 4)

Parameter	PV Rooftop	Battery	PV Central	Battery Central	Heat Pump Central	Total
Capacity	92 kWp (6 kWp/house)	15 kWh (per house 23 hrs)	116.3 kWp (207 unit)	500 kWh (5 hours)	418.75 kW (16.75 kW/ house)	
Modul Cost	390[10] $/kWp	200[2] $/kWp	390[11] $/kWp	200[11] $/kWp	400[11] $/kW	
Installation Cost	380[11] $/kWp	10[11]% CAPEX/yr	380[11] $/kWp	10[2]% CAPEX/yr	8,800[12] $/year	
Discount rate	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	
Economic Life	25[11] Years	10[14] Years	25[2] Years	10[14] Years	15[12] Years	20 Years
Fixed O&M Costs	-	2.02% CAPEX/yr	-	2.02% CAPEX/yr	1150[12]$/year	
Variable O&M Costs	2.52 %CAPEX/yr	3.1[11]$/MWh	2.52%CAPEX/yr	3.1[11] [1]$/MWh	-	
Annual production						108,746 kWh
Capital Cost	36,040 $/year	150,000 $/year	45,361 $/year	200,000 $/year	335,000 $/year	
Installation Cost	35,116 $/year	30,000 $/year	44,198 $/year	40,000 $/year	17,600 $/year	
CAPEX	71,157 $/year	180,000 $/year	89,559 $/year	240,000 $/year	352,600 $/year	933,316 $/year
Fixed O&M Costs	-	414 $/year	-	4,040 $/year	2,300 $/year	
Variable O&M Costs	1,009 $/year	3,750 $/year	1,270$/year	119 $/year	-	
OPEX	1,009 $/year	3,444 $/year	1,270$/year	4,159$/year	2,300 $/year	12,183 $/year
NPV CAPEX (20 yrs)	68,751 $/20 yrs	173,913 $/20 yrs	86,530 $/20 yrs	231,884 $/20 yrs	340,676 $/20 yrs	901,754 $/20 yrs
NPV OPEX (20 yrs)	13,857 $/20 yrs	47,297 $/20 yrs	17,441$/20 yrs	57,111 $/20 yrs	31,583 $/20 yrs	167,290$/20 yrs
NPV Production (20 yrs)						2,101,365 kWh/20 yrs
Renovation Costs						85,036 $/20 yrs
LCOE						0.27 $/kWh
Payback Time						42 years

Scenario 3. Natural Gas and Hydrogen Blended System

In the context of the current shift toward sustainable solutions and the growing imperative for environmentally friendly fuel options, the integration of blended natural gas has emerged as a significant phase in the energy sector's transformation. This development serves as a crucial milestone on the path of fully hydrogen-based energy deployments. The breakdown of the overview details of Levelized Cost of Energy (LCOE) is explained in Table 43.

Table 43. Levelized cost of energy in 2030 for scenario 3-Natural gas and hydrogen blended system (system approach is in chapter4)

Parameter	PV Rooftop	Battery	PV Central	Battery Central	Electrolyser	Compressor	Hydrogen Storage	Regular Boiler	Total

[10] ARENA. 2016. Prediction 2030.

[11] Ronge, Jan. Francois, Isable. 2021. BatHybuild study. Solhyd. KU Leuven. WaterstofNet

[12] Energy Future Lab. 2022

[13] HM government. 2021. Environmental Discount Rate Review.

[14] Etronixcenter. 2016

Capacity	92 kWp (6 kWp/house)	15 kWh (per house 23 hrs)	272 kWp (483 unit)	1,000 kWh (7.4 hrs)	9.31 Nm3/hr	5.5 kW	7,645 kg (327 m3 350 bar)	418.75 kW (16.75 kW/ house)	
Modul Cost	390[15] $/kWp	200[16] $/kWh	390[16] $/kWp	200[16] $/kWh	3 $/kg	960[16] $/year	2.97[17] $/kg	1,303[18] $/unit	
Installation Cost	380[16] $/kWp	10[16] $/kWh	380[16] $/kWp	10[16] $/kWh	3[16] $/kg	35.4[22] $/kW	60,000[19] $/year (fixed)	1700[20]$/unit	
Auxiliary Cost	-	-	-	-	-	-	-	490[21] $/unit	
Discount rate	3.5%[22]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	
Lifetime	25[16] years	10[23] years	25[16] years	10[14] years	10[16] years	10[24] years	25[25] years	15[12] years	20 years
Fixed O&M Costs	-	10[16] $/kW	-	10[16] $/kW	5[26]% CAPEX	3.28[22] $/kW	-	4[27] % CAPEX	
Variable O&M Cost	2.8% CAPEX	3.1[16] $/MWh	2.52% CAPEX	3.1[16] $/MWh	10[28]% CAPEX	6[29]% CAPEX	15%[30] installation	6[31] % CAPEX	
Fuel Costs	-	-	-	-	-	-	-	0.088[32] $/kWh	
Gas demand	-	-	-	-	-	-	-	411,652 kWh	
Annual production									666,230 kWh
Capital Cost	36,040 $/yr	150,000 $/yr	106,188$/yr	400,000$/yr	22,935$/yr	10,560$/yr	90,822$/yr	65,150$/yr	
Install Cost	35,116 $/yr	30,000$/yr	103,465$/yr	80,000$/yr	4,587$/yr	389$/yr	60,000$/yr	85,000$/yr	
Auxiliary Cost	-	-	-	-	-	-	-	24,500$/yr	
CAPEX /year	71,157$/yr	180,000 $/yr	209,652$/yr	480,000$/yr	27,522$/yr	10,949$/yr	150,822$/yr	174,650$/yr	1,304,753 $/yr
Fixed O&M Costs	-	414 $/year	-	8,080 $/year	1,147 $/year	18 $/year	-	2,606 $/year	
Variable O&M Costs	1,009 $/year	3,030 $/year	2,676 $/year	350$/year	2,293 $/year	634$/year	9,000$/year	3,909 $/year	
OPEX /year	1,009 $/yr	3,444 $/yr	10,300 $/yr	8,430$/yr	3,440 $/yr	652 $/yr	9,000 $/yr	12,515 $/yr	35,464 $/yr
Fuel Costs /year	-	-	-	-	-	-	-	36,225	
NPV CAPEX (20 yrs)	68,751 $/20 years	173,913 $/20 yrs	202,563 $/20 yrs	463,768 $/20yr	26,591 $/20yr	10,579 $/20yr	145,722 $/20yr	168,744 $/20yr	1,260,631 $/20yrs
NPV OPEX (20 yrs)	13,857 $/20 years	47,297 $/20 yrs	40,828 $/20yrs	115,764 $/20yr	47,241 $/20yr	8,948 $/20yr	123,586 $/20yr	6,515 $/20yr	486,984 $/20 yrs
NPV Fuel costs (20 yrs)	-	-	-	-	-	-	-	778,075 $/20yr	778,075 $/20 yrs
NPV Production (20 yrs)									12,874,008 kWh/20yrs
LCOE									0.17 $/kWh
Payback Year									0 year

This calculation unveils the details of heating demands through electrolyze with the utilization of 10 Nm3/h of PEM electrolyser. This is essential to produce the required 7,645 kilograms of hydrogen. A pressure of 350 bar is applied with a density measuring 23.38 kg/m3, resulting in an annual volume of 327 cubic meters

15 ARENA. 2016. Prediction 2030.

16 Bauercomp.com. 2023. (Accessed 15 August 2023)

17 Horizon-europe. 2023. Advance materials for hydrogen storage

18 Bosch Boiler. Electraboiler.nl (Accessed 14 August 2023)

19 Abdin et al. 2020

20 Which? 2023. How much does a new boiler costs? Which.co.uk (Accessed 14 August 2023)

21 Heatable. 2023. How much does the average boiler service cost in 2023? (UK)

22 HM government. 2021. Environmental Discount Rate Review.

23 Etronixcenter. 2016

24 Nigen International. 2023.

25 Bionaz, David. 2022. Life cycle environmental analysis of hydrogen based energy storage system

26 BEIS. 2021. Levelized cost of hydrogen

27 BEIS. Electricity generation costs. 2016. Costs prediction 2030

28 Dawood, Furat. 2020. Stand-Alone Microgrid with 100% Renewable Energy

29 Vives, Ana Maria V. 2023. Techno-economic Analysis of large-scale green hydrogen production

30 Abdin et al. 2020

31 BEIS. Electricity generation costs. 2016. Costs prediction 2030

32 Ofgem. 2023. Ofgem.gov.uk (Accessed 04 September 2023)

of green hydrogen. To ensure a steady supply, about 22 cylinders of hydrogen storage with an 80 diameters and 350 bar pressure have been thoughtfully constructed.

The robust infrastructure and hydrogen production system represent a significant and crucial to evaluate the economic viability of such an approach. A comprehensive analysis of the Levelized Cost of Energy (LCOE) offers in-depth breakdown of the cost considerations associated with the natural gas and hydrogen blended system.

With a stable Levelized Cost of Energy of 0.20 dollars per kWh, will be applied in 2030 throughout the projected lifespan of 20 years. Where the capital investment of this system is reaching to 52,190 per households, and the annual operation and maintenance costs per year is 3% of the CAPEX, accounted for 1,419 per year. In addition to the operational costs, the fuel costs are also comparatively modest, constituting just 3% of the overall capital costs.

From the findings on the Table 43, it is showed that the most significant capital cost is sourced from PV rooftop, followed by the battery central, and hydrogen storages. The installation costs are also significant, though the auxiliary costs of are relatively low.

The table also shows that the levelized costs of energy (LCOE) for natural gas and hydrogen blended system is 0.20$/kWh. Kevin Knosala et al, mentioned that hydrogen production utilizing PEM electrolyser although not fully deployed by 100% solar power, with 34%-61% electricity grid, it costs lower in the range of 0.14-0.18$/kWh. This is significantly comparable, since the more solar power is applied, the higher costs is produced. However, the cost of hydrogen is expected to decrease in the near future as the technology improves and economies of scale are achieved.

Scenario 4. Microgrid Hydrogen Boiler System

In this scenario, a fully integrated 100% hydrogen system is locally distributed. And its design parameters reveal an intriguing perspective. As detailed in Table 44, it is evident that the installation of 907 kWp solar panels is essential to meet the hydrogen demand. The centralized production approach of PV panels may benefit within the neighbourhood. The centralization not only simplifies transmission and maintenance but also offers cost-efficiency by reducing the number of installation costs. Moreover, it allows for enhanced design flexibility, offering the possibility of future expansion to accommodate the growing demand.

In parallel in this scenario, the electricity requirements for household appliances are satisfied through individual PV rooftop systems, as the same as previous system. Each rooftop is equipped with approximately seven PV panels, complemented by a 15 kWh wall battery. Yet, due to the increased need for hydrogen production, a more substantial investment in renewable energy is necessary. This translates to a requirement of 3,220 square meters of PV panels to meet the heightened demand. To ensure uninterrupted power supply, the system also includes other utilities, such as 2 MWh of batteries and 1,090 cubic meter of hydrogen storages with pressured at 350 bar.

The intriguing dimension becomes apparent when analysing the levelized cost of energy, which stands at 0.30 dollars per kilowatt-hour, as depicted in Table 44. It is important to note that a comprehensive examination of the operation and maintenance costs reveals that they constitute 3% of the annual capital expenses, highlighting the sustainability and cost-efficiency of this microgrid hydrogen boiler system.

Table 44. Levelized cost of energy in 2030 for scenario 4-Microgrid hydrogen boiler system (system approach is in chapter 4)

Parameter	PV Rooftop	Battery	PV Central	Battery Central	Electrolyser	Compressor	Hydrogen Storage	Hydrogen Boiler	Total
Capacity	92 kWp	15 kWh	907 kWp	2,000 kWh	31 Nm3/h	16 kW	25,483 kg	418.75 kW	

	(6kWp /house)	(per house 23 hrs)	(1,610 unit)	(10 hrs)			(1,090 m3 350 bar)	(16.75 kW/ house)	
Modul Cost	390[33] $/kWp	200[16] $/kWh	390[16]$/kWp	200[16] $/kWh	3 $/kg	960[34] $/year	2.97[35] $/kg	2500[36]$/unit	
Installation Cost	380[16]$/kWp	10[16] $/kWh	380[16]$/kWp	10[16] $/kWh	3[16] $/kg	35.4[22] $/kW	60,000[37] $/year (fixed)	2500[38] $/unit	
Auxiliary Cost	-	-	-	-	-	-	-	590[39]$/unit	
Discount rate	3.5%[40]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	
Lifetime	25[16] years	10[41] years	25[16] years	10[14] years	10[16] years	10[42] years	25[43] years	15[12] years	20 years
Fixed O&M Costs	-	10[16] $/kW	-	10[16] $/kW	5[44]% CAPEX	3.28[22] $/kW	-	4[45] % CAPEX	
Variable O&M Costs	2.8% CAPEX	3.1[16] $/MWh	2.52% CAPEX	3.1[16] $/MWh	10[46]% CAPEX	6[47]% CAPEX	15%[48] installation	6[49] % CAPEX	
Pipe length	-	-	-	-	-	-	-	-	180 m
Pipe upgrading costs	–	-	–	-	-	-	-	-	300$/m
Annual production									848,592 kWh
Capital Cost	36,040 $/yr	150,000 $/yr	353,958$/yr	800,000 $/yr	76,450 $/yr	30,720 $/yr	302,741 $/yr	125,000 $/yr	
Install Cost	35,116 $/yr	30,000$/yr	344,882 $/yr	160,000 $/yr	15,290 $/yr	1,233 $/yr	60,000 $/yr	85,000 $/yr	
Auxiliary Cost	-	-	-	-	-	-	-	24,500 $/yr	
CAPEX /year	71,157$/yr	180,000 $/yr	698,841 $/yr	960,000 $/yr	91,740 $/yr	31,853 $/yr	362,741 $/yr	234,500 $/yr	2,630,831 $/yr
Fixed O&M Costs	-	414 $/yr	-	16,160$/yr	3,822 $/yr	105 $/yr	-	5,000 $/yr	
Variable O&M Cost	1,009 $/yr	3,030 $/yr	9,911 $/yr	906$/yr	7,645 $/yr	1,843 $/yr	9,000 $/yr	7,500 $/yr	
OPEX/ year	1,009 $/yr	3,444 $/yr	9,911$/yr	17,066 $/yr	11,467 $/yr	1,948 $/yr	9,000 $/yr	18,500 $/yr	66,286 $/yr
Gridlines upgrade	-	-	-	-	-	-	-	-	54,000 $
NPV CAPEX (20 yrs)	68,751 $/20 years	173,913 $/20 yrs	675,209 $/20yrs	927,536 $/20yrs	88,637 $/20yrs	61,551 $/20yrs	350,474 $/20yrs	226,570 $/20yrs	2,541,866 $/20yrs
NPV OPEX (20 yrs)	13,857 $/20 years	47,297 $/20 yrs	136,093 $/20yrs	234,351 $/20yrs	157,469 $/20yrs	26,752 $/20yrs	123,586 $/20yrs	171,647 $/20yrs	911,054 $/20yrs
NPV Production (20 yrs)									16,397,913 kWh/20yrs
LCOE									0.19 $/kWh
Payback Year									0 year

Table 44 explained that the capital costs of the hydrogen production system is high, which reaches to 105,233$ per household. The most significant capital costs are from generating the electricity for hydrogen production including photovoltaics, and backup power supply; batteries, and hydrogen storages. However, even though the costs of those appliances are considered quite high, the costs of solar panels has been

33 ARENA. 2016. Prediction 2030.

34 Bauercomp.com. 2023. (Accessed 15 August 2023)

35 Horizon-europe. 2023. Advance materials for hydrogen storage

36 Iheat.co.uk. 2023. Hydrogen -Ready Boiler Costs

37 Abdin et al. 2020

38 Which? 2023. How much does a new boiler costs? Which.co.uk (Accessed 14 August 2023)

39 Heatable. 2023. How much does the average boiler service cost in 2023? (UK)

40 HM government. 2021. Environmental Discount Rate Review.

41 Etronixcenter. 2016

42 Nigen International. 2023.

43 Bionaz, David. 2022. Life cycle environmental analysis of hydrogen based energy storage system

44 BEIS. 2021. Levelized cost of hydrogen

45 BEIS. Electricity generation costs. 2016. Costs prediction 2030

46 Dawood, Furat. 2020. Stand-Alone Microgrid with 100% Renewable Energy

47 Vives, Ana Maria V. 2023. Techno-economic Analysis of large-scale green hydrogen production

48 Abdin et al. 2020

49 BEIS. Electricity generation costs. 2016. Costs prediction 2030

decreasing rapidly in recent years. This trend is expected continue as well as the cost of hydrogen production along with the increased of hydrogen demand in the future.

Scenario 5. Hydrogen Fuel Cell Waste-Heat System

In this specific system, the primary source of heating is derived from the waste-heat of a fuel cell, which its temperature can reach to 60 degrees. The efficiency of fuel cell in generating heat falls within the range of 37% to 40%. This efficiency factor has a significant impact on energy consumption, with approximately 62,647 kilograms of hydrogen needed to sustain the system. The remaining output of this system is electricity, which can be fed back into the grid. Consequently, the analysis in Table 45 highlights the system's relatively low levelized cost of energy (LCOE), primarily due to the fuel cell's capacity to generate electricity efficiently. This efficient electricity generation negates the need for additional power for household appliances, making it a self-sufficient energy source.

Enhancing its self-sufficiency, the system incorporates three stacks of 1 MWh batteries, ensuring autonomy for up to 7 hours. To facilitate the electrolysis process, two units of electrolysers with different sizing are deployed. A stack rated at 30 Nm3/hr capacity, and one stack of 20 Nm3/hr capacity. A fuel cell with a capacity of 140 kW further contributes to the system. And ultimately, to ensure the availability of hydrogen, robust hydrogen storages are established, comprising 179 cylinders with an 80 cm diameter, pressuring at 350 bar, accommodating the hydrogen demand.

Despite the intriguing aspects of this system, there are concerns regarding its overall efficiency. The reliance on a fuel cell as the main heating source, which exhibits relatively low efficiency, results in elevated energy costs. The substantial demand for hydrogen to maintain the heating process is a noteworthy challenge, raising questions about whether the heating needs of the system can be adequately met.

From the Table 45, the most significant cost is the capital cost (CAPEX) of the system, which reaches very high approximately at 238,238$ per household installation, where the operational costs is also still high up to 2% of the CAPEX, about 3,747$ per household. However, this calculation does not consider any prediction from the government which is expected to decrease significantly in the near future. Furthermore, while the LCOE of this system is calculated to be 0.18 dollars per kilowatt-hour, indicating it is comparable with the prediction of fully 100% hydrogen in a range of 0.14$/kWh- 0.18$/kWh by Kevin Knosala et al.

However, based on the finding on Table 45 revealed that the overall cost of hydrogen fuel cells are considered high due to its large amount of energy consumption. Therefore this system is considered inefficient with total system efficiency contributes only 24%. A number of capital expenses also reach 14 times higher than a base case; natural gas grid system. On the other hand, operational and maintenance costs also high, which accounted for 3,747$ per household, while a base case only require 419$ per household. In consequent, this microgrid hydrogen boilers system may pose challenges to the overall system economy viability.

Table 45. Levelized cost of energy in 2030 for scenario 5-Cogeneration hydrogen fuel cell system (system approach is in chapter4)

Parameter	PV Central	Battery Central	Electrolyser	Compressor	Hydrogen Storage	Fuel Cell	Total
Capacity	2,231 kWp (2,960 unit)	3,000 kWh (7.28 hrs)	62,647 kg	48 kW	76 Nm3/h	136 kW	
Modul Cost	390[16]$/kWp	200[16] $/kWh	3 $/kg	960[50] $/year	2.97[51] $/kg	3,700[52,53]	
Installation Cost	380[16]$/kWp	10[16] $/kWh	3[16] $/kg	35.4[22] $/kW	60,000[54] $/year (fixed)	0.20[57] $/kWh	
Discount rate	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	1.5%[56]	
Lifetime	25[16] years	10[14] years	10[16] years	10[55] years	25[56] years		20 years
Fixed O&M Costs	-	10[16] $/kW	5[57]% CAPEX	3.28[22] $/kW	-	500[56]$/yr	
Variable O&M Costs	2.52% CAPEX	3.1[16] $/MWh	10[58]% CAPEX	6[59]% CAPEX	15%[60] installation	500[56]$/yr	
Pipe length	-	-	-	-	-	-	180 m
Pipe upgrading costs	–	-	–	-	-	-	300$/m
Annual production							2,086,145 kWh
Capital Cost	870,157	1,200,000 $/yr	187,941 $/yr	92,160 $/yr	744,246 $/yr	1,668,916 $/yr	
Install Cost	847,845	240,000 $/yr	37,588 $/yr	3,398 $/yr	60,000 $/yr	3,700 $/yr	
CAPEX /year	1,718,002	1,440,000 $/yr	225,529 $/yr	95,558 $/yr	804,246 $/yr	1,672,616 $/yr	5,955,952 $/yr
Fixed O&M Costs	-	24,240 $/yr	9,397 $/yr	315 $/yr	-	500 $/yr	
Variable O&M Costs	24,364 $/yr	1,030 $/yr	18,794 $/yr	5,530 $/yr	9,000 $/yr	500 $/yr	
OPEX / year	24,364 $/yr	25,270 $/yr	28,191 $/yr	5,844 $/yr	9,000 $/yr	1,000 $/yr	132,670 $/yr
NPV CAPEX (20 yrs)	1,659,905 $/20yrs	1,391,304 $/20yrs	225,529 $/20yrs	92,327 $/20yrs	777,050 $/20yrs	1,647,898 $/20yrs	5,794,013 $/20yrs
NPV OPEX (20 yrs)	334,567 $/20yrs	347,001 $/20yrs	563,823 $/20yrs	80,255 $/20yrs	123,586 $/20yrs	16,915 $/20yrs	1,466,147 $/20yrs
NPV Production (20 yrs)							40,311,983 kWh/20yrs
Pipeline Upgrade Costs							54,000$
LCOE							0.18
Payback Year							0 year

50 Bauercomp.com. 2023. (Accessed 15 August 2023)

51 Horizon-europe. 2023. Advance materials for hydrogen storage

52 Ramsden, Todd. RNEL. 2013. An Evaluation of Total Cost of Ownership of Fuel Cell- Powered Material Handling Equipment

53 Charles, Kubert. 2010. Clean Energy States Alliance. Fuel Cell Technology.

54 Abdin et al. 2020

55 Nigen International. 2023.

56 Bionaz, David. 2022. Life cycle environmental analysis of hydrogen based energy storage system

57 BEIS. 2021. Levelized cost of hydrogen

58 Dawood, Furat. 2020. Stand-Alone Microgrid with 100% Renewable Energy

59 Vives, Ana Maria V. 2023. Techno-economic Analysis of large-scale green hydrogen production

60 Abdin et al. 2020

Scenario 6. Hydrogen Hybrid Heat Pump System

Table 46. Levelized cost of energy in 2030 for scenario 6 – Hydrogen hybrid heat pump system (system approach is in chapter 4)

Parameter	PV rooftop	Battery	PV Central	Battery Central	Electrolyser	Compressor	Hydrogen Storage	Fuel Cell	Heat Pump	Total
Capacity	92 kWp (6kWp /house)	15 kWh (per house 23 hrs)	266 kWp (475 units)	500 kWh (10 hours)	9 Nm3/h	5.5 kW	7,471 kg (320 m2)	16.21 kW	418.75 kW (16.75 kW /house	
Modul Cost	390[61] $/kWp	200[16] $/kWh	390[16]$/kWp	200[16] $/kWh	3 $/kg	960[62] $/year	2.97[63] $/kg	3,700[64,65]	400[66] $/kW	
Installation Cost	380[16]$/kWp	10[16] $/kWh	380[16]$/kWp	10[16] $/kWh	3[16] $/kg	35.4[22] $/kW	60,000[67] $/year (fixed)	0.20[57] $/kWh	8,800[68] $/year	
Discount rate	3.5%[69]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	3.5%[13]	1.5%[56]	3.5%[13]	
Lifetime	25[16] years	10[70] years	25[16] years	10[14] years	10[16] years	10[71] years	25[72] years		15[12] Years	20 years
Fixed O&M Costs	-	10[16] $/kW	-	10[16] $/kW	5[73]% CAPEX	3.28[22] $/kW	-	500[56]$/yr	1150[12]$/year	
Variable O&M Costs	2.8% CAPEX	3.1[16] $/MWh	2.52% CAPEX	3.1[16] $/MWh	10[74]% CAPEX	6[75]% CAPEX	15%[76] installation	500[56]$/yr	-	
Pipe length	-	-	-	-	-	-	-	-	-	150 m
Pipe upgrading costs	-	-	-	-	-	-	-	-	-	300$/m
Annual production										248,800 kWh
Capital Cost	36,040 $/yr	150,000$/yr	103,778 $/yr	400,000$/yr	22,414 $/yr	21,120 $/yr	88,761 $/yr	199,040	335,000 $/yr	
Install Cost	35,116 $/yr	30,000$/yr	101,117$/yr	80,000$/yr	4,483 $/yr	779 $/yr	60,000 $/yr	3,700	17,600 $/yr	
CAPEX /year	71,157 $/yr	180,000$/yr	204,894$/yr	480,000 $/yr	26,897 $/yr	21,899 $/yr	148,761 $/yr	202,740	352,600 $/yr	1,688,948$/yr
Fixed O&M Costs	-	3,030 $/yr	-	8,080 $/yr	1,121 $/yr	72 $/yr	-	500 $/yr	2,300 $/yr	
Variable O&M Cost	1009 $/yr	354 $/yr	2,906 $/yr	319 $/yr	2,241 $/yr	1,267 $/yr	9,000 $/yr	500 $/yr	-	
OPEX/year	1,009 $/yr	3,384 $/yr	2,906 $/yr	8,399 $/yr	3,362 $/yr	1,339 $/yr	9,000 $/yr	1,000 $/yr	2,300 $/yr	32,760$/yr
NPV CAPEX (20 yrs)	68,751 $/20yrs	173,913 $/20yrs	197,965 $/20yrs	463,768 $/20yrs	25,988 $/20yrs	21,120 $/20yrs	143,731 $/20yrs	202,740 $/20yrs	340,676 $/20yrs	1,638,690 $/20yrs
NPV OPEX (20 yrs)	13,857 $/20yrs	46,463 $/20yrs	142,213 $/20yrs	115,336 $/20yrs	46,169 $/20yrs	18,392 $/20yrs	123,586 $/20 yrs	13,732 $/20yrs	31,583 $/20yrs	449,853 $/20yrs
NPV Production (20 yrs)										4,807,729 kWh/20yrs
Renovation Costs										85,036$
Pipelines Costs										54,000$
LCOE										0.45 $/kWh
Payback Year										126 years

61 ARENA. 2016. Prediction 2030.

62 Bauercomp.com. 2023. (Accessed 15 August 2023)

63 Horizon-europe. 2023. Advance materials for hydrogen storage

64 Ramsden, Todd. RNEL. 2013. An Evaluation of Total Cost of Ownership of Fuel Cell- Powered Material Handling Equipment

65 Charles, Kubert. 2010. Clean Energy States Alliance. Fuel Cell Technology.

66 Ronge, Jan. Francois, Isable. 2021. BatHybuild study. Solhyd. KU Leuven. WaterstofNet

67 Abdin et al. 2020

68 Energy Future Lab. 2022

69 HM government. 2021. Environmental Discount Rate Review.

70 Etronixcenter. 2016

71 Nigen International. 2023.

72 Bionaz, David. 2022. Life cycle environmental analysis of hydrogen based energy storage system

73 BEIS. 2021. Levelized cost of hydrogen

74 Dawood, Furat. 2020. Stand-Alone Microgrid with 100% Renewable Energy

75 Vives, Ana Maria V. 2023. Techno-economic Analysis of large-scale green hydrogen production

76 Abdin et al. 2020

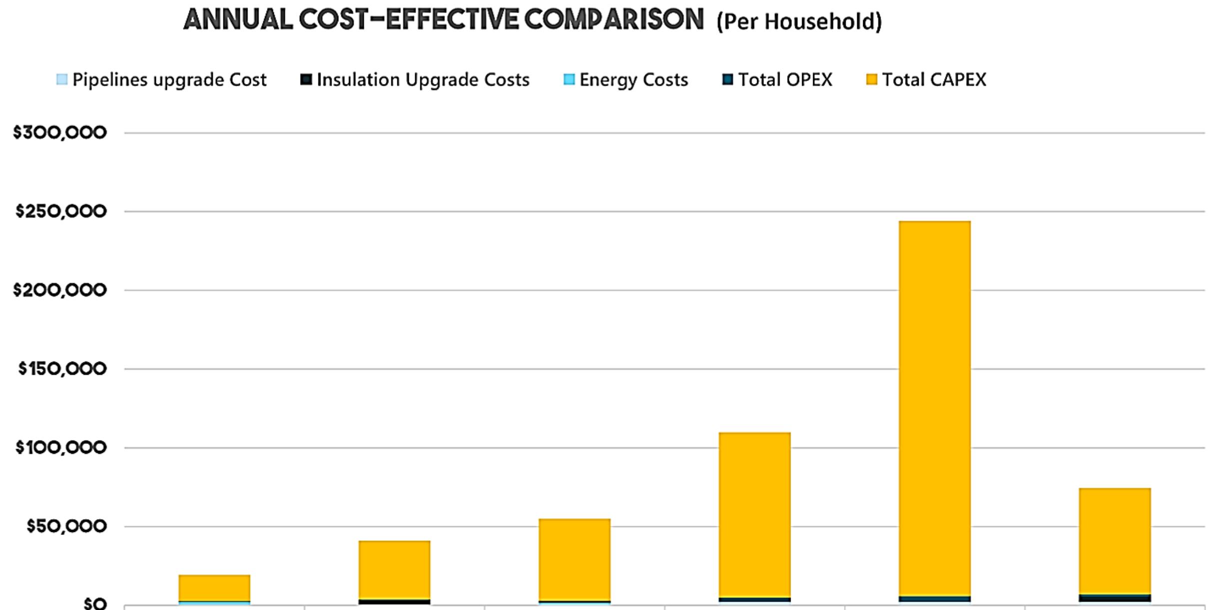
Table 46 presents an overview of the detailed cost analysis of scenario 6, which deployed a combination of hydrogen fuel cell and a heat pump system. This system power is derived from a centralized photovoltaic (PV) setup. What's particularly noteworthy in this scenario is the levelized cost of energy, which emerges as a promising indicator. The is mainly due to the low energy consumption of the system. The system includes a 5.5 kW PV rooftop, a 1,000 kWh batteries, a 9.31 kW of PV central, a 272 kW of electrolyser, 418.75 kWh compressor, 30 cylinders of storages for 7,645 kgs hydrogen, and 16.75 kW boiler per household.

A closer examination Table 46 is illustrated that this particular system translates to reduce the capital expenditures (CAPEX) and operating expenditures (OPEX) in comparison with other hydrogen scenarios. Due to its high efficiency which has overall system efficiency approximately 163%. These financial advantages in the system becoming an economically viable choice.

It is important to highlight that to realize the full potential of this system, considering the use of heat pump in the system, well-insulated houses are required, therefore, an ambitious renovations for insulation are essential. These upgrades focus on glazing enhancements, optimizing the building's thermal performance. The calculated levelized cost of this energy system is projected to be around 0.43 dollars per kilowatt-hour, to remind that in the costs are included the appliances, the operational and maintenance cost, and a discount rate of 3.5% every year.

Overall, the cost effectiveness analysis of the system is promising, even though the initial costs (CAPEX) are high reaches to 67,558$ over the lifetime, but its operational costs are low up to 1,308$ per year, with its levelized cost of energy is in the range of 0.45$ per kWh.

Conclusion of Cost-Effective Analysis



Total CAPEX	$16,832	$37,333	$52,190	$105,233	$238,238	$67,558
Total OPEX	$419	$487	$1,419	$2,654	$3,747	$1,310
Percentage OPEX	2%	1%	3%	3%	2%	2%
Energy Costs	$2,070		$1,449			
Insulation Upgrade Costs		$3,401				$3,401
Pipelines upgrade Cost				$2,160	$2,160	$2,160
TOTAL COSTS	$19,321	$41,221	$55,058	$110,047	$244,145	$74,430

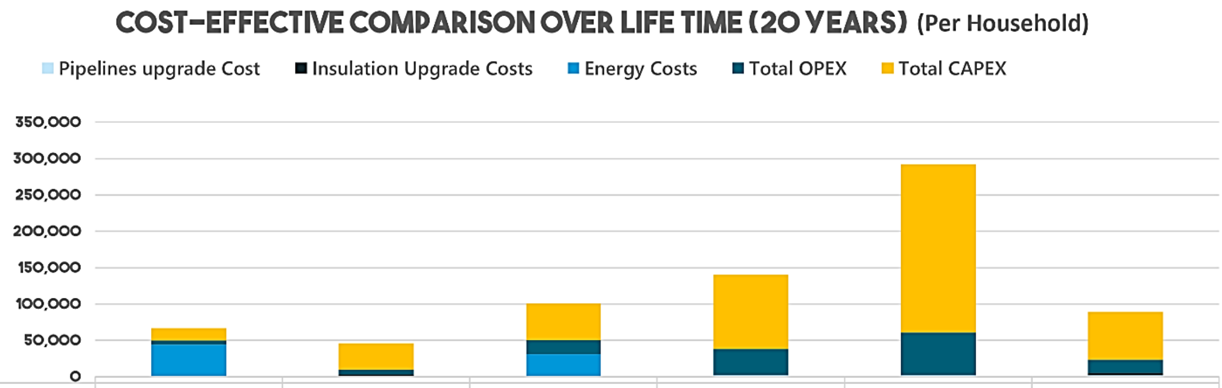
Figure 41. Comparative study of cost effective analysis per year (illustrated by the author)

This comprehensive bottom-up study delved into the exploration of hydrogen systems within the context of buildings, utilizing solar powered as the main source of hydrogen production. An in-depth analysis reveals a notable characteristic of this system – the relatively high capital expenditure. In general, The significant high of capital expenses attributed to the renewable energy infrastructure as numerous of solar panels are applied. In addition of the high CAPEX, the greater investment also contributed to the localized hydrogen production, which in turn, requires more consumption of energy, then requires more increase number of solar power appliances, and batteries either. Therefore, the expenses of related to solar power infrastructure experience an increase.

Figure 41 serves as visual representation of the comprehensive analysis conducted on capital investment, operational maintenance, and fuel expenditures across six distinct energy system scenarios. Notably, it becomes evident hydrogen-based energy systems in Scenario 3, 4, 5, and 6, demonstrate a considerably higher total costs. In fact, these costs range from 3 to 12.5 times higher than the base case or natural gas grid system in *Scenario 1*.

To provide a clear example, *Scenario 3*; natural gas and hydrogen blended system contributes to the most cost-effective among the hydrogen energy systems, accounted for 55,058 dollars per year, compared to the base case just one third of that notable amount. In addition to hydrogen boiler systems, *Scenario 4* which deploys 100% hydrogen gas into the systems, exhibits costs that are doubled than those incurred costs by scenario 3 which applies only 30% of hydrogen blend.

Furthermore, another cost-effectiveness of hydrogen-based system, *Scenario 6*, the hybrid hydrogen and heat pump system, indicates that by considering an additional of 30 thousand dollars of the expenses on *Scenario 2*, this system is enable to incorporate hydrogen fuel cell including available storages in the system. This system is also valuable since hydrogen generation was produced by solar panels, so the fuel costs (natural gas costs) is absence. And the last scenario of hydrogen-based, *Scenario 5*, cogeneration does not yield a favorable result, which concluded that this system may not applicable to run in the future. However, It is important to consider that this prediction may exclude the possibility of where hydrogen demand is increased thus the capital costs would be lower.



Total CAPEX	16,263	36,070	50,425	$101,675	$231,761	$65,548
Total OPEX	$5,750	$6,692	$19,479	$36,442	$58,646	$17,994
Percentage OPEX	35%	19%	39%	36%	25%	27%
Energy Costs	$44,461		$31,123			
Insulation Upgrade Costs		3,401				3,401
Pipelines upgrade Cost				$2,160	$2,160	$2,160
TOTAL COSTS	$66,475	$46,163	$101,028	$140,277	$292,566	$89,103

Figure 42. Comparative study of cost effective analysis over lifetime (illustrated by the author)

To compare the result related to the long-term expenses over a 20-year period, as illustrated in the Figure 42, it becomes evident that the operational and maintenance costs associated with hydrogen are significantly raised to follow its capital expenditure. Approximately ranged from 19% to 39% of the capital expenditures, the operational and maintenance expenditures (OPEX) are calculated. It should be noted that *Scenario 6*, the hybrid hydrogen and heat pump system, exhibits a high performance or the most cost-effective of the total expenditures across other considered hydrogen-based energy systems over Scenario 3,4,5, and 6, including the costs of capital investment (CAPEX), operational expenditure (OPEX), and fuel costs.

Another reveal from findings, for over lifetime period of 20 years, it has been noticed that *Scenario 5*, cogeneration hydrogen fuel cell system which involves the utilization of a hydrogen waste heat fuel cell system, demonstrated a notably higher energy consumption, which it consequents to the increased of energy expenses and more purchase of appliances. Therefore, the capital and operational expenditure will lead to the higher costs.

However, among all the considered energy systems, including both hydrogen and non-hydrogen-based energy systems, *Scenario 2*, all-electric heat pump system is mentioned as the most cost-effective, which elucidates almost half the total costs of the scenario 6, making it relatively economical choice. Other systems on *Scenario 3*, and *Scenario 4* depict competitive results which may decrease its costs in the future where hydrogen demand is increased. These results especially on Scenario 4 may consider high about 2.2 times more than a base case on *Scenario 1*, natural gas grid system.

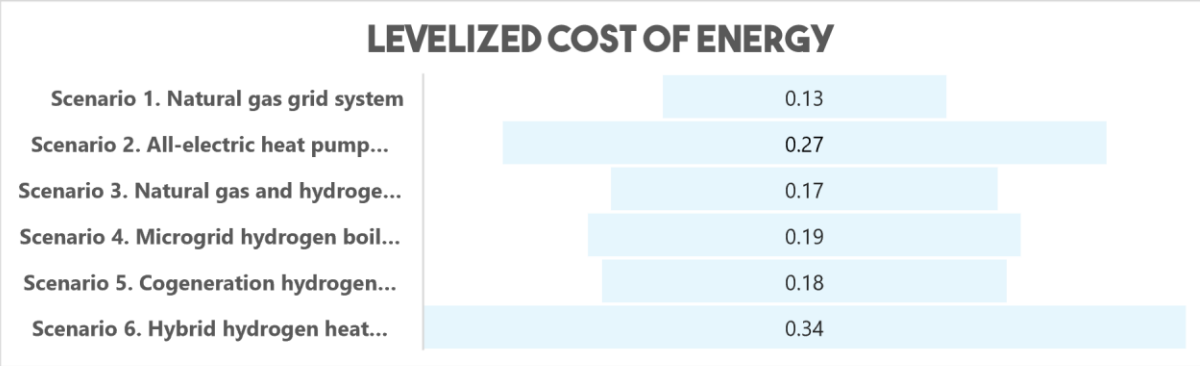


Figure 43. LCOE of six different scenarios in hydrogen production in 25 housings (illustrated by the author)

According to the data presented in Figure 43, it is projected that the levelized costs of various hydrogen sources will be competitive by 2030. A levelized cost of energy on a base case (*Scenario 1,* natural gas grid system) stands at the value of 0.13 dollars per kWh, this value includes an overall system cost which including all appliances, fuel cost, and operational and maintenance costs. In comparison, alternative hydrogen-based energy systems exhibit ambitious cost estimates, ranging from 0.17 to 0.34 dollars per kWh. These figures are significant and align closely with the earlier discussions on cost of hydrogen production from renewable source. As projected by Kevin Knosala et al, it is anticipated that by 2030, green hydrogen will be valued at approximately 0.14-0.18$ per kilowatt-hour. To remind that the renewable sources were related to all sources of renewable energy generation, not just those powered by solar energy as researched in this this study.

Scenario 2, all electric heat pump system reveals a considerable amount of levelized cost of energy about 0.27 dollars per kWh. This cost is considered significant high than other hydrogen-based energy systems due to its additional expenditure of upgrading insulation costs. This upgrading cost is also applied in *Scenario 6,* which employed heat pump on the system. Upgrading insulations are required to meet low temperature of heating by heat pumps, considering ambitious renovations applied in the dwellings. Meanwhile, the levelized cost of energy on *Scenario 6*, Hybrid hydrogen and heat pump system is estimated to 0.34 dollars per kilowatt-hour, the highest amount of the alternatives.

Scenario 3, natural gas and hydrogen blended system is estimated to deliver a levelized cost of energy at 0.17 dollars per kWh, with a difference of 0.04 dollars than a base case utilizing 30% of green hydrogen blended into the gas. This is considered significant but valuable since hydrogen gas fuel was produced local solar powered. Moreover, it would be more worthy if the use of hydrogen is increased to 100% into the grid. Where an increase value of 0.02 dollars to 0.19 dollars per kWh was estimated in this scenario (*Scenario 4*, Microgrid hydrogen boiler system).

Scenario 5, where deploying a waste-heat of fuel cell for heating, cogeneration hydrogen fuel cell system represents a compelling result which predicted at 0.18 dollars per kWh. This value considered low with other hydrogen-based energy system, as a result of another production of electricity within the system by fuel cell, therefore, the production of electricity from solar powered is decreased, thus the number PV installations were also decreased.

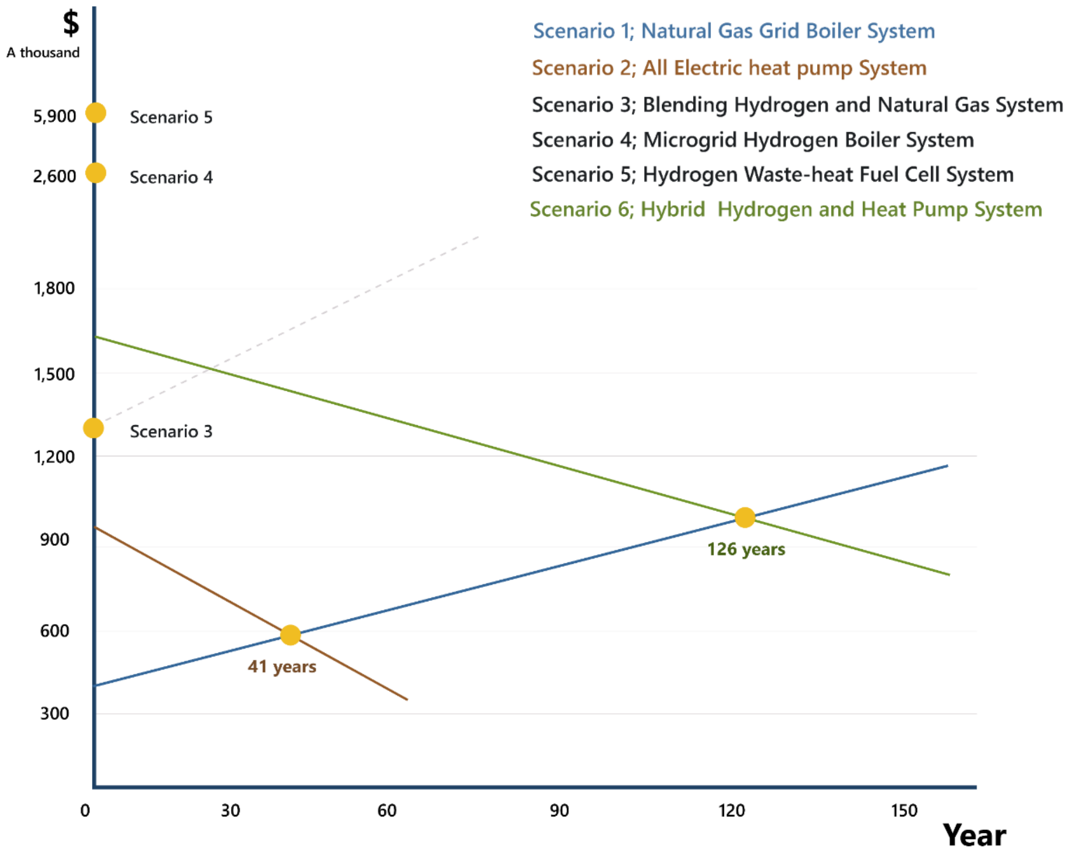


Figure 44. Payback time in six different scenarios of hydrogen systems (illustrated by the author)

Payback time is calculated by dividing the initial investment by the annual energy savings of the systems, which every attribute of the scenarios are referred to the base case. It is evident from the Figure 44 that hydrogen may increase the payback ratio in the energy system along with the rise of capital investment and the number of devices applied in hydrogen production. In another hand, the total generation of energy in the systems also plays important roles, which explained as the more total generation of energy, the higher annual energy costs will be produced. Therefore, the shorter of payback time will eventually be resulted.

Scenario 2 and 6 perform relevant payback ratios which calculated to 41 and 126 years respectively than of Scenario 1, natural gas gris system. These scenarios delivered effective systems and consumed less energy sources which effect on the positive valuable payback ratio. A negative payback ratio occurred in Scenario 3, 4, and 5 which apparently could not meet generating enough returns to recover the initial investment cost within the expected timeframe. Despite the high upfront cost of the energy, the low revenue or savings by the systems can cause this result, which generate very less energy cause low efficiency, which cost savings or costs generated by the project are not sufficient to cover the investments. Therefore, the payback ratio may be extended, leading to a negative ratio.

8. CARBON EMISSION EQUIVALENT ASSESSMENT

The dominant process for hydrogen production is currently Steam Methane Reforming (SMR) of natural gas which considered as the highest rank of carbon equivalent emission of hydrogen production. In this process, the greenhouse gas (GHG) emissions intensity reaches up to 8.9 to 11.9 kg CO_2e per kg of Hydrogen [117] However, since the energy used to produce hydrogen is renewable, producing it through electrolysis will not produce any emissions. In this research, green hydrogen powered by solar panels is utilized in hydrogen production, considering the prediction of 2050 that an half of the renewable hydrogen demand would be delivered by solar electrolysis.

Conducting a Life Cycle Analysis is to examine the environmental impact including the emissions of the raw material extraction, production, and distribution in the system. The production of electricity is also included, photovoltaic manufacturing and operation will always present in every stage. Other than that, the transportation and the construction of the power plant, as well as the operation into the system will be taken into account. Process of electrolysis is included in the process of hydrogen production in scenario 3,4,5, and 6. However, hydrogen which has no direct emission yet the operation and maintenance or production of the raw materials contributes such emissions in the local plant. The method compare in this paper are shown in Figure 45 appealed the methods compared in this study is given.

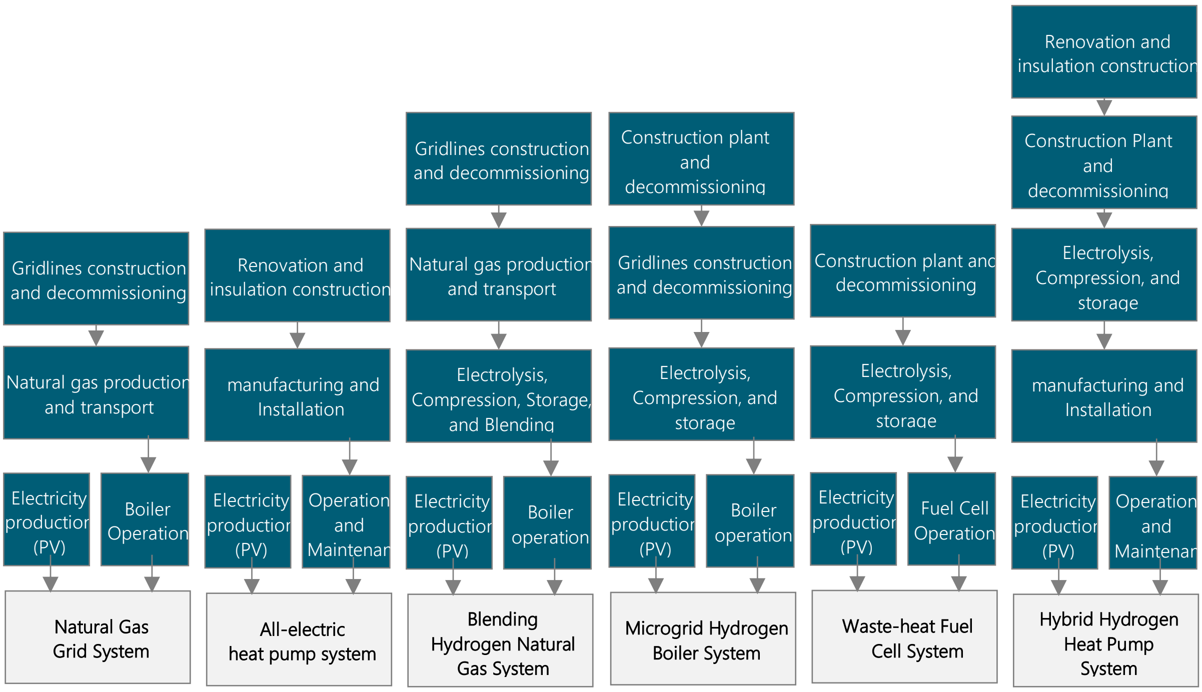


Figure 45. Scheme Stages of 6 different scenarios of life cycle emissions assessment (illustrated by the author)

The assessment presented below employs a mathematical method that relies on energy consumption data obtained from a sample of recently renovated buildings, a light renovation data, which represents typical current renovation practices these days. However, with the exception of scenarios 2 and 6, where a heat pump is incorporated into the system, an ambitious renovation data is applied which also takes into account the enhancement of insulation during the construction procedures.

8.1 Carbon Emissions Equivalent Analysis

In scenario 1, a base case; Natural gas grid system, which reflects the prevalent heating system in English homes which approximately 90% relying on natural gas [118]. Various emissions are produced and expelled through channels or tubes. The emissions encompasses range of substances, including Nitrogen Oxides (NOx), Carbon Monoxides (CO), and Carbon dioxide (CO_2), Methane (CH4), nitrous Oxide (N2O) volatile organic compounds (VOCs), trace amounts of Sulfur dioxide (SO2), and particular matter (PM). However, not all these emissions contribute equally to the overall greenhouse gas (GHG) effect. Specifically, during the combustion, the CO2 emissions factor assigned to natural gas boilers amounts to 233 grams of CO^2e/kWh. Methane emissions, on the other hand, contribute approximately 10 mg per kWh, while Nitrogen oxide emissions are estimated at about 2 mg/kWh. Table 47 provides a detailed breakdown gasses during boiler operation.

However, it is important to note that natural gas emissions are not limited to direct emission during boiler operation. The life cycle analysis of natural gas also encompasses grid transmissions and transportation, which play significant roles in its overall carbon footprint. Carbon emissions in this phase primarily originate from two key sources, First, during the operation of the heater utilities, there are direct emissions released. This including leakage of pipelines resulting carbon emission released in the atmosphere.

Assessing the possibility of leakage from gridlines is a crucial aspect. Mitchell et al. conducted a study on the UK's natural gas distribution system, revealing a leakage rate exceeding 1.9%. This rate falls somewhere between the Medium and High case scenarios, estimating between 5.3% and 10.8%. In this analysis, the small hole leakage is assumed, where the internal pressure of the pipeline remains constant, preventing the gas from rubbing against the pipe walls. Consequently, this study maintains that a leakage rate of approximately 1% of the gas supply will be considered.

Table 47. Average Air Emissions of natural gas grid system (Cetinkaya et al, Mitchell et al, Casasso et al.)

Description	Average air emissions	(g/kWh)	(g/kWh)
Pipe Construction (initial) [119]	Carbon dioxide (CO_2)	3.95	
	Carbon Monoxide (CO)	0.01	
	Nitrogen Dioxides (NO_2)	0.02	
	Nitrous Oxides (N_{2O})	0.00	
	Non-methane hydrocarbons (NMHCs)	0.03	
	Particulates (PM)	0.11	
	Sulfur Oxides (SO)	0.11	
	TOTAL		4.25
Natural gas production and transport [119]	Benzene	0.03	
	Carbon dioxide (CO_2)	28.22	
	Carbon Monoxide (CO)	0.1	
	Methane (CH_4)	5.64	
	Nitrous Oxides (NO_2)	0.18	
	Nitrous Oxides (N_2O)	0.00	
	Non-methane hydrocarbons (NMHCs)	0.26	
	Particulates (PM)	0.01	
	Sulfur Oxides (SO)	0.11	
	TOTAL		34.55
Leakage [120]	1 % of Natural gas transport	0.0345	0.0345
Gas Boiler [121]	Carbon dioxide (CO_2)	233.582	
	Methane (CH_4)	10.669	
	Nitrous Oxides (N_{2O})	2.368	
	TOTAL		235.60 g/kWh
Air Emissions on a system	Grand Total		274.40 g/kWh

As the electricity is generated through solar powered, direct emissions from photovoltaics are considered. And the use of photovoltaics are not emit any air emissions during operation. However, to comprehensively asses the environmental impact, carbon emissions equivalents during manufacturing and transport are compared. Table 48 explains the quantity of carbon emissions equivalents on the photovoltaics.

Table 48. Carbon emissions resulting from the PV Solar process

Description	Processes	Carbon emissions eq. (g/kWh)
PV Solar [119]	Materials and manufacturing of PV modules	45.63
	Transportation	13.85
	Wiring	1.81
	Installation	1.12
	Operation & Maintenance	4.84
	Decommissioning and Disposal	1.85
	TOTAL (PV solar plant construction and modules)	69.10* g/kWh

Regarding the construction of gridline installation, Table 49 explains the specific information on the calculation of carbon emissions during the construction process, measured per meter. In this study, which takes place in Hanley, which encompasses grid connection of approximately 180 meter within one block consist of 25 houses, the emissions are calculated at 1.07 kg per meter. Consequently, the construction process in this context results in emissions of approximately 193 kilograms.

Table 49. Carbon footprint emissions of the construction process of gridline instalment (Weigert, Maximilian. 2022)

Process	Kg CO2eq Emissions per m
On-site product manufacturing	0.37
Transport within the site	0.57
Installation of the pipes	0.12
Removal of waste and disposal	0.01
TOTAL (construction and gridlines)	1.07 kg CO^2eq/m^2

While the total emissions of carbon dioxide equivalent prediction in this system is presented in Table 50.

Table 50. Average carbon emissions of natural gas grid system

Process	Energy Consumption (kWh)	Average emissions (g/kWh)	Total Emissions (kg)
Natural gas production [119]	588,075	4.98	2,929
PV solar (for electricity demand) [119]	86,405	69.1*	5,971
Air emissions Boiler Operation	588,075	274.40	161,369
Construction and gridline installment [119]	180 (m)	1070 (g/m)	193
TOTAL			170,461 kg

From the data, it becomes evident that primary contributors to carbon emissions are the air emissions from boilers operation, accounting for about 94% of the total carbon emissions. Additionally, emissions from the manufacturing of PV systems also significant impact. Surprisingly, the emission caused by natural gas production represents only placed 6% of total emissions.

In scenario 2, the use of heat pumps is explored as means to reduce carbon emissions in domestic heating. The carbon emissions associated with heat pump depend on the source of the electricity. In this study, solar panels generate the electricity, resulting in no direct emissions. However, emissions from other sources, such as infrastructure, construction upgrades, and material manufacturing, are taken into account. The study also considers the lifecycle emissions of the products and its disposal.

Improving insulation during construction phase can lead to substantial energy savings over the building's operational lifetime. This is due to the synergy between heat pumps and well-insulated buildings, resulting in significant energy savings and increased overall energy efficiency. However, it is crucial to acknowledge that emissions can occur during the construction process due to various factors associated with material production, transportation, and installation. Table 51 provides an overview of the total carbon emissions in different processes of construction stage for ambitious insulation per square meter.

Table 51. Carbon footprint emissions of the construction process of upgrading insulation (Weigert, Maximilian. 2022)

Process	Kg CO2eq Emissions per m^2
On-site product manufacturing	0.00
Transport within the site	0.20
Installation of the insulation	0.27
Removal of waste and disposal	0.26
TOTAL (insulation upgrade)	0.73 kg CO^2eq/m^2

As a result of implementing insulation improvements in the renovation project, the carbon footprint is reduced to approximately 730 grams per square meter within the neighbourhood. Consequently, if the entire neighbourhood undergoes renovation, the cumulative carbon footprints would be approximately 2,168 kilograms. On the other hand, the deployment of heat pumps comes with the potential for accidental emissions of refrigerants. Most heat pumps currently use hydrofluorocarbon (HFCs) as refrigerants, which have a short atmospheric lifetime but high global warming potential (GWP). According to International Energy Agency (IEA), HFCs accounted for about 2.5% of global greenhouse gas (GHG) emissions in 2019 [3]. However, specialized maintenance, recycling, and the use alternative refrigerants in heat pumps can reduce emissions resulting from the leakage. In this study, a large capacity of 84 kW air source heat pumps is utilized, for which Intergovernmental Panel on Climate Change (IPCC) suggests a possible leak rate in the range of 2-2.5% (IPCC, 2005). Thus, equates to 2% per year operating leak rate in this scenario.

In this area, the usage of pipelines is no longer required due to the absence of gridlines installation, Instead, connections are established through the utilization of air source heat pumps, powered by local photovoltaics. This approach has the potential to reduce the carbon footprint associated with steel pipelines and mitigate pipe leakage.

Table 52. Carbon emissions profiles of Scenario 2, all electric heat pump system

Processes	Energy Consumptions (kWh)	Average emissions CO_2e (g/kWh)	Total Emissions (kg)
Refrigerants use and 2% leakage [123]	108,746	163	17,726
Manufacturing, Equipment and installation [123]	108,746	17.19	1,869
Heat pump operation and maintenance [124]	108,746	15.25	1,658
PV solar (PV air emissions on Table 45) [119]	86,405	69.1	5,971
Insulation Upgrade	2970 (m^2)	730 (g/m^2)	2,168
Air emissions	108,746	0.00	0.00
TOTAL			29,392 kg

According to the statistics provided in Table 52, the cumulative carbon emissions within the neighbourhood amount to 28 tons per neighbourhood consisting of 25 residential properties. In contrast to natural gas boilers, it is apparent that it has the capability to reduce emissions significantly by up to 83% when powered by photovoltaic energy. However, the predominant factor contributing to emissions in this system is the utilization of refrigerants, accounting for about half of the overall emissions. In the next upcoming paragraphs, scenario of 3,4,5 and 6 will be discussed and the production of hydrogen is analyzed, utilizing solar powered with varying life cycle analysis released,

In scenario 3, a blend of hydrogen and natural gas is employed to meet the demand. Considering the consumption of 247 MWh of energy is needed to run the heating system. Thus, 458 units of 600 watt peak photovoltaic capacity is run to balance the demands. Hence, with 1,647 m^2 of photovoltaics local production is employed in this scenario. The emissions of PV production and manufacture will be accounted for in this system. Table 53 is presented the life cycle analysis of carbon emissions per lifetime project of this system.

Table 53. Life cycle emissions stages of Scenario 3. Natural gas and hydrogen blended system

Processes	Energy Consumptions (kWh)	Average emissions CO_2e (g/kWh)	Total Emissions (kg)
Natural gas production [119]	411,652	4.98	2,050
PV solar (for hydrogen production) [119]	254,578	69.10	17,591
Electrolysis process and compression [119]	254,578	6.40	1,628
PV solar (for electricity demand) [119]	86,405	69.10	5,971
Air emissions Boiler Operation	411,652	274.40	112,957
Construction and gridline installment [119]	180 (m)	1070 (g/m)	193
TOTAL			140,390 kg

As indicated in Table 53, the overall life cycle emissions value in this scenario exhibits a significant change of carbon emissions released in the atmosphere. However, it is hypothesized that incorporating a 30% hydrogen blend into natural gas grid system can potentially result in approximately 48 tons reductions per year of carbon emissions. On the other hand, if compared to a complete hydrogen microgrid system it is more valuable as it does not release any carbon equivalent emissions.

In scenario 4, a larger number of photovoltaics are applied due to fully support the Microgrid hydrogen boiler system. To balance the substantial energy consumption of 848 MW, 1,513 units of solar panels with 600 watt peak capacity of each panel will be employed in 3,220 square meter area. However, another additional emissions of upgrading pipelines will also involve in this scenario will explains in Table 54.

Table 54. Carbon footprint emissions of the construction process of the pipelines upgrade (Weigert, Maximilian. 2022)

Process	Kg CO2eq Emissions per m^2
On-site product manufacturing	0.37
Transport within the site	0.57
Installation of the insulation	0.12
Removal of waste and disposal	0.26
TOTAL (pipelines upgrade)	1.32 kg CO^2eq/m^2

Table 55 explains the stage of processes how fully hydrogen solar-powered can decrease carbon emissions in Scenario 4 - Microgrid hydrogen boiler system.

Table 55. Carbon emissions assessment of Scenario 4. Microgrid Hydrogen Boiler system

Processes	Energy Consumptions (kWh)	Average emissions CO_2e (g/kWh)	Total Emissions (kg)
Plant construction [119]	848,592	20.29	17,218
PV solar (for hydrogen production) [119]	848,592	69.10	56,638
Electrolysis process and compression [119]	848,592	6.40	5,428
PV solar (for electricity demand) [119]	86,405	69.10	5,971
Construction and gridlines installment [119]	180 (m)	1,070	193
Pipelines upgrade [119]	180 (m)	1,320	238
Air emissions	848,592	0.00	0.00
TOTAL			87,684 kg

It is evident that the contribution of direct emissions in this area is practically obsolete, as there are no air emissions contributed. This is due to hydrogen production is generated from solar energy, which produces minimal emissions, primarily in infrastructure and supply chain activities. Therefore, despite the capital investment and emissions associated with construction activities, the overall emission can be reduced by up to 37%. The major contributors to emissions in this scenario are related to PV manufacturing and production emissions, accounting for over half of the total emissions.

In scenario 5, the used of fuel cell is implemented, and emissions from fuel cells are primarily associated with maintenance and operation, with minimal emissions released. Notably, there are no direct emissions, as the system primarily results in water vapour. The construction phase only pertains to the hydrogen plant, which involves the construction of the heating network, plant maintenance, and other activities aimed at emissions reduction. Table 56 provides an overview of the total carbon emissions in this Scenario 5.

Table 56. Carbon emissions of life cycle assessment of Scenario 5. Waste heat Fuel Cell

Processes	Energy Consumptions (kWh)	Average emissions CO_2e (g/kWh)	Total Emissions (kg)
Plant construction [119]	2,086,145	20.29	42,328
PV solar (for hydrogen production) [119]	2,086,145	69.10	144,153
Electrolysis process and compression [119]	2,086,145	6.40	13,344
Fuel Cell Operation and maintenance	2,086,145	2.48	5,174
Air emissions		0.00	0.00
TOTAL			204,998 kg

While the system does not release direct emissions, the extensive use of photovoltaics leads to significant emissions during their manufacture. In fact, approximately 70% of the total emissions in this scenario can be contributed to the production of PV.

Scenario 6 entails a complex process that integrates various systems. This system includes insulation upgrades, with a higher degree of insulation compared to other scenarios. The renovation encompasses modifications to windows glazing, flooring and enhancements to the walls. However, in this system, an enhancement of glazing will be provided, as other improvements have been done in the light renovation before applying this ambitious renovation. For the comprehensive overview of the carbon emissions equivalents within the scenario, refers to Table 57.

Table 57. Total carbon emissions equivalent of Scenario 6. Hybrid hydrogen heat pump system.

Processes	Energy Consumptions (kWh)	Average emissions CO_2e (g/kWh)	Total Emissions (kg)
Plant construction [119]	248,800	20.29	5,048
Manufacturing, equipment and installation	248,800	17.19	1,485
PV solar (for hydrogen production) [119]	248,800	69.1	17,192
Electrolysis process and compression [119]	248,800	6.40	553
Fuel Cell Operation	248,800	2.48	617
Heat pumps operation and maintenance	248,800	15.25	3,794
Refrigerants use and leakage (2%)	248,800	163	40,554
PV solar (for electricity demand) [119]	86,405	69.1	5,971
Upgrading insulation renovation	2,970 (m^2)	730	2,168
Air emissions	248,800	0.00	0.00
TOTAL			81,213 kg

Within this scenario, approximately 49% of the total emissions are attributed to refrigerant use and leakage, with another 21% arising from PV manufacturing emissions. The reminder is derived from the operation of the plant, the heat pump itself, and the renovation upgrades, which collectively contribute only 2% of the overall emissions.

Despite the complex layout of this scenario, the overall carbon emissions equivalent in comparison to the other alternative hydrogen systems is the most minimal. This observation is substantiated by the data, which reveals that energy consumption directly impacts carbon emissions. The less energy used, the lower the carbon emissions, and the hybrid hydrogen and heat pump system demonstrates the potential to reduce carbon emissions by around 45% when compared to the regular natural gas system.

Conclusion of Carbon Emissions Analysis

Based on the comprehensive data collected during the previous life cycle analysis, it becomes evident that hydrogen is renewable energy sources that does not contribute any emissions while operation. However, emissions in the production, manufacturing, transportation of the various components, and activities associated within the system still result in the release of carbon emissions. Figure 46 illustrates a graphic of carbon emission equivalents which corresponds to a reduction in carbon emissions during one year and over the lifetime.

In scenarios involving fossil fuel resources, the simple heating system process has a minimal processes and heating system. However, direct emissions of air pollutants have a substantial effect, accounting for over ninety percent of the emissions in the entire life cycle analysis.

The incorporation of thirty percent of hydrogen into natural gas has been found to reduce air pollutants by up to 34% compared to a system solely reliant on natural gas, resulting in decrease of approximately 48 tons per year. However, the remaining emissions in this system are primarily caused by the complex processes associated with hydrogen production.

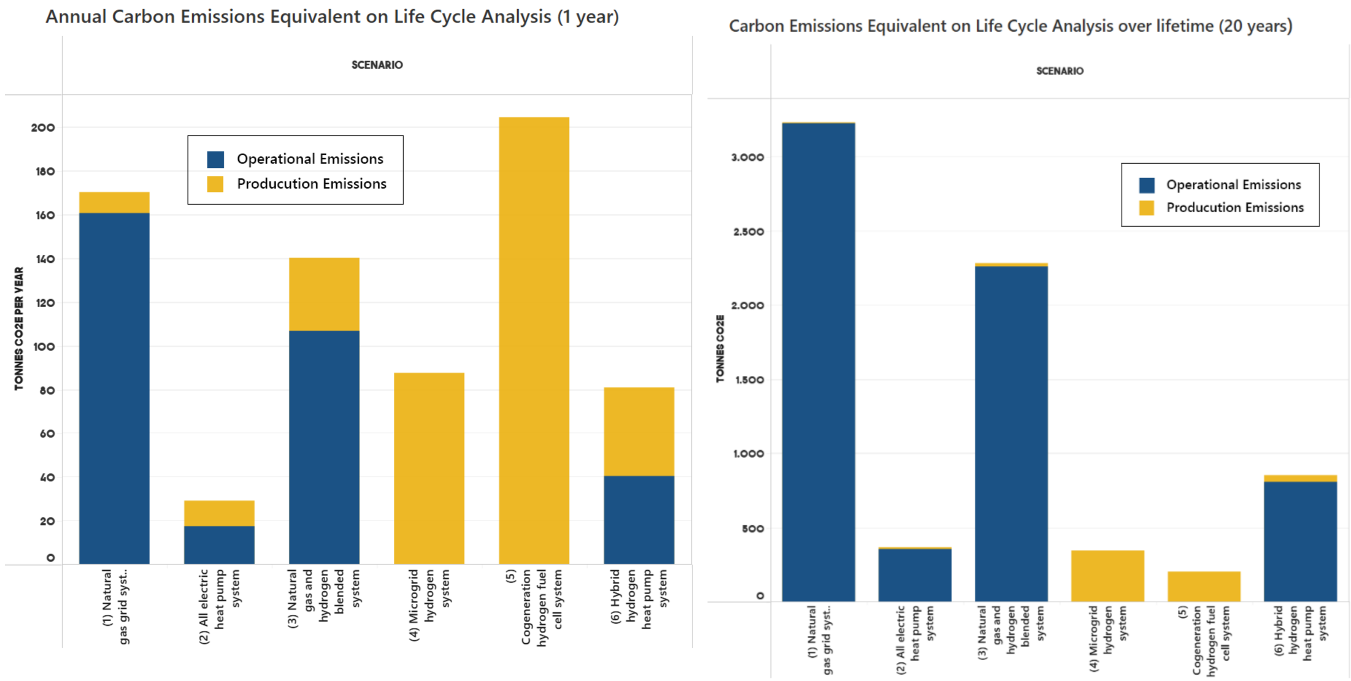


Figure 46. Graphic illustration comparison of Annual carbon emissions equivalents across six different system (author illustration)

In the other hand, the utilisation of a full hydrogen sources in Scenario 4 and 5 have yielded less emissions with absence of operational emissions. This represents a significant step toward the integration of renewable energy sources into the existing system. However, it is essential to acknowledge that the emissions also depends on how hydrogen is generated, since utilizing solar powered, the hydrogen is completely free operational emissions.

Additionally, when incorporating heat pumps into a hydrogen system; namely Hybrid hydrogen and heat pump system results in significant reductions over a lifetime. In this Scenario 6, the total emissions comprises approximately a double than a heat pump solely system, which primarily it is contributed by the leakage of the pipelines. It is concluded that hydrogen systems show potential results to develop in the near future since there is no emissions occurring in these systems. Figure 47 highlights the specific sources of emissions across six different scenarios based on the process of each system.

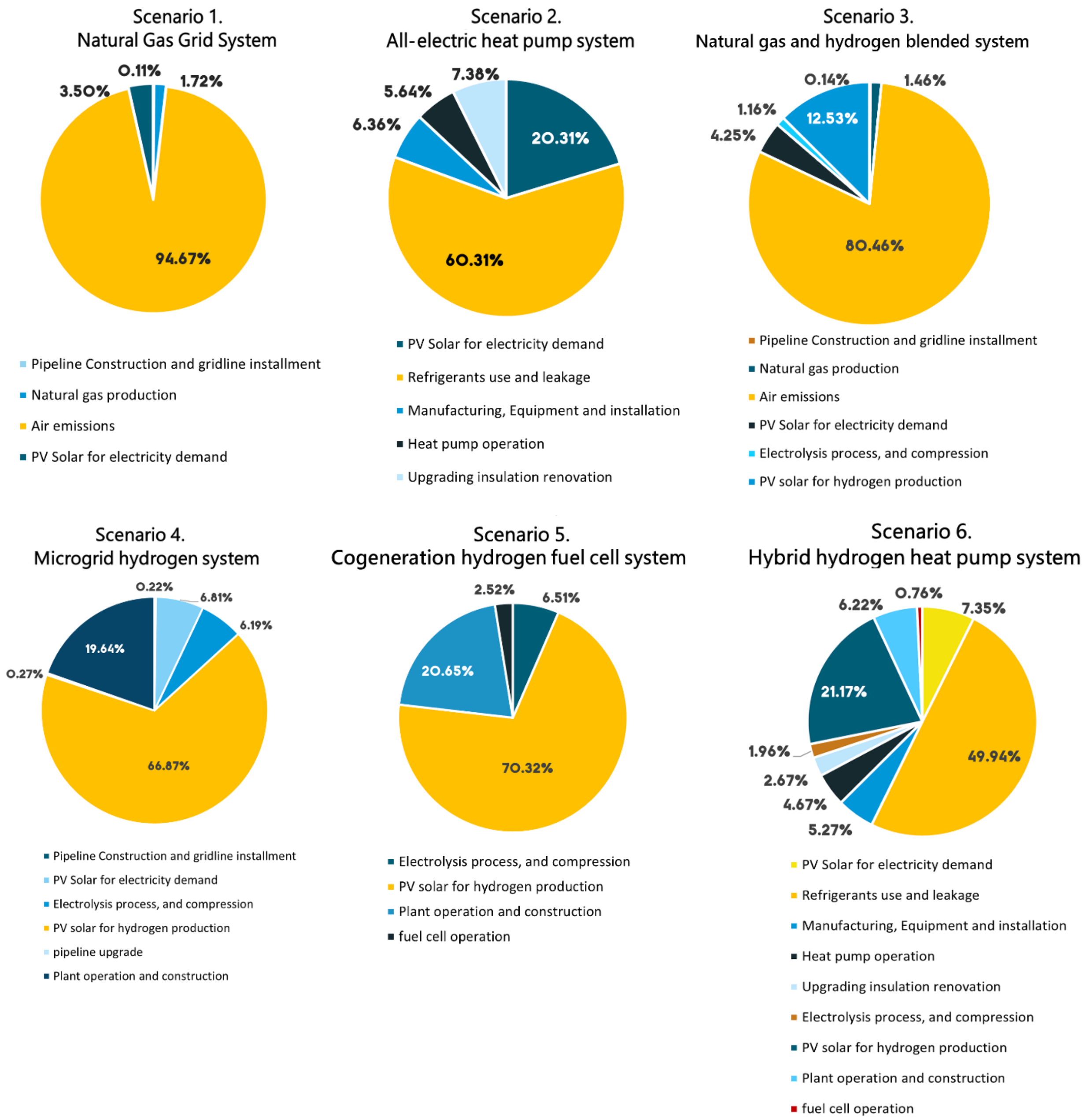


Figure 47. Pie chart of the emissions contribution in each life cycle process (illustrated by the author)

The comparison charts in Figure 47 highlight several crucial factors across six different systems per year. There are some key values which considered performs vital in the whole systems. In fossil-based systems, in Scenario 1 and Scenario 3 air pollutions have major impacts. The air pollution caused by the operation of natural gas in the system and through the leakage of the pipelines has contributed to more than 80% of each system.

On the other hand, in Scenario 4 and 5, which incorporating a fully hydrogen into the systems, does not emit any operational emissions, primarily contributed to the production emissions of the components . And for Scenario 2 and 6, a significant impact of emissions fell to the leakage of refrigerants and the production emissions including construction, and gridlines instalment. The renovation for installation upgrade also contributes less than ten percent to the total emission per system.

HyStreet Facility sits at the end of the most complete onshore ‘beach to burner’ demonstration of hydrogen. HyStreet provides the domestic end-use with 100% hydrogen boilers providing heating, Northern Gas Network’s H21 project demonstrates distribution in the below 7 barg regime and National Grid’s currently- under-construction FutureGrid facility will demonstrate transmission in large diameter, high pressure systems (up to 70 barg).

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9. DISCUSSION AND RECOMENDATION

9.1 Analysis of three different criteria

A comparative analysis was conducted in this study with the aim of understanding the possibilities of integrating hydrogen into buildings. The previous chapter discussed the criteria related to energy consumption, cost effectiveness, and carbon emissions. There are six distinct scenarios involving current and future energy system technologies, including the use of hydrogen. It is an unarguable fact that the all-electric heat pump system provides the most impressive performance in all aspects. However, this system requires high capital costs for its upgrades. In this regard, the insulation must be improved since the use of the heat pumps for heating purposes requires low temperature conditions. Despite its high upfront costs and expenses for insulation upgrades, this system has a high efficiency of 360%, which covers most of the entire nets in the radar chart displayed in Figure 47. During the winter, however, the availability of energy from solar power sources is limited due to decreasing solar yield. Therefore, the integration of hydrogen into the heating system may have the potential benefit of increasing energy availability during this period.

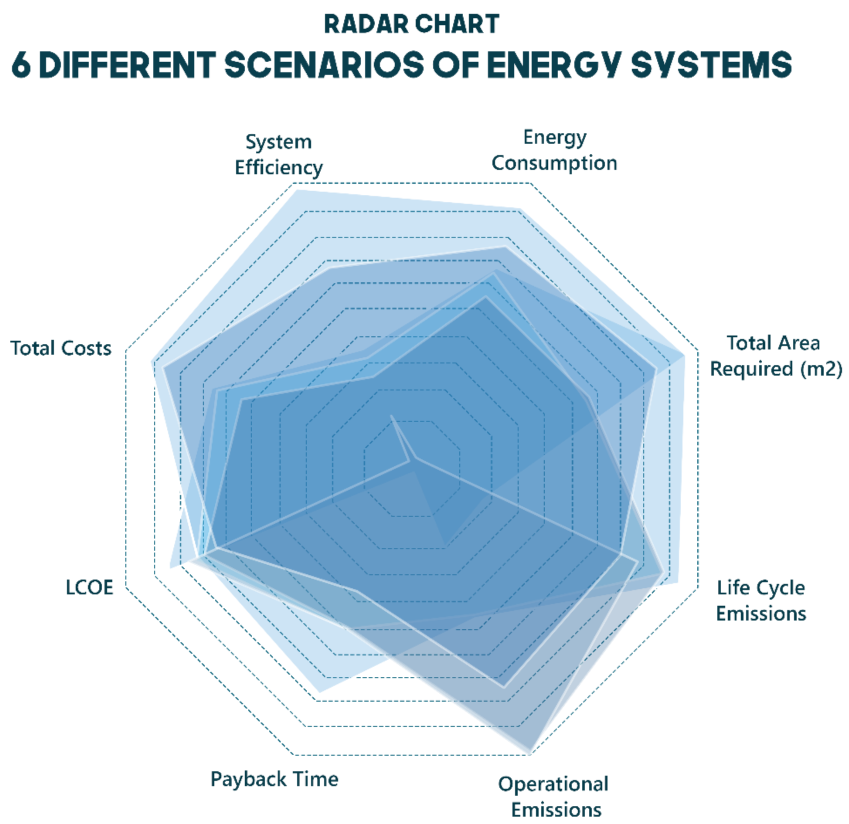

Figure 48. Compilation of six different scenarios of energy system (illustrated by the author)

Hydrogen Hybrid Heat Pump System can be regarded as a visible solution for providing energy in the cold season. However, as clearly depicted in the radar chart, this system achieves about 75% of the entire nets. This is because this system also needs high capital costs which has an impact on the extended period of payback. As hydrogen does not release air emissions to the atmosphere, although there are still possibilities of refrigerant leaks in the heat pumps. In addition, the energy costs of this system is also considered low due to the reduced energy consumption, with a total efficiency of 163%. This is impressive, considering that the use of heat pumps makes this system able to achieve over one hundred per cent efficiency despite the complexity of the hydrogen production process. This proves that the application of this system can save more energy and has its own appeal for cases with collective heating.

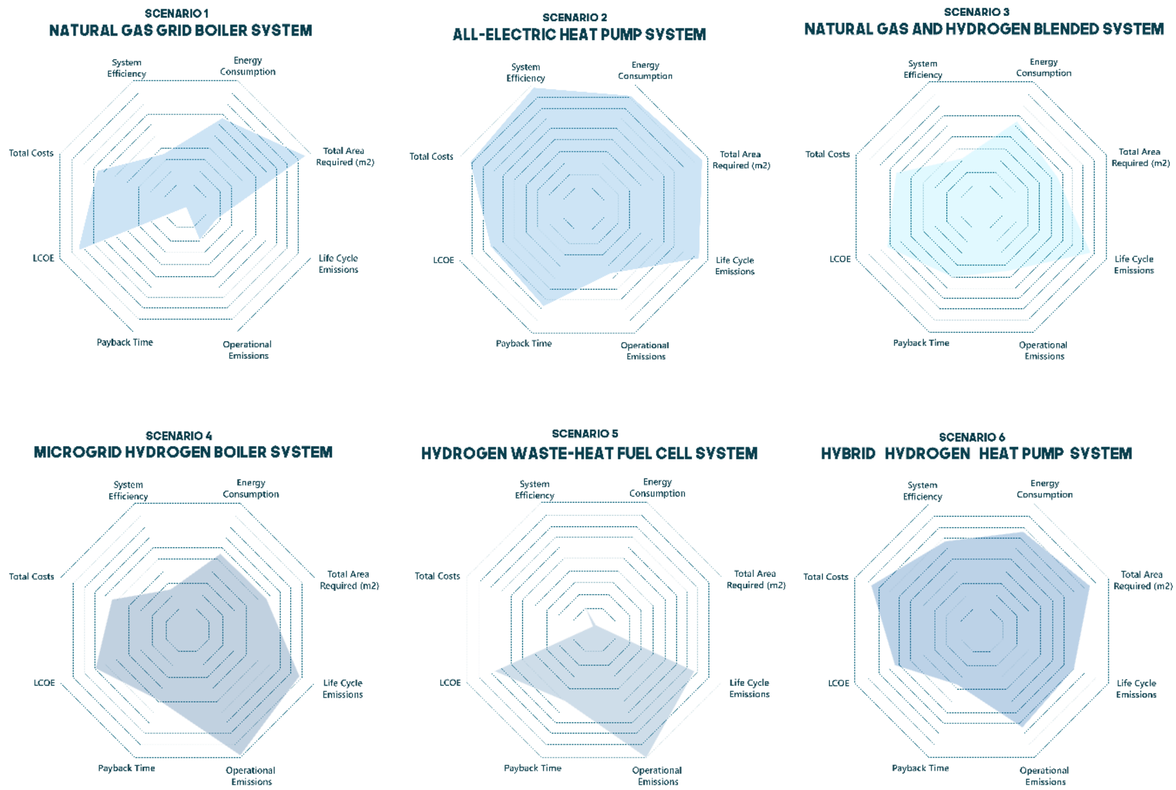

Figure 49. Result of multicriteria analysis in sic different scenarios of energy system (illustrated by the author)

Although having a slightly higher initial investment cost, the utilisation of a Hydrogen Microgrid Boiler System can serve as a viable alternative to Hydrogen Hybrid Heat Pump System. However, the implementation of such system requires upgrading grid infrastructure and improving regular boilers to hydrogen boilers. Hence, this system is deemed suitable for application to a collective heating system as it has the potential to reduce costs associated with pipeline upgrades. Nevertheless, the proximity of the hydrogen source to the designated area must still be taken into account. Furthermore, the potential for green hydrogen production using solar power sources is dependent upon the solar yield. In terms of overall efficiency, this system achieves a level of approximately 60% efficiency. This system also releases no air emissions, although the emissions generated during the construction, manufacturing, and maintenance processes are observable.

When discussing the integration of natural gas into the regular system, both Scenario 1 (Natural Gas Grid System) and Scenario 3 Natural Gas and Hydrogen Blended System) exhibit favourable performance in terms of energy consumption and total efficiency. Specifically, Scenario 1 achieves an energy consumption rate of 86%, while Scenario 3 has a total efficiency of 76%. However, during the operation, these aforementioned systems release a substantial amount of carbon emissions into the atmosphere, amounting to 161,369 tonnes of carbon equivalents. By incorporating a 30% hydrogen into the system, this emission level can be significantly reduced to 112,957 tonnes of carbon emissions. This is consistent with the decarbonisation plans set for 2050, which entail a gradual transition from natural gas to renewable energy sources. For this purpose, the potential for developing a full hydrogen boiler system will be highly recommended, therefore no emissions emits in the atmosphere. However, it must be noted that even though these systems will remain accessible for several years, its longevity will be limited as fossil fuel technologies will eventually be replaced by newer net-zero technologies.

One example of a system with suboptimal performance is the waste-heat hydrogen fuel cell system, as showed in Figure 42. This particular system has been identified as a less efficient option; it is depicted in a small form in the figure as it only relies on utilising the waste heat generated by the fuel cells, resulting in a low production efficiency of 35-40% and a low total system efficiency of only 24%. While this system produces surplus electricity that can be converted and stored as hydrogen, it still falls to adequately fulfil the requirements of a heating system as the energy production significantly outweighs the heating demand.

For the reasons above, the utilisation of hydrogen through a waste heat fuel cell system is potentially incompatible. The potential utilisation of hydrogen can be further explored with other possibilities of using hydrogen through fuel cells or boilers.

9.3 Long-term Heating Strategies and Hydrogen Forecast in 2030

The momentum behind hydrogen is strong. Nine countries – accounting for around 30% of emissions from the global energy sector today – have released their national strategies in 2021-2022 including The UK [125]. The announcements of new projects and pilot projects for hydrogen in domestic applications are abundance, however, only 5% of them have taken firm investment decisions due to uncertainties around the future evolution of demand. There is a lack of clarity about regulations and infrastructure available to deliver hydrogen to end users. Despite these uncertainties of hydrogen deployment plans, the future availability of hydrogen by 2030 needs to be addressed. Clear policy targets are strongly needed to send out appropriate signals to consumers and market actors.

The projection of Net Zero Energy scenario requires the sales of fossil fuel being shifted gradually along with the improvement of hydrogen deployments in The UK, especially within the neighbourhood of Stoke-On-Trent. Strategies related the specific utilization of hydrogen for domestic needs may consider to how it should be prioritized for, regarding the high investment costs the market demands. This condition may not be applied in scenarios where there is an increase in hydrogen supply as a result of a decrease in hydrogen production costs and a simultaneous rise in demand.

Since heat pumps are found to occupy the highest performance and obtain supports from the government, the production of heat pumps is expected to increase from 55,000 in 2021 to 600,000 by 2028., This proves that all-electric heat pump system is still regarded as an excellent option and has the potential to be developed further as it has been found more efficient than the other heating systems. Therefore, the government is advised to prioritise removing significant barriers to its implementation, including significant high upfront costs compared to the gas boilers. Expansion of the use of heat pumps throughout the UK, along with clear training and reskilling strategies, are also necessary to support the transition to low carbon heating.

Despite various advancements of hydrogen technologies, the window of opportunity for a rapid transition to adjusting net zero-emission energy system is narrowing. Numerous studies are currently assuming that the next step will be taken due to the substantial growth of hydrogen although it is still considered inefficiency and full of complexity. However, hydrogen will not play a big role in the heating system of buildings and the neighbourhoods before 2030[6]. In the meantime, the government may push the transition of blending hydrogen into the existing system and be available to support the transition before it is fully deployed into hydrogen boilers, by also considering grid instalment upgrades. It is predicted that by 2030 onwards, green hydrogen will be produced in larger scales due to increasing industrial and transportation applications, and then become more cost-effective in the built environment. The use of hydrogen boilers is beneficial when low temperature heating is not available or when all-electric heating is not possible. Yet, when low temperature heating is available, the all-electric heating system which covers the most heating demand in domestic purposes is still more preferrable.

Integrating Combined Heat and Power (CHP) in the heating system for buildings is particularly interesting. While fuel cells only produce a sixth of the total energy, with the addition of heat pumps will be able to meet more heating demand with low energy consumption. This may be efficient if hydrogen production is not limited. However, in fact, solar yield in Stoke-On-Trent is extremely low during winter. In December, for instance, with 950 square metre of PV panels, there is a mismatch between the heating demand and the energy production; PV panels only produce 5,645 kWh, whereas the heating demand reaches 29,072 kWh. This is where hydrogen can take a part. As long as the heat pumps are still potentially applicable while electricity is supplied, they can be prioritised as the heating system. When the energy demand reaches its peak, hydrogen fuel cells will play a role in meeting the demand, ultimately saving the use of hydrogen and the production of energy. This system will also be especially useful in areas with a considerable distance from the electrical grid. This can also be seen from the utilisation of hydrogen in new neighbourhood which has the potential for a local green hydrogen production.

9.4 Hydrogen as a Peak Shaver (System optimized in Hybrid hydrogen & Heat Pump)

Hydrogen when utilizing as a peak shaver offers significant value in improving the overall efficiency of energy systems, particularly in addressing seasonal variations in energy production and demand. This configuration proves advantageous in maximizing the utilization of the heat pump, known for its ability to minimize energy consumption. In the context of this hybrid hydrogen and heat pump system, the utilization of a controller is essential for establishing a schedule that not only preserves the existing workflow but also leverages the advantages of a smart integrated building system. This ensures that energy resources are managed optimally and that the system operates efficiently while adapting to changing environmental conditions and demands.

9.4.1 Annual set up of hybrid hydrogen and heat pump system

Understanding the hourly energy demand enables the system to allocate energy resources effectively. By analyzing this data, also provides insights into specific hours or seasons to peak or fall, guiding the selection the most suitable energy source of heating, whether from hydrogen or a heat pump. Figure 50 presents the energy demand model for 25 houses, revealing that during the period between hour 3800 and 6400, roughly spanning mid-May to mid-September, the energy demand remains relatively low. Interestingly, the result of some heating demands during that period, still exist although in the summer days. Upon closer examination of the model, the excel model apparently in simplified simulation where the result appears overestimated.

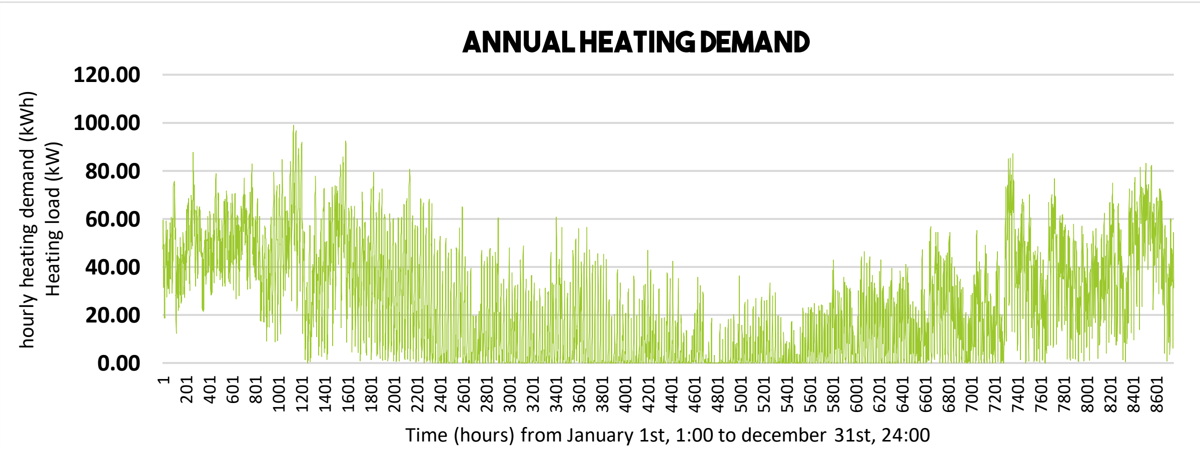

Figure 50. Hourly energy demand of 25 houses (one block)

In this study, the system is controlled to respond the specific environmental conditions; including temperature, solar radiation, and peak hours. These factors are critical in determining an optimal operational schedule that ensures its performance and efficiency. Solar radiation data, in particular, plays a central role in determining the availability of sunlight. Figure 51 provides a visual representation of solar radiation. Indicating that sun consistently rises throughout the year with varies amount from 20 to 1000 during its peak in warm days. During the day in winter the solar radiation is relatively low and during summer it reaches its higher amounts.

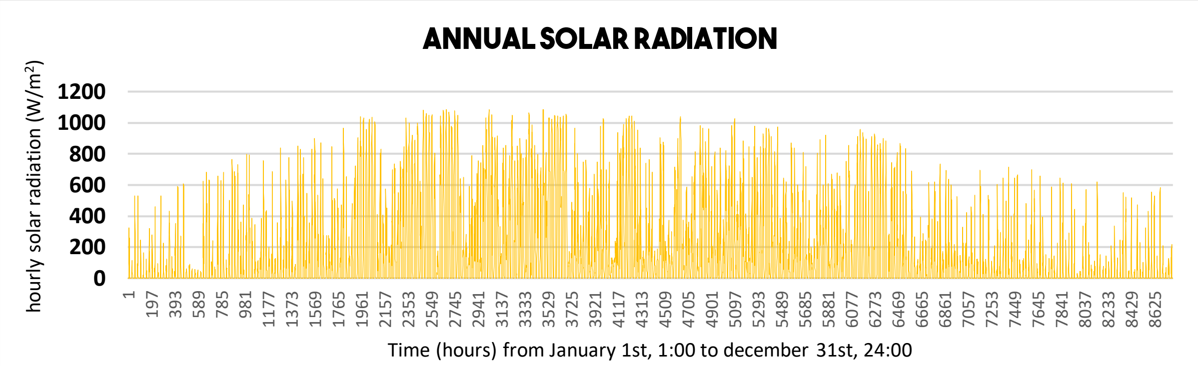

Figure 51. Solar radiation in Hanley, Stok-On-Trent through the year

With the implementation of this control system, the overall system efficiency has been greatly improved, resulting in remarkable 191% of energy consumption. Figure 52 illustrates the annual energy consumption for both configuration of a heat pump and hydrogen. It is evident that, despite the high energy demand demonstrated in Figure 50 even during summer or winter, the control system effectively curbs energy usage, preventing the excess use of energy.

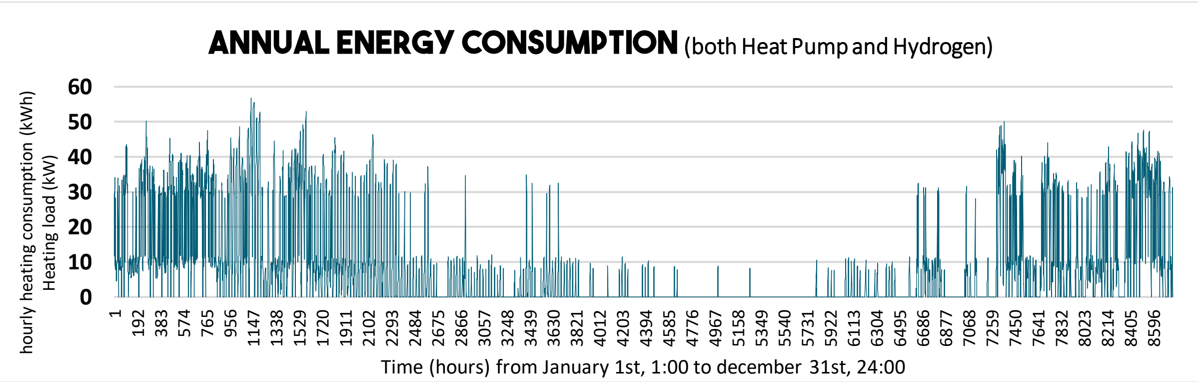

Figure 52. Annual energy consumption in Hybrid hydrogen and heat pump system within 25 households

Figure 53 corresponds the hourly use of heat pump, which reaches a static capacity of 12 kW, but is maintained at a lower demand level. Furthermore, this usage remains consistent daily, except during the summer season when it is intelligently controlled to minimize the energy. The detail use will explain in monthly set up of the control system.

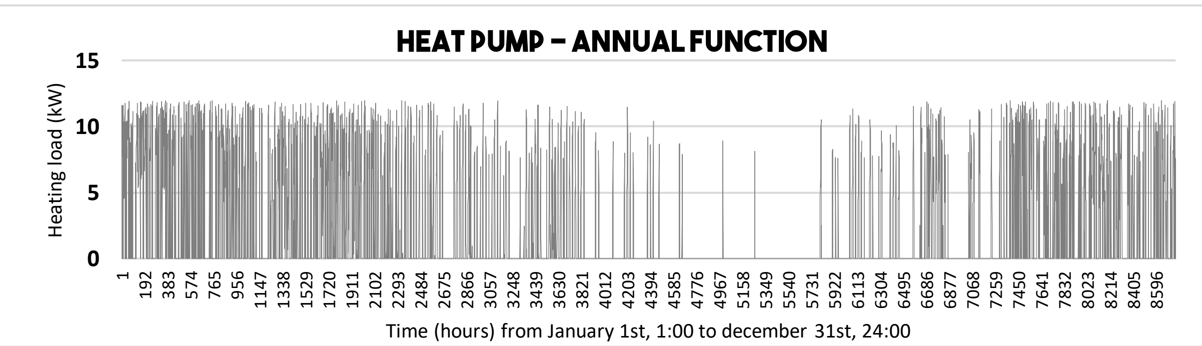

Figure 53. Heating Consumption through heat pump application in Hybrid hydrogen and heat pump system within 25 households

To complement the system, hydrogen comes into play during high peak demands, especially in cold hours when temperatures drop below the average, during periods of low solar yield, or when the demand exceeds the maximum hourly capacity. Consequently, hydrogen is activated to ensure a consistent energy supply under these challenge conditions.

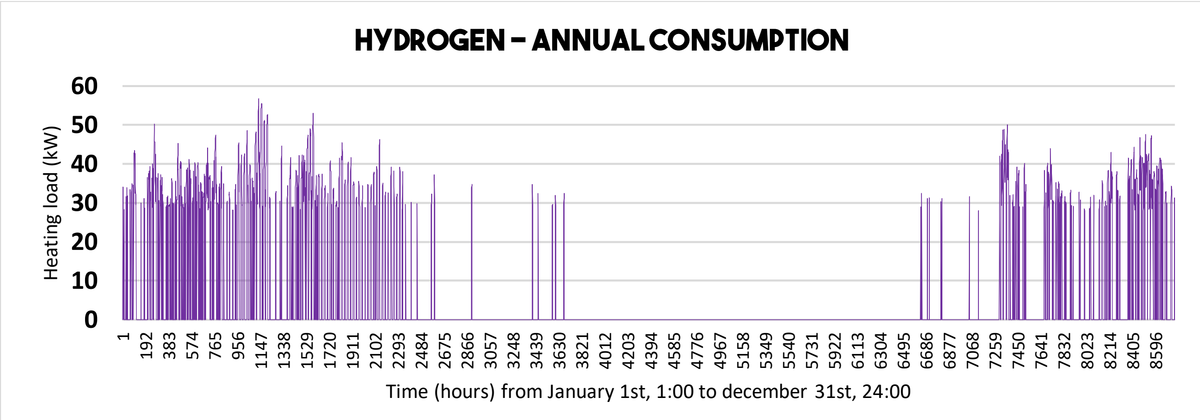

Figure 54. Heating consumption through hydrogen application in Hybrid hydrogen and heat pump system within 25 households

As a versatile component of the system, hydrogen bridges the gap in energy supply during adverse conditions, ensuring a reliable and uninterrupted operation. It serves as a backup solution when other utilities or sources may fall short.

In the subsequent explanation of how the system control operates, will delve into the specific details of how smart integration of hydrogen and a heat pump optimizes energy efficiency and enhance overall performances.

9.4.2 Monthly set up of hybrid hydrogen and heat pump system

The operational control has undergone trials and errors to identify and refine the parameters that contribute to the most efficient energy consumption. As a result, the optimization eventually relies on three parameters; including air temperature, solar radiation, and peak capacity on every hour. These variables then will be adjusted and applied on the control setting. Table 58 describes the parameters that guiding the control operation in Hybrid hydrogen and heat pump system.

Table 58. Parameters of a control setup in Hybrid hydrogen and heat pump system

No	Parameters	1		2		3	
		Bare Minimum	Remark	Average	Remark	Limit Maximum	Remark
A	Temperature	<9.84 °C	A1	9.84 °C (to 18°C)	A2	18°C	A3
B	Solar Radiation	0 W/m2	B1	750 W/m2	B2	>750 W/m2	B3
C	Heat load hour (25 households)	<48.9 kWh	C1	48.9 kWh (to 98.99 kWh)	C2	>98.99 kWh (Max amount in data)	C3

No	Heating with Hydrogen source	Heating by a Heat Pump	Heating turn off
1.	A1	A2	A3
2.	B1, B2	B1, B2	B3
3.	C2, C3	C1	

The following steps outline how the system dynamically responds to environmental conditions and the energy demand. The system works as follows:

- High Temperature. Firstly, when the temperature falls within the range of 18-28.22 degrees Celsius or exceeds this range, the system ensures that the heating is completely turned off. This prevents unnecessary heating when the temperature is completely or excessive hot. However, an advance dynamic control when the temperature exceed this range can also be switched to a cooling system.
- Low-Temperature solar heating. In conditions where there is sunlight but the temperature is relatively low, the system activates heat pump to provide heating. Along with solar energy with available to store as hydrogen. This ensures energy efficiency by harnessing solar energy directly when maintaining comfort.
- Lowest Temperature. Additionally, when there is sunlight, but the temperature is at its lowest, the system prioritizes heating via hydrogen. This method utilizes hydrogen source to provide effective heating during extremely cold conditions.
- Low to Average Capacity. When the heating demand ranges from zero to average heating capacity, the heat pump is activated to generate the required heating.
- Average to Maximum Capacity. In cases where the heating demand exceeds the average capacity but remains within the maximum capacity, the system activates the hydrogen source.
- Excess Capacity. If the energy demand excess the maximum average heating capacity of the system, it automatically switches to hydrogen to meet the increased demand. This prevents overloading the heat pump

The control system dynamically adjusts between the heat pump and hydrogen sources, optimizing energy utilization. It ensures that heating demands are consistently met while minimizing the energy consumption. As demonstrated in Figure 55, this adaptability showcases the system's responsiveness to varying conditions, reinforcing its efficiency and optimization.

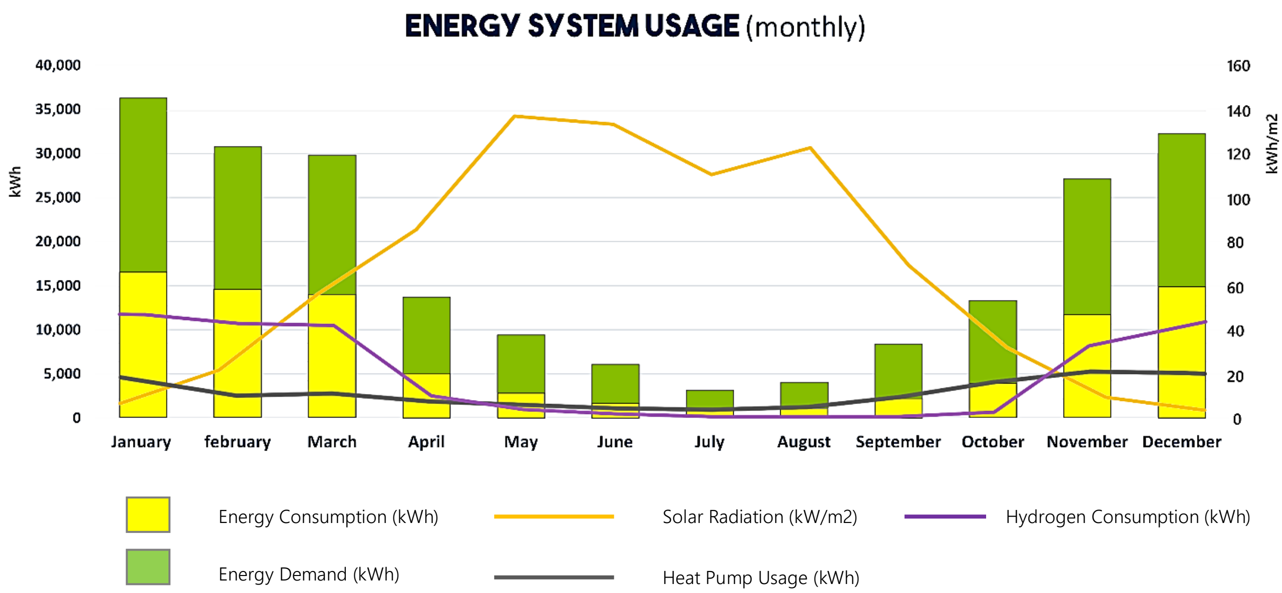

Figure 55. Hybrid Hydrogen heat pump as peak shaver (graphic is illustrated by author)

9.4.3 Daily set up of hybrid hydrogen and heat pump system

To provide a detailed breakdown of the hourly settings for the Hybrid and heat pump system, Figure 56 offers an insight into the daily configuration on Januari 1st. The graph illustrates the highest heating demand occurring during the early morning and evening hours. In January, with temperatures ranging from 3.02 to 9.35 degrees Celsius, heating remains active throughout the day to maintain comfort.

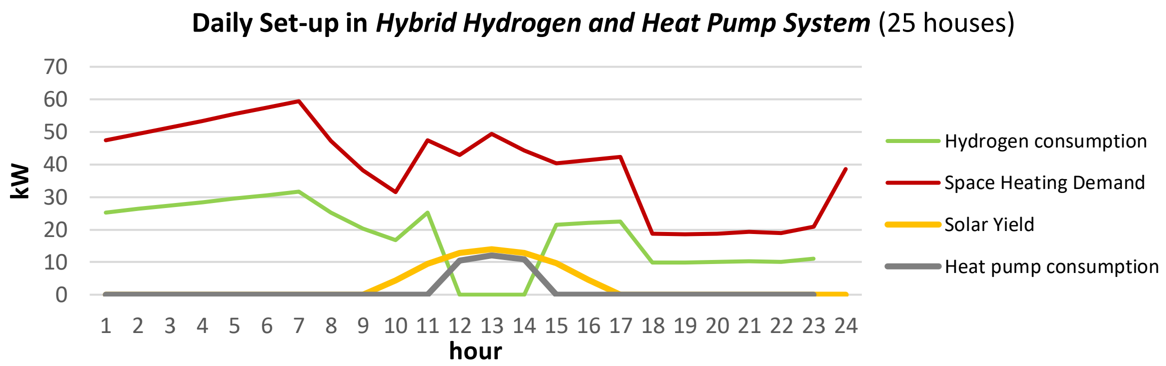

Figure 56. Daily set-up in Hybrid and Heat pump system within 25 houses in 1st of January.

Furthermore, the graphic indicates that even during winter season, solar radiation is present, as in this calculation, it is started between 12 to 3 pm, with an intensity range from 55 to 177 watts per square meter. During these hours, a low-temperature heating system, operated by the heat pump, is the most effective. However, in the peak hours of the early morning and evening, hydrogen takes over to meet the heightened demand. The more detailed setting is explained as follows:

- Hours 0-6: Hydrogen is fully utilized as there is no solar yield during this period.
- Hours 7-12: Increased activity during these hours results in higher hydrogen consumption, which subsequently decreases as solar radiation begins to rise.
- Hours 13-18: Solar yield reaches its peak this timeframe, allowing the heat pump to take the lead. Consequently, hydrogen consumption is minimized.
- Hours 19-24: As solar yield diminishes, hydrogen is reactivated to meet the demand.

Overall, this dynamic control strategy, which alternates between heat pumps and hydrogen, proves to be cost-efficient and energy-saving. However, continued research into scheduling and other parameters remains crucial for further system improvement.


HydroTown

10. NEIGHBOURHOOD SCALE IMPLEMENTATION

10.1 System Analysis in the Neighbourhood

A hybrid hydrogen with heat pump system is a promising technology that can provide efficient and sustainable heating, where the stored hydrogen can fulfil the heating demand in a cold season. This seasonal energy storage benefits the system when large amount of heating demand is needed. This system utilises a fuel cell to generate electricity, which is then used to power a heat pump. The heat pump extracts heat from the outside air and transfers it inside the home, providing an efficient heating.

With regard to the utilisation of hydrogen, several challenges need to be addressed, including the high investment cost and the infrastructure to distribute hydrogen. However, the advantage of hydrogen which emits no air emissions should be considered as a sustainable solution for the energy system. As the technology continues to develop, the cost of these systems is expected to decrease, along with the cost-effectiveness of the upfront costs and the safety measurements of the hydrogen use.

Despite these challenges, the hybrid hydrogen with heat pump system has the potential to revolutionise the way homes are heated. This system can be applied in areas where hydrogen grid is in far distance, or in new neighbourhoods with potential local green hydrogen production.

Table 59. Comparison between regular System Hybrid Hydrogen Heat Pump and Hybrid system as Peak Shaver

Description	1 Block (25 Dwellings)		1 Neighbourhood (234 Dwellings)
	Regular	Peak Shaver	Peak Shaver
Energy Demand	484,113 kWh	484,113 kWh	4,375,889 kWh
Energy Consumption	335,205 kWh	229,455 kWh	2,147,702 kWh
CAPEX over lifetime	$65,548 /house (20 years)	$47,600 /house (20 years)	$41,148 /house (20 years)
OPEX	$17,994 / house (20 years) OR	$14,003 /house (20 years) OR	$ 6,570/house (20 years) OR
	$1,310 /house /year	$1,020/ house /year	$478/house /year
LCOE	$0.34	$0.34	$0.24
Payback Time of a Base Case	126 years	33 years	26 year
Efficiency	163%	211%	190%

As explained in the previous chapter, in the regular system, a hybrid hydrogen with heat pump system operates not efficiently. When heating is required, the stored hydrogen from electrolyser production will be employed and the fuel cell will start to operate producing electricity. This electricity from fuel cell will generate heat pump to produce heating to cover the demand. In result, it requires less energy than hydrogen boiler system of up to a third of its energy consumption. Thus, optimisation is necessary to use this system efficiently.

In the optimized system, by utilizing this system as a peak shaver, the demand for energy consumption can be reduced. When heat pump is recognised for the most efficient heating system, the utilisation of heat pump by the source of direct solar-powered electricity will be prioritised. Then, to minimise the high hydrogen usage during winter or in the evening when the heating demand reaches its peak, the stored hydrogen will play a big role. About 25 houses using regular and peak shaver scenarios in the hybrid hydrogen and heat pump system are compared in this study. The number of dwellings in one housing block then extends to 234 in one neighbourhood. Table 59 presents the comparison of the use of hybrid hydrogen with heat pump system. Meanwhile, the comparison of the components of the system which can be seen in Table 60.

Table 60. Component comparison between regular and peak shaver use of hybrid heat pump and hydrogen in 25 and 234 houses

Description	1 Block (25 Dwellings)		1 Neighbourhood (234 Dwellings)
	Regular	Peak Shaver	Peak Shaver
PV rooftop	92 kWp, 7 units	92 kWp, 7 units	865 kWp, 432 units
Individual Battery	15 kWh / house, 1 unit	15 kWh / house, 1 unit	15 kWh / house, 1 unit
PV central	266 kWp (950 m2)	162 kWp (600 m2)	1,516 kWp (6,000m2)
Battery Central	1 MWh (7 hours)	562 kWh, (281 kWh 2 stacks) (4 hours)	6 MWh (1 MWh 6 stacks) (4 hours)
Electrolyser	9.6 Nm3/h (10 Nm3/h 1 stack)	5.25 Nm3/h (10 Nm3/h 1 stack)	55 Nm3/h (30 Nm3/h 2 stacks)
Compressor	5.5 kW 1 unit	5.5 kW 1 unit	32 kW (16 kW 2 stacks)
H2 Storage	7,471 kg 350 bar (320 m3) (58 cylinders)	3,358 kg 350 bar (174 m3) (24 cylinders)	42,577 kg 350 bar (1,821 m3) (308 cylinders)
Fuel Cell	16 kW	7.3 kW	92 kW
Heat Pump	418.75 kW	418.75 kW	3,919 kW
TOTAL AREA (exterior) (interior)	1,327 m^2 (950 m^2) (377 m^2)	765 m^2 (600 m^2) (165 m^2)	8,176 m^2 (6,000 m^2) = 110 m x 55 m (2,176 m^2) = 50 m x 44 m

10.2 Peak shaving application within the system

A strategy is designed to manage and optimise energy consumption during periods of high demand or a peak load. This system combines two technologies, namely heat pump and stored hydrogen, to efficiently provide heating and cooling services while ensuring energy availability when it is needed most. Figure 57 outlines how this system works, including the conditions where each appliance is activated and operated efficiently.

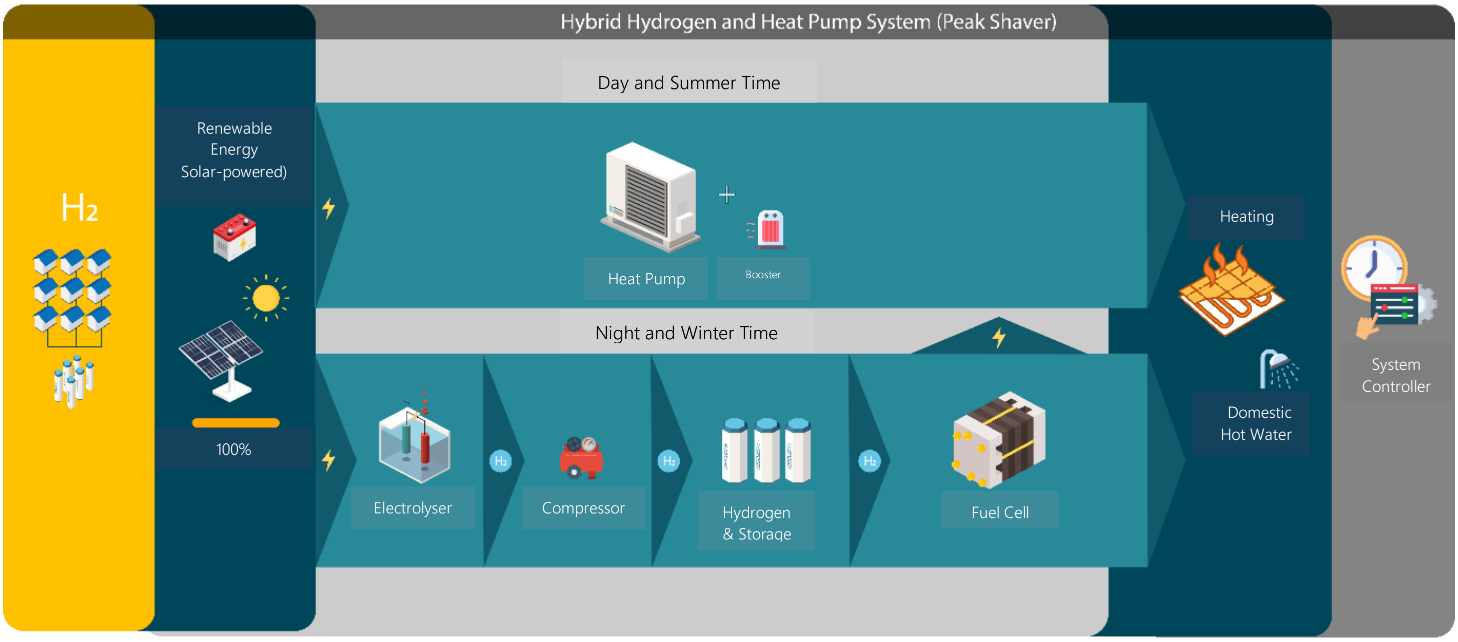

Figure 57. The illustration of how hybrid hydrogen and heat pump use as a peak shaver (illustrated by the author)

A heat pump is an energy-efficient device that transfers heat from a lower-temperature sources to a higher-temperature space. In this study, air source heat pump which can provide both heating and cooling by reversing its operation is utilised. Additionally, hydrogen is used in this system as an energy carrier and storage. During periods of low energy demand, surplus electricity is used to electrolyse water and produce hydrogen, which is then stored for later use. Meanwhile, fuel cell functions to produce electricity with a certain amount of waste heat produced. When the electricity is produced, heat pump will convert it to heating for efficient energy consumption. In this system, however, heat pump activates regularly with the hydrogen energy. This will consume high amount of hydrogen, thus requiring more storages.

The following is how the peak shaver scenario works. During low heating demand, the heat pump operates directly using electricity from the grid or other renewable sources. This is the most energy-efficient mode of this system. Surplus electricity generated from renewable sources (solar power) can be used to electrolyse water to produce hydrogen, which will later be stored to serve as an energy reservoir.

When there is an increase load in energy demand or during peak periods, the system switches to stored hydrogen as the primary energy source. The stored hydrogen is converted back to electricity through a fuel cell. This electricity is then used to power the heat pump to meet the increased heating or cooling demand. This will allow the system to avoid drawing additional power from the grid during peak demand, thereby reducing the strain on the grid and potentially avoiding higher electricity costs during peak hours. This peak shaver can be used to control the flow of energy between the heat pump, the hydrogen fuel cell, and the thermal storage system, ensuring that the system is operating efficiently and that the peak demand of electricity is reduced. The use of peak shaver in a hybrid hydrogen and heat pump system can be beneficial for both the grid and the environment. Some benefits of this system are:

- Decreased peak demand for electricity. This can help to reduce the need for new power plants or solar panels and decrease the capital costs of the system
- Increased system efficiency. The heat pump can operate more efficiently when the demand is lower.

Overall, the use of a peak shaver in a hybrid hydrogen and heat pump system can be a way to improve the efficiency and sustainability of the domestic energy system.

10.2.1 HydroTown; Hydrogen implementation in the neighbourhoods

The integration of hydrogen into the local community of Stoke-On-Trent represent a pioneering step towards decarbonization. By harnessing the power of solar energy, this innovative initiative is poised to make a profound impact on approximately 234 households residing within a 104,319 square metre area. This paradigm shift by a visionary project then known as *HydroTown,* centres around the implementation of photovoltaics fields on 8,176 square meter outdoor area which placed on an idle space at the front of the neighbourhood. This location is suitable as a welcome sign before entering the neighbourhood. For safety reasons, this hydrogen plant is not located in the border, but rather situated further away from the residential area. To produce the demand of 1,417 GWh of hydrogen, approximately 6,000 square metre area is needed to install the solar panels in outdoor. And a total of 2,176 m^2 is required to accommodate all appliances, including heat pump, hydrogen storages, batteries, fuel cell, compressors, and other small components. Figure 58 is depicted the perspective view where the building producer is incorporated within the neighbourhood.

Figure 58. The implementation of solar hydrogen production in 234 dwellings in Hanley, Stoke-On-Trent (illustrated by the author)

The HydroTown project carries with the potential to catalyse a profound transformation within the neighbourhood. The project is symbolized the community's commitment to a more sustainable future. The design of the local producer underscores this dedication to sustainability and energy efficiency, as each material selection is made with careful consideration. For instance, the wooden frames incorporated into the canopy of a parking lot as illustrated in the visualization on Figure 59. These frames serve a dual purpose – it provides shade and create a space for the installation of Building Integrated Photovoltaics (BIPV) on glazing. This innovative approach not only offers shelter to vehicles but also maximizes the utilization of the available limited space. This design will benefit to redefine the neighbourhood's landscape while promoting a greener and more energy-efficient future for all its residents.

Figure 59. One of visualizations of HydroTown in Stoke-On-Trent (illustrated by author)

Despite the wooden frames and BIPV systems, the entire design and construction of this local hydrogen production are built to minimize its environment impact. The project employs recycled and low-impact building materials, reducing waste and energy consumption. Moreover, to keep the landscape green and avoid deforestation by not cutting surrounding trees not only enhances the aesthetic appeal but also contributes to a local biodiversity and air quality.

Figure 60. One of visualizations of HydroTown in Stoke-On-Trent (illustrated by author)

Furthermore, solar panels in the surrounding area will serve as a constant reminder to the neighbourhood, encouraging residents to embrace a more environmentally and sustainable green lifestyle. The HydroTown project will represent an open gate for the next hydrogen future in domestic application.

11. GENERAL CONCLUSION

In this study, a set of solar-based renewable energy scenarios are defined, with a total of six scenarios being simulated and compared. This study aims to explore design solutions to incorporate hydrogen in the heating system of buildings, to investigate the potential application of hydrogen technologies with a bottom-up approach, and to assess an insight of energy performances, cost effectiveness, and carbon emissions of each system.

As a starting point, hydrogen will begin to play a role in domestic applications once its distribution becomes common. The demand for hydrogen will grow as other green energy sources become increasingly visible and predictable. This increase is expected to occur in conjunction with the increased policy support and the expanded use of hydrogen in the industrial sector.

In this study, it has been noticed that an all-electric heat pump system boasts the lowest energy consumption by nearly one-fifth of the natural gas grid system. In terms of cost-effectiveness, it is not surprising that hydrogen technologies will demand the highest upfront investments among all energy systems, with waste-heat fuel cell systems having the highest cost. However, it is not clear whether future demand of hydrogen will be cost-competitive with other energy sources, as its costs may decrease just like PV technology in recent years. Another point to note is that, apart from capital expenditure, the cost of each energy depends on how much energy is spent in one area; the more energy consumed, the higher the cost of the energy system. Eventually, although hydrogen technology does not emit any air emissions to the atmosphere, the emissions during its production are abundance. However, over its lifetime of 20 years, this total quantity will remain the same, in contrast to the emissions of natural gas which increase gradually as it releases 170 tons of emission per year, the addition of 30% hydrogen to the system can reduce the emissions to 107 tons of carbon equivalents per year.

During the transition period, a clear timescale for the phase out of natural gas heating in new and existing buildings should be applied. To shift from fossil-fuel based energy at the current year, the government should prioritise supporting the expansion of heat pump in the UK, along with lowering its capital investments, this applies as low temperature heating becomes available in the UK dwellings. However, the drawback of this system is the high cost of electricity in peak seasons which causes the supply to increase intensely in winter. For this reason, the combination of hydrogen in this study is very useful for meeting the heating demand in peak seasons. Even though hydrogen technology has rather high upfront costs, it is still a good investment for 2030 as the costs of the appliances will eventually decrease.

From an energy perspective, hybrid hydrogen and heat pump system (Scenario 6) can outperform other hydrogen technology systems as a system with the lowest energy consumption so reduces the total costs of energy system over its lifetime. By incorporating a heat pump into hydrogen fuel cell system, the electricity produced by fuel cell, can provide heating with a total system efficiency of 163%. Compared with the system relying solely on a heat pump, as seen in scenario 2, achieves an efficiency of approximately 360%. In this hybrid hydrogen and heat pump system, optimising the system by prioritising the usage of the heat pump is a good strategy to gain its efficiency. Here, a control system is highly needed to determine that the heat pump will be directly used in the summer and during the day or when the heating demand is low, whereas hydrogen will take the role during peak hours, in the winter, and/or in the evening.

From a cost perspective, while hydrogen is flowed intensively and distributed in the city, microgrid hydrogen boiler system as in Scenario 4 can be utilised. Meanwhile, another technology that only use waste-heat of cogeneration hydrogen fuel cell system will not be as valuable to apply in any situation as it considered inefficiency and has an extremely high costs. However, a system which blend natural gas and hydrogen with boiler as in Scenario 3 can be implemented in the transition period, while this system will completely shift to Scenario 4 employed 100% hydrogen gas in the future.

In conjunction with the optimized hybrid hydrogen and heat pump system, the energy can be potentially saved to half of the usual energy consumption in non-optimized system which constantly utilizes hydrogen and heat pump whenever heating is active, even during summer or when the heating demand is low. With this optimized hybrid system as a peak shaver, the total cost per household for both capital and operational costs over its lifetime (20 years) applied in 25 dwellings is predicted to be higher than those applied in 234 dwellings for one households. Accounted for $63,073 and $49,925 respectively. This means that the larger system applied in the neighbourhood, the less costs it requires for maintenance and its capital. Furthermore, it is important to consider the land availability. In this study, about 6,882 square meter is needed to place the required appliances. For safety, the hydrogen plant should have natural ventilation to protect any chemical response to avoid any explosive mixture in the neighbourhood.

Further studies is needed on each topic, especially with a comprehensive analysis of cost-effectiveness and investment rate per scenario. More detailed investigations can also be useful regardless the use of hybrid heat pump appliances. In addition, a specific study on a control system which explained how and when hydrogen will be used to fulfill the heating demand is highly recommended. A dynamic model is required to delve deep in understanding the conditions in which hydrogen is preferably used. By doing so, a more representative balance can be made, and the capacity of the system components can be more optimised.

12. REFLECTION

Topic

The research is focused on hydrogen as an energy carrier in buildings and neighbourhoods. Hydrogen and energy storage basis are not part of the Building Technology track, hydrogen is more based on the chemical engineering or sustainability energy technology department. However, the application of hydrogen gas substances rather than natural gas pipelines are very much aligns with the development of architectural part in the topic of Zero Energy and Climate Design course. This, will enhance the upcoming technology sources of renewable energy in the current system.

Additionally, regarding to the limitation of the research context, this study is considered broad, caused it covers three different topics in one titled study. Therefore, the focus of this study is separated. However, with the narrowed result in the end of the research, these criteria is recognized reasonable to understand that each analysis plays crucial parts to draw comprehensive conclusions.

Methodology

The approach of the study is focusing on bottom-up analysis, which considering micro attributes to delve deeper to the bigger picture of societal or neighbourhood impact. Thus, several models and calculation have been done to reach the outstanding value of the design. However, considering hydrogen as a new technology coming in the future, providing specific information which are mostly still in prediction, affected on the information and data retrieval. The absence of specialized expertise and information regarding this emerging technology constitutes an ongoing longer study to acquire further knowledge from reputable and dependable sources or organizations.

Design

Additionally, given the constraints of the study and the limited timeframe, the investigation into design development might be enhanced to reflect on the actual system which being said to not solely dependent on the solar-powered energy. Ensuring that other forms of green energy, such as wind power, green electricity, and heat networks would be ideally spotted on. Therefore, these alternative sources will be incorporated and further developed in the design investigation on a wider scale. Consequently, the calculation of the cost and carbon emissions equivalent would be enhanced correspondingly.

Societal Impact

The applied technology has been worked in industrial and transportation use, the opportunity of this technology use is fired on. This would offer a stage of innovation to work with other department that would be valuable in the future. Therefore this impact in buildings and neighbourhoods remains positive. Even though this project has not been applied in the built environment, however, the sooner this technology will be more visible in energy transition in buildings with the support of the government and policy makers for a hydrogen economy.

Result

Even though the system has resulted to a narrow down value, the utilization of hydrogen in buildings should be dependent upon contextual factors and the accessibility of the hydrogen source. However, the outcome of an optimized hybrid hydrogen heat pump system exhibits a commendable level of total system efficiency. But the levelized costs and capital costs are high. Therefore, an optimized system with the controlled system is required on more dynamic operation to reach more desired result of energy consumption.

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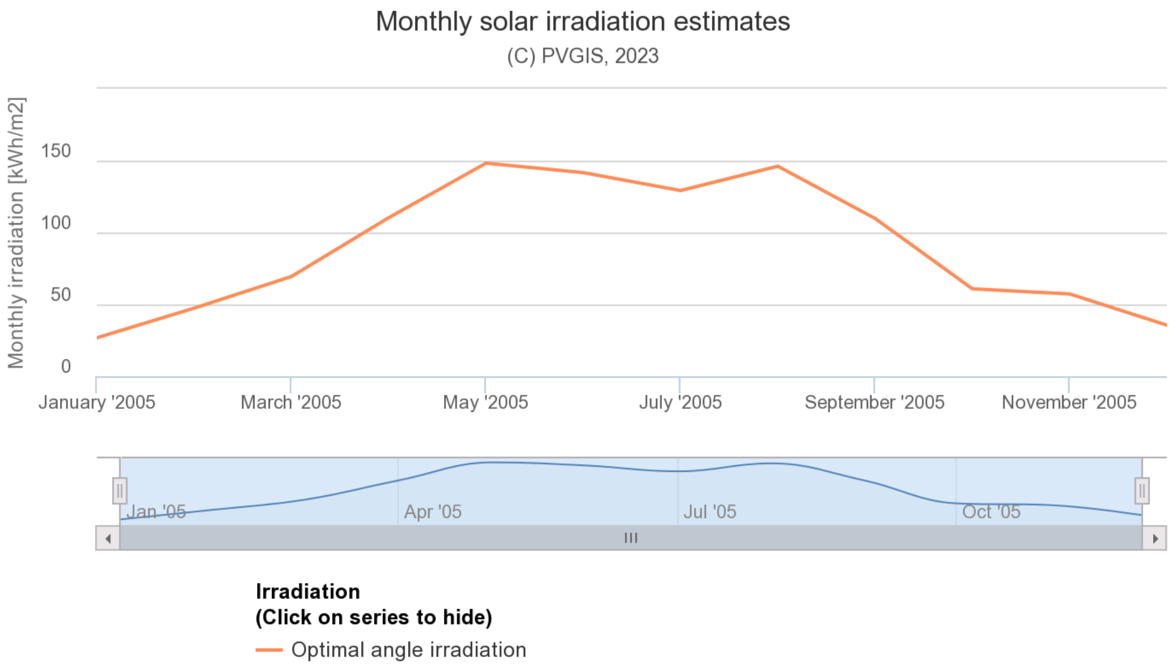
13. LIST OF FIGURES

14. APPENDICES

Monthly Solar Irradiation from PV-GIS in Stoke-On-Trent



Type A

Base Case (Without Renovation) of Building Type A

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No Cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	67.20	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	67.20	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	72.00	m^2	Window percentage roof	0	%
Total ground floor area	72.00	m^2			
Floor height	2.80	m			
Total floor surface area	144.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	0.63	m^2K/W			
Rc roof	0.43	m^2K/W			
Rc floor	1.69	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	4.80	W/m^2K	Total Window (glass + frame) area	26.9	m^2
U facade wall	1.60	W/m^2K	Total Facade wall area	174.7	m^2
U roof	2.30	W/m^2K	Total Roof area	72.0	m^2
U floor	0.59	W/m^2K	Total Ground floor area	72.0	m^2
Infiltration					
ACH	0.80	/h			
Building volume	403.20	m^3			
Flow rate infiltration	322.56	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	20.16	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	6.72	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	144.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						

Building warm tap water demand					
Water density	1000.00	kg/m^3			
Daily average volume of warm tap water per person	0.10	m^3/day			
Daily average volume of warm tap water in building	0.40	m^3/day			
Maximum simulatenous flow rate	0.00	m^3/s			
Specific heat of water	4187.00	J/kgK			
Temperature cold water	10.00	°C			
Temperature hot water	60.00	°C			
Building electrical energy demand					
Ventilation					
Pressure drop	0.00	Pa			
Efficiency ventilator	0.70				
Power ventilator	0.00	W			h
Lighting & Appliances					
Light power per square meter	3.00	W/m^2			
Floor area	144.00	m^2			
Appliances power per square meter	3.00	W/m^2			
Floor area	144.00	m^2			

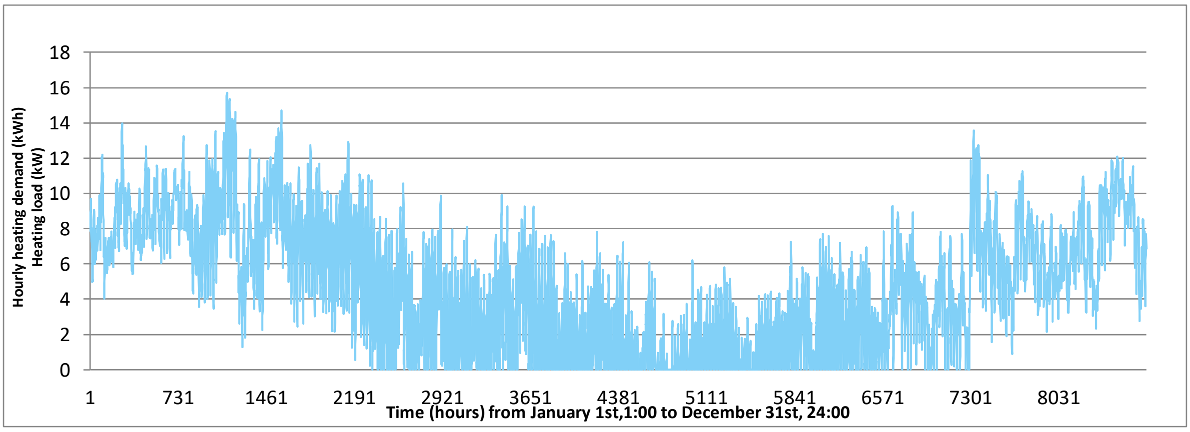
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	41,687	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,781	kWh
Nominal power space heating	15.70	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	20.94	kW
Nominal Power electricity	0.86	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Light Renovation of Building Type A

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(NO ooling)		
Total façade area (incl. glass) North	33.60	m²	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m²	Window percentage North-East	0	%
Total façade area (incl. glass) East	67.20	m²	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m²	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m²	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m²	Window percentage South-West	0	%
Total façade area (incl. glass) West	67.20	m²	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m²	Window percentage North-West	0	%
Total roof area (incl. glass)	72.00	m²	Window percentage roof	0	%
Total ground floor area	72.00	m²			
Floor height	2.80	m			
Total floor surface area	144.00	m²	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.67	m²K/W			
Rc roof	7.69	m²K/W			
Rc floor	1.69	m²K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m²K			
alfao (convection/radiation coefficient indoor)	25.00	W/m²K			
U window	2.20	W/m²K	Total Window (glass + frame) area	26.9	m²
U facade wall	0.60	W/m²K	Total Facade wall area	174.7	m²
U roof	0.13	W/m²K	Total Roof area	72.0	m²
U floor	0.59	W/m²K	Total Ground floor area	72.0	m²
Infiltration					
ACH	0.70	/h			
Building volume	403.20	m³			
Flow rate infiltration	282.24	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m³/h per person			
Flow rate ventilation	100.00	m³/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m²	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m²	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	20.16	m²	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m²	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m²	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m²	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	6.72	m²	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m²	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m²	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	144.00	m²						
Light power per square meter	3.00	W/m²						
Appliances power per square meter	3.00	W/m²						
Building warm tap water demand								
Water density	1000.00	kg/m³						
Daily average volume of warm tap water per person	0.10	m³/day						
Daily average volume of warm tap water in building	0.40	m³/day						
Maximum simulatenous flow rate	0.00	m³/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	60.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m²						
Floor area	144.00	m²						
Appliances power per square meter	3.00	W/m²						
Floor area	144.00	m²						

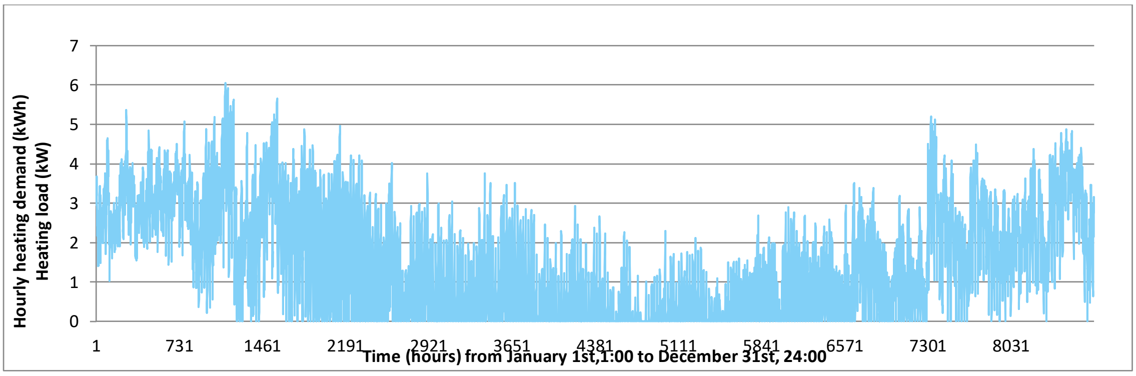
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	13,412	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,781	kWh
Nominal power space heating	6.05	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	20.94	kW
Nominal Power electricity	0.86	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Ambitious Renovation for Building Type A

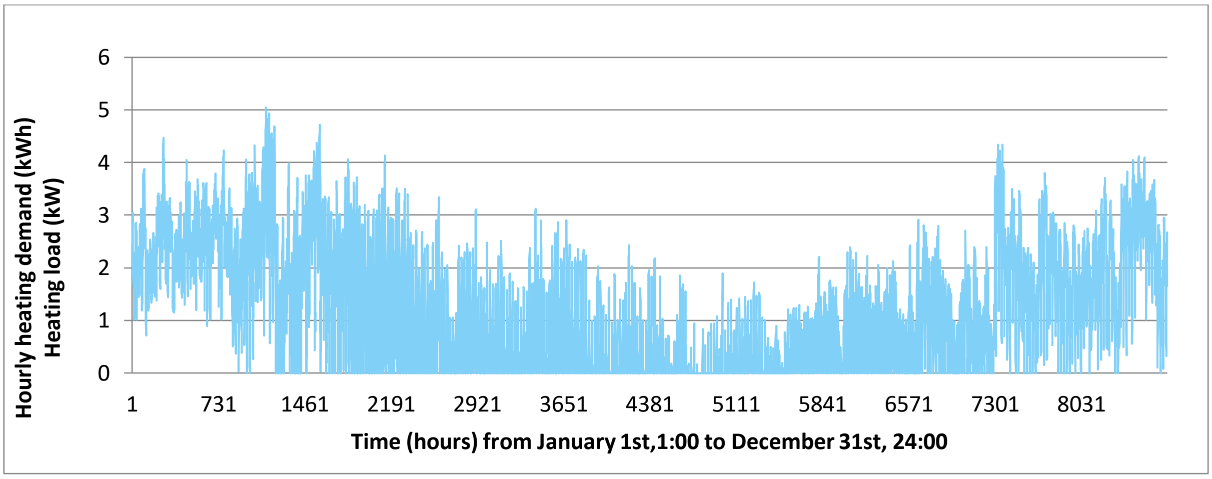
Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No cooling)		
Total façade area (incl. glass) North	33.60	m²	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m²	Window percentage North-East	0	%
Total façade area (incl. glass) East	67.20	m²	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m²	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m²	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m²	Window percentage South-West	0	%
Total façade area (incl. glass) West	67.20	m²	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m²	Window percentage North-West	0	%
Total roof area (incl. glass)	72.00	m²	Window percentage roof	0	%
Total ground floor area	72.00	m²			
Floor height	2.80	m			
Total floor surface area	144.00	m²	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.49	m²K/W			
Rc roof	7.52	m²K/W			
Rc floor	1.52	m²K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m²K			
alfao (convection/radiation coefficient indoor)	25.00	W/m²K			
U window	1.60	W/m²K	Total Window (glass + frame) area	26.9	m²
U facade wall	0.60	W/m²K	Total Facade wall area	174.7	m²
U roof	0.13	W/m²K	Total Roof area	72.0	m²
U floor	0.59	W/m²K	Total Ground floor area	72.0	m²
Infiltration					
ACH	0.50	/h			
Building volume	403.20	m³			
Flow rate infiltration	201.60	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m³/h per person			
Flow rate ventilation	100.00	m³/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m²	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m²	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	20.16	m²	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m²	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m²	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m²	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	6.72	m²	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m²	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m²	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	144.00	m²						
Light power per square meter	3.00	W/m²						
Appliances power per square meter	3.00	W/m²						
Building warm tap water demand								
Water density	1000.00	kg/m³						
Daily average volume of warm tap water per person	0.10	m³/day						
Daily average volume of warm tap water in building	0.40	m³/day						
Maximum simulatenous flow rate	0.00	m³/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	60.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m²						
Floor area	144.00	m²						
Appliances power per square meter	3.00	W/m²						
Floor area	144.00	m²						

RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	10,642	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,781	kWh
Nominal power space heating	5.05	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	20.94	kW
Nominal Power electricity	0.86	kW



Type B

Base Case (Without Renovation) of Building Type B

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(NO ooling)		
Total façade area (incl. glass) North	25.20	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	16.80	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	25.20	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	16.80	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	54.00	m^2	Window percentage roof	0	%
Total ground floor area	54.00	m^2			
Floor height	2.80	m			
Total floor surface area	54.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	0.63	m^{2}K/W			
Rc roof	0.67	m^{2}K/W			
Rc floor	1.39	m^{2}K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^{2}K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^{2}K			
U window	4.80	W/m^{2}K	Total Window (glass + frame) area	6.7	m^2
U facade wall	1.60	W/m^{2}K	Total Facade wall area	77.3	m^2
U roof	1.50	W/m^{2}K	Total Roof area	54.0	m^2
U floor	0.72	W/m^{2}K	Total Ground floor area	54.0	m^2
Infiltration					
ACH	0.80	/h			
Building volume	151.20	m^3			
Flow rate infiltration	120.96	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	5.04	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	1.68	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	54.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.40	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						

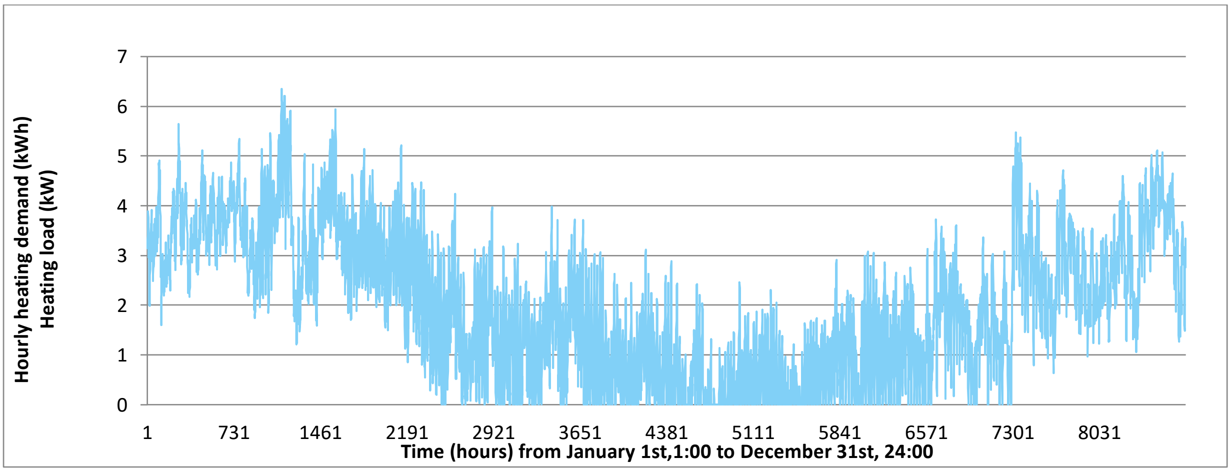
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	17,791	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	1,418	kWh
Nominal power space heating	6.35	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.32	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Light Renovation of Building Type B

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No Cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	16.80	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	16.80	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	54.00	m^2	Window percentage roof	0	%
Total ground floor area	54.00	m^2			
Floor height	2.80	m			
Total floor surface area	54.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.67	m^{2}K/W			
Rc roof	7.69	m^{2}K/W			
Rc floor	1.39	m^{2}K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^{2}K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^{2}K			
U window	4.80	W/m^{2}K	Total Window (glass + frame) area	6.7	m^2
U facade wall	0.60	W/m^{2}K	Total Facade wall area	94.1	m^2
U roof	0.13	W/m^{2}K	Total Roof area	54.0	m^2
U floor	0.72	W/m^{2}K	Total Ground floor area	54.0	m^2
Infiltration					
ACH	0.70	/h			
Building volume	151.20	m^3			
Flow rate infiltration	105.84	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per	person		
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	5.04	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	1.68	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	54.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.40	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						

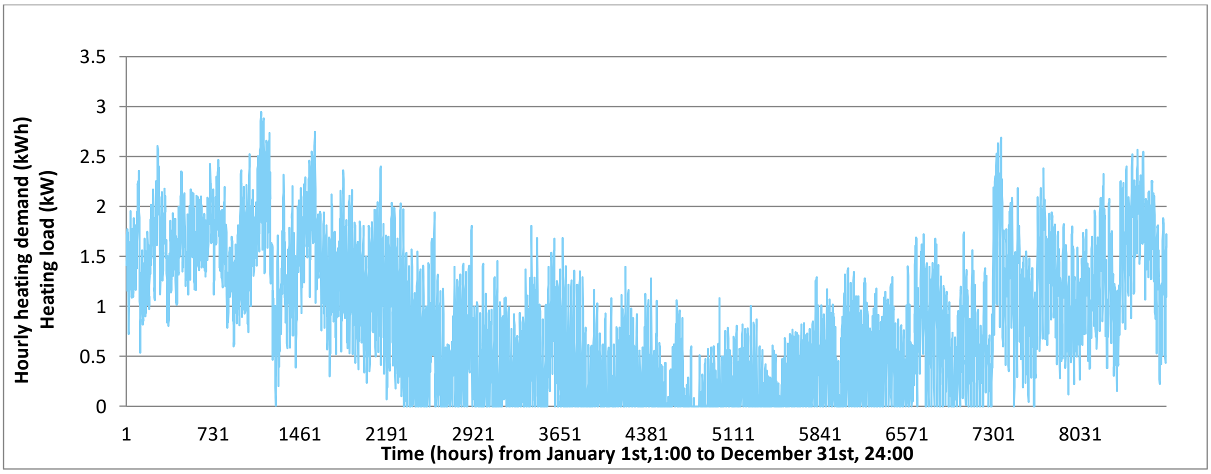
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	7,450	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	1,418	kWh
Nominal power space heating	2.95	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.32	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Ambitious Renovation for Building Type B

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	OC	(NO ooling)		
Total façade area (incl. glass) North	25.20	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	16.80	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	25.20	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	16.80	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	54.00	m^2	Window percentage roof	0	%
Total ground floor area	54.00	m^2			
Floor height	3.00	m			
Total floor surface area	54.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.49	m^2K/W			
Rc roof	7.52	m^2K/W			
Rc floor	1.22	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	1.60	W/m^2K	Total Window (glass + frame) area	6.7	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	77.3	m^2
U roof	0.13	W/m^2K	Total Roof area	54.0	m^2
U floor	0.72	W/m^2K	Total Ground floor area	54.0	m^2
Infiltration					
ACH	0.50	/h			
Building volume	162.00	m^3			
Flow rate infiltration	81.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	5.04	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	1.68	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	54.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.40	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	54.00	m^2						

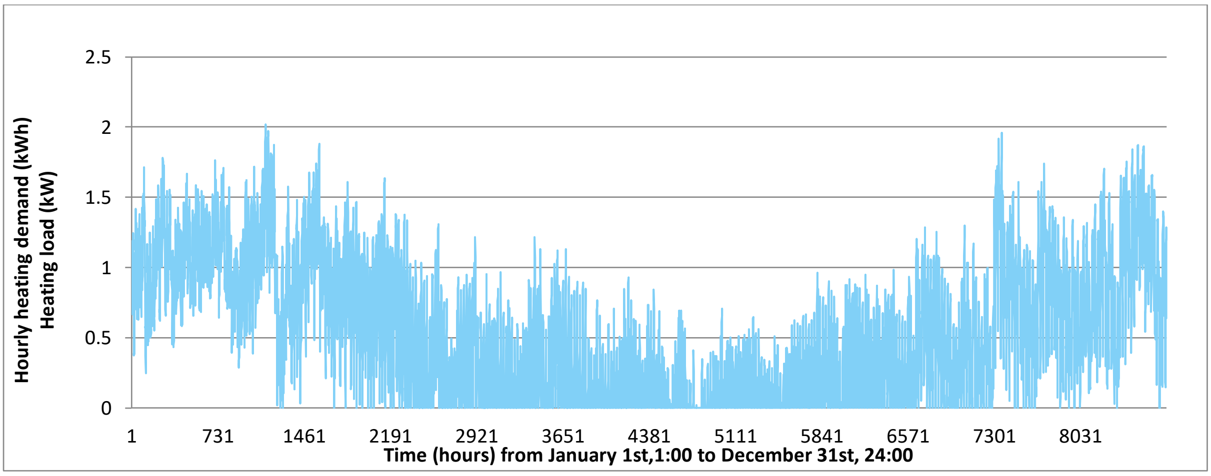
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	4,736	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	1,418	kWh
Nominal power space heating	2.02	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.32	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Type C

Base Case (Without Renovation) of Building Type C

Building Input Parameters			Fill in the buildng data		data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	OC	(NO Cooling)		
Total façade area (incl. glass) North	42.00	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	44.80	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	42.00	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	44.80	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	0.63	m^2K/W			
Rc roof	2.50	m^2K/W			
Rc floor	2.00	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	3.10	W/m^2K	Total Window (glass + frame) area	17.9	m^2
U facade wall	1.60	W/m^2K	Total Facade wall area	155.7	m^2
U roof	0.40	W/m^2K	Total Roof area	60.0	m^2
U floor	0.50	W/m^2K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.80	/h			
Building volume	336.00	m^3			
Flow rate infiltration	268.80	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	13.44	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	4.48	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	5.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	120.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.50	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						

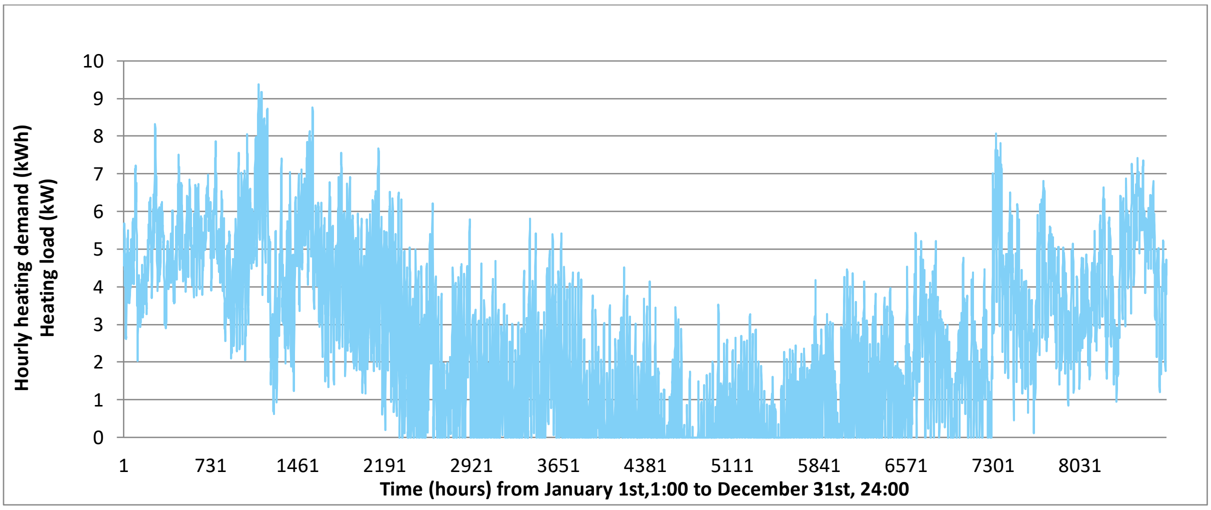
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	23,557	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	9.38	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Light Renovation of Building Type C

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	20.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(NO ooling)		
Total façade area (incl. glass) North	42.00	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	44.80	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	42.00	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	44.80	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.67	m^2K/W			
Rc roof	2.50	m^2K/W			
Rc floor	2.00	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	3.10	W/m^2K	Total Window (glass + frame) area	17.9	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	155.7	m^2
U roof	0.40	W/m^2K	Total Roof area	60.0	m^2
U floor	0.50	W/m^2K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.60	/h			
Building volume	336.00	m^3			
Flow rate infiltration	201.60	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	125.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

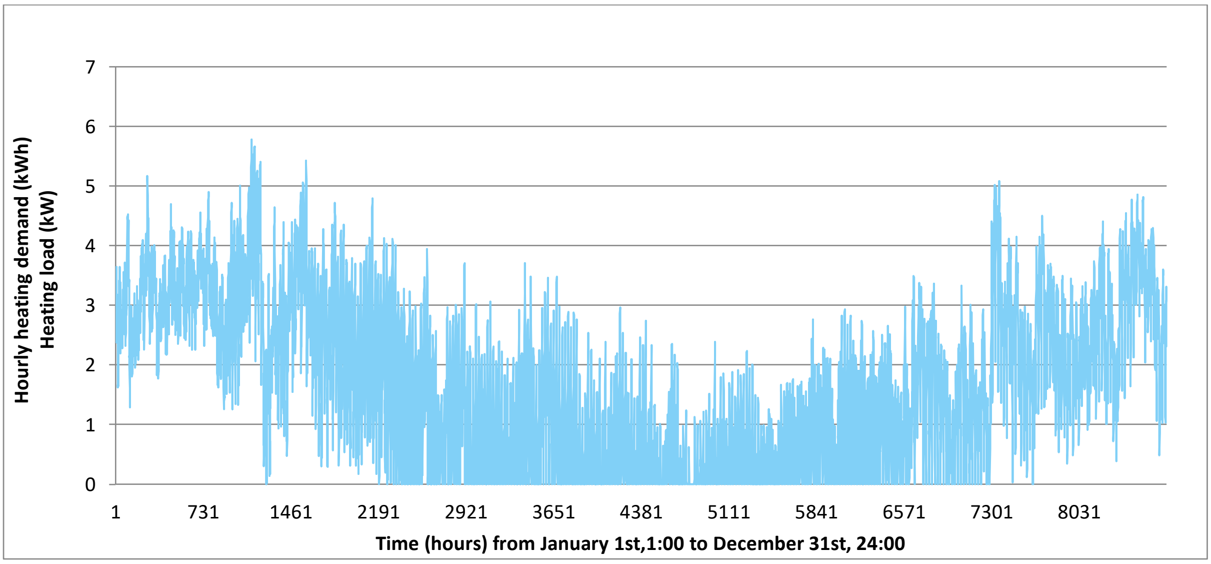
Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	13.44	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	4.48	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	5.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	120.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.50	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						

RESULTS
ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	15,052	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	5.78	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Ambitious Renovation for Building Type C

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(NO ooling)		
Total façade area (incl. glass) North	42.00	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	22.40	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	21.00	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	22.40	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.49	m^{2}K/W			
Rc roof	2.33	m^{2}K/W			
Rc floor	1.83	m^{2}K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^{2}K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^{2}K			
U window	1.60	W/m^{2}K	Total Window (glass + frame) area	9.0	m^2
U facade wall	0.60	W/m^{2}K	Total Facade wall area	98.8	m^2
U roof	0.40	W/m^{2}K	Total Roof area	60.0	m^2
U floor	0.50	W/m^{2}K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.50	/h			
Building volume	336.00	m^3			
Flow rate infiltration	168.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	125.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	6.72	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	2.24	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	5.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	120.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.50	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						

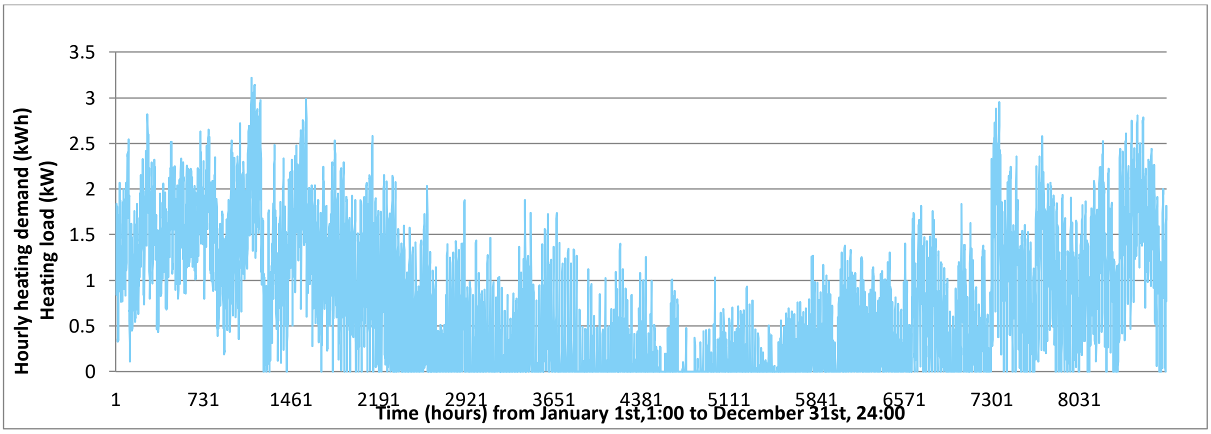
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	6,490	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	8,490	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	3.22	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Type D

Base Case (Without Renovation) of Building Type D

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	56.00	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	56.00	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	0.63	m^2K/W			
Rc roof	0.67	m^2K/W			
Rc floor	1.69	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	3.10	W/m^2K	Total Window (glass + frame) area	22.4	m^2
U facade wall	1.60	W/m^2K	Total Facade wall area	156.8	m^2
U roof	1.50	W/m^2K	Total Roof area	60.0	m^2
U floor	0.59	W/m^2K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.80	/h			
Building volume	336.00	m^3			
Flow rate infiltration	268.80	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	16.8	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	5.6	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							

Internal heat gains		
Number of people	4.00	people
Heat gain per person	117.00	W/person
Fraction light power thermally released	1.00	
Lighten floor percentage	1.00	
Total Floor Area	120.00	m^2
Light power per square meter	3.00	W/m^2
Appliances power per square meter	3.00	W/m^2

Building warm tap water demand		
Water density	1000.00	kg/m^3
Daily average volume of warm tap water per person	0.10	m^3/day
Daily average volume of warm tap water in building	0.40	m^3/day
Maximum simultatenous flow rate	0.00	m^3/s
Specific heat of water	4187.00	J/kgK
Temperature cold water	10.00	°C
Temperature hot water	50.00	°C

Building electrical energy demand		
Ventilation		
Pressure drop	0.00	Pa
Efficiency ventilator	0.70	
Power ventilator	0.00	W
Lighting & Appliances		
Light power per square meter	3.00	W/m^2
Floor area	120.00	m^2
Appliances power per square meter	3.00	W/m^2
Floor area	120.00	m^2

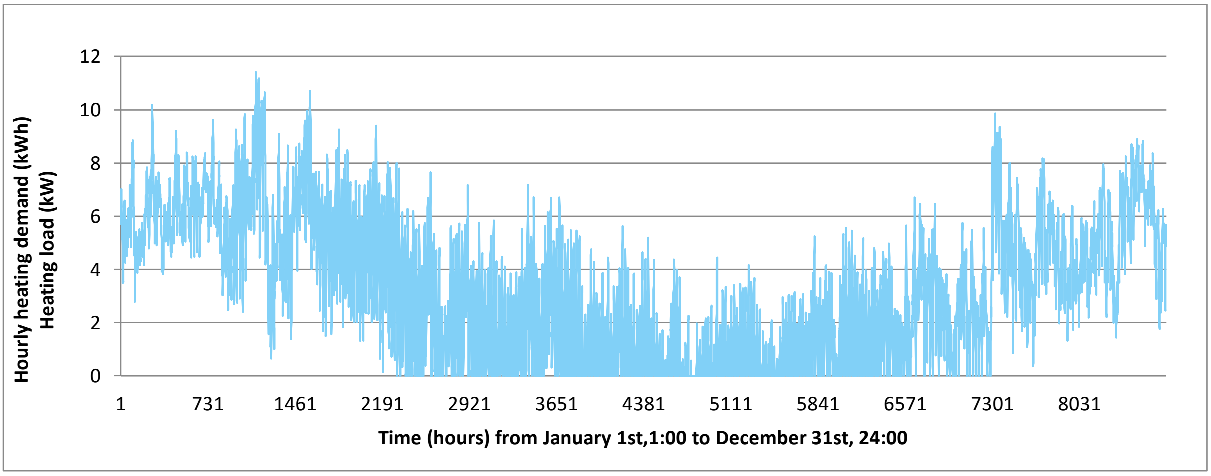
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	29,609	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	11.43	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	56.00	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	56.00	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.67	m^2K/W			
Rc roof	7.69	m^2K/W			
Rc floor	1.69	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	3.10	W/m^2K	Total Window (glass + frame) area	22.4	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	156.8	m^2
U roof	0.13	W/m^2K	Total Roof area	60.0	m^2
U floor	0.59	W/m^2K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.70	/h			
Building volume	336.00	m^3			
Flow rate infiltration	235.20	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	100.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	16.8	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	5.6	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	120.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.40	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	120.00	m^2						

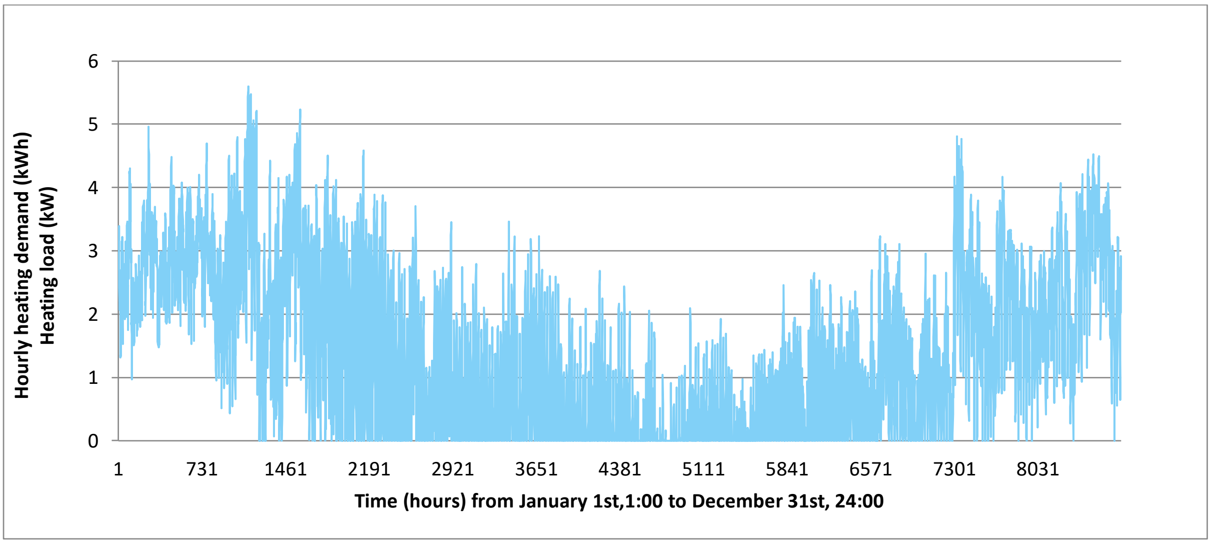
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	12,596	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	5.60	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Ambitious Renovation for Building Type D

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	OC	(No cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	8.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	56.00	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	56.00	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	60.00	m^2	Window percentage roof	0	%
Total ground floor area	60.00	m^2			
Floor height	2.80	m			
Total floor surface area	120.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.49	m^2K/W			
Rc roof	7.52	m^2K/W			
Rc floor	1.52	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	1.60	W/m^2K	Total Window (glass + frame) area	22.4	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	164.8	m^2
U roof	0.13	W/m^2K	Total Roof area	60.0	m^2
U floor	0.59	W/m^2K	Total Ground floor area	60.0	m^2
Infiltration					
ACH	0.50	/h			
Building volume	336.00	m^3			
Flow rate infiltration	168.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	16.8	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	5.6	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	4.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	120.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						

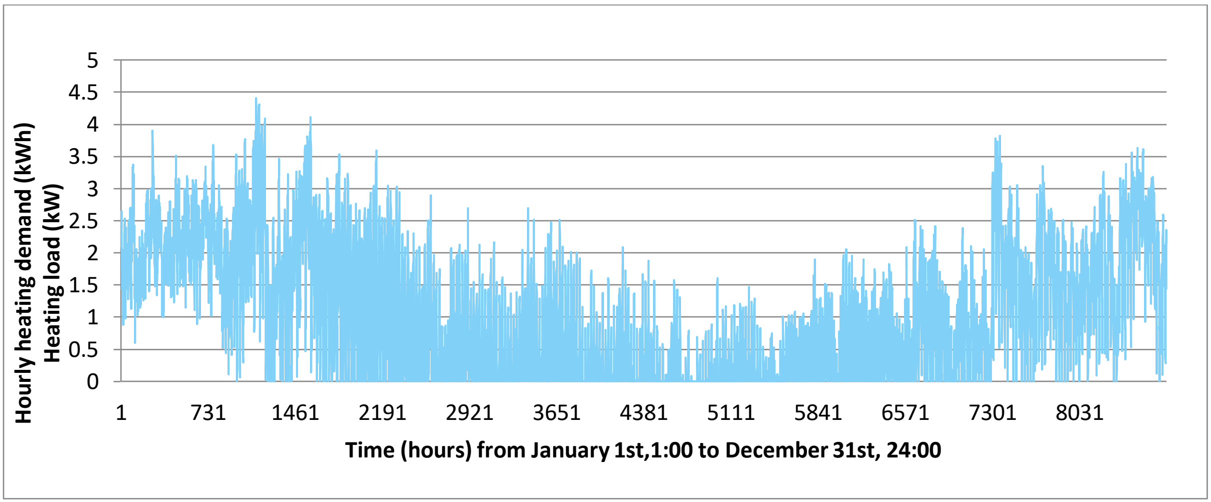
Building warm tap water demand		
Water density	1000.00	kg/m^3
Daily average volume of warm tap water per person	0.10	m^3/day
Daily average volume of warm tap water in building	0.40	m^3/day
Maximum simulatenous flow rate	0.00	m^3/s
Specific heat of water	4187.00	J/kgK
Temperature cold water	10.00	ºC
Temperature hot water	50.00	ºC

RESULTS
ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	9,275	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	6,792	kWh
Year electricity demand	3,151	kWh
Nominal power space heating	4.41	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.72	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Type E

Base Case (Without Renovation) of Building Type E

Building Input Parameters			Fill in the buildng data	Don't change these data	
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(No cooling)		
Total façade area (incl. glass) North	33.60	m²	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m²	Window percentage North-East	0	%
Total façade area (incl. glass) East	22.40	m²	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m²	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m²	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m²	Window percentage South-West	0	%
Total façade area (incl. glass) West	22.40	m²	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m²	Window percentage North-West	0	%
Total roof area (incl. glass)	96.00	m²	Window percentage roof	0	%
Total ground floor area	96.00	m²			
Floor height	2.80	m			
Total floor surface area	96.00	m²	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	0.63	m²K/W			
Rc roof	0.43	m²K/W			
Rc floor	1.39	m²K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m²K			
alfao (convection/radiation coefficient indoor)	25.00	W/m²K			
U window	4.80	W/m²K	Total Window (glass + frame) area	9.0	m²
U facade wall	1.60	W/m²K	Total Facade wall area	103.0	m²
U roof	2.30	W/m²K	Total Roof area	96.0	m²
U floor	0.72	W/m²K	Total Ground floor area	96.0	m²
Infiltration					
ACH	0.80	/h			
Building volume	268.80	m³			
Flow rate infiltration	215.04	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m³/h per person			
Flow rate ventilation	75.00	m³/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m³/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m³			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m²	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m²	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	6.72	m²	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m²	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m²	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m²	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	2.24	m²	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m²	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m²	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	3.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	96.00	m²						
Light power per square meter	3.00	W/m²						
Appliances power per square meter	3.00	W/m²						
Building warm tap water demand								
Water density	1000.00	kg/m³						
Daily average volume of warm tap water per person	0.10	m³/day						
Daily average volume of warm tap water in building	0.30	m³/day						
Maximum simulatenous flow rate	0.00	m³/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m²						
Floor area	96.00	m²						
Appliances power per square meter	3.00	W/m²						
Floor area	96.00	m²						

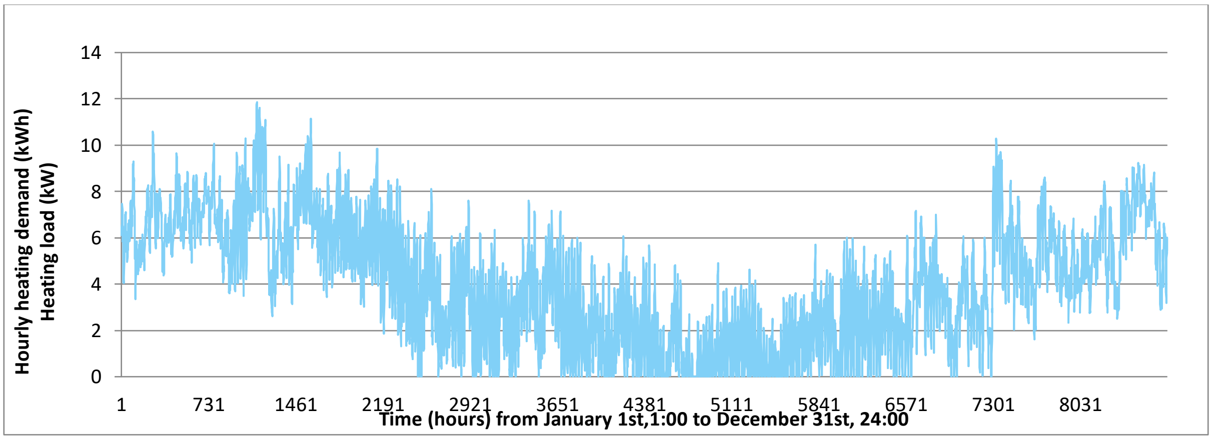
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	35,261	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	5,094	kWh
Year electricity demand	2,521	kWh
Nominal power space heating	11.87	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.58	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Light Renovation of Building Type E

Building Input Parameters			Fill in the buildng data		change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	OC	(NO ooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	22.40	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	22.40	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	96.00	m^2	Window percentage roof	0	%
Total ground floor area	96.00	m^2			
Floor height	2.80	m			
Total floor surface area	96.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.67	m^2K/W			
Rc roof	7.69	m^2K/W			
Rc floor	1.39	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	2.20	W/m^2K	Total Window (glass + frame) area	9.0	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	103.0	m^2
U roof	0.13	W/m^2K	Total Roof area	96.0	m^2
U floor	0.72	W/m^2K	Total Ground floor area	96.0	m^2
Infiltration					
ACH	0.70	/h			
Building volume	268.80	m^3			
Flow rate infiltration	188.16	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

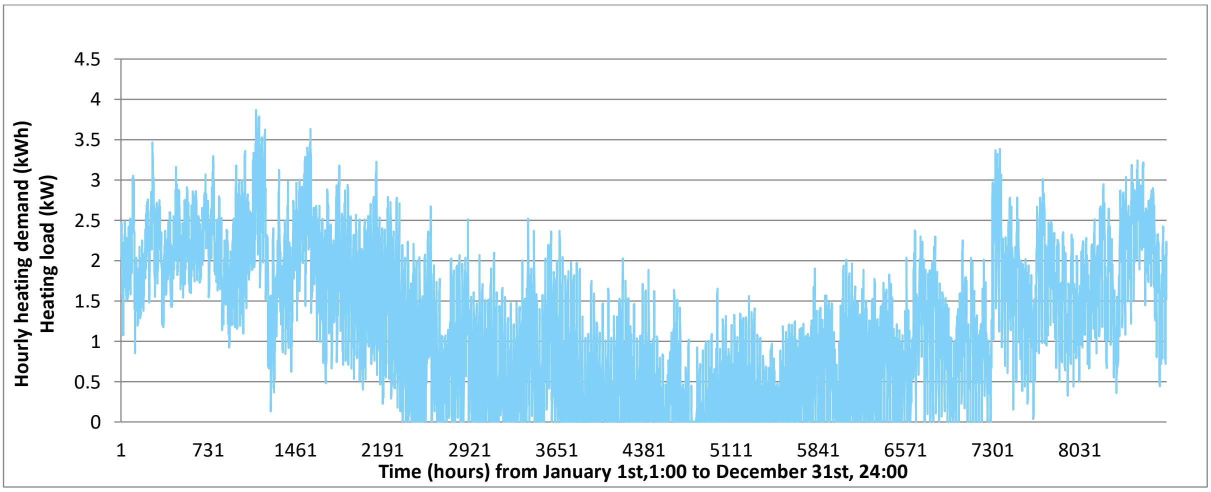
Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	6.72	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	2.24	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	3.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	96.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.30	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	96.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	96.00	m^2						

RESULTS
ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	10,572	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	5,094	kWh
Year electricity demand	2,521	kWh
Nominal power space heating	3.86	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.58	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



Ambitious Renovation for Building Type E

Building Input Parameters			Fill in the buildng data		Don't change these data
Indoor temperature heating mode	18.00	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	60.00	0C	(NO Cooling)		
Total façade area (incl. glass) North	33.60	m^2	Window percentage North	0	%
Total façade area (incl. glass) North-East	0.00	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	22.40	m^2	Window percentage East	30	%
Total façade area (incl. glass) South-East	0.00	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	33.60	m^2	Window percentage South	0	%
Total façade area (incl. glass) South-West	0.00	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	22.40	m^2	Window percentage West	10	%
Total façade area (incl. glass) North-West	0.00	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	96.00	m^2	Window percentage roof	0	%
Total ground floor area	96.00	m^2			
Floor height	2.80	m			
Total floor surface area	96.00	m^2	(This is the sum of all floor areas, from every level)		
Transmission					
Rc façade walls	1.49	m^2K/W			
Rc roof	7.52	m^2K/W			
Rc floor	1.22	m^2K/W			
alfai (convection/radiation coefficient indoor)	7.50	W/m^2K			
alfao (convection/radiation coefficient indoor)	25.00	W/m^2K			
U window	1.60	W/m^2K	Total Window (glass + frame) area	9.0	m^2
U facade wall	0.60	W/m^2K	Total Facade wall area	103.0	m^2
U roof	0.13	W/m^2K	Total Roof area	96.0	m^2
U floor	0.72	W/m^2K	Total Ground floor area	96.0	m^2
Infiltration					
ACH	0.50	/h			
Building volume	268.80	m^3			
Flow rate infiltration	134.40	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			
Ventilation					
Heat recovery efficiency	0.90				
Ventilation flow rate per person	25.00	m^3/h per person			
Flow rate ventilation	75.00	m^3/h			
Additional natural ventilation in cooling mode	0.00	/h	(in ACH)		
Flow rate additional natural ventilation in cooling mode	0.00	m^3/h			
Dry air heating capacity	1000.00	J/kgK			
Density of air	1.20	kg/m^3			

Solar factors						Threeshold solar radiation for blind down	250	W/m2
Solar heat factor glass (N)	0.80		Window area (glass + frame) (N)	0.0	m^2	Solar heat factor blinds (N)	1	
Solar heat factor glass (N-E)	0.80		Window area (glass + frame) (N-E)	0.0	m^2	Solar heat factor blinds (N-E)	1	
Solar heat factor glass (E)	0.80		Window area (glass + frame) (E)	6.72	m^2	Solar heat factor blinds (E)	1	
Solar heat factor glass (S-E)	0.80		Window area (glass + frame) (S-E)	0.0	m^2	Solar heat factor blinds (S-E)	1	
Solar heat factor glass (S)	0.80		Window area (glass + frame)(S)	0.0	m^2	Solar heat factor blinds (S)	1	
Solar heat factor glass (S-W)	0.80		Window area (glass + frame) (S-W)	0.0	m^2	Solar heat factor blinds (S-W)	1	
Solar heat factort glass (W)	0.80		Window area (glass + frame)(W)	2.24	m^2	Solar heat factor blinds (W)	1	
Solar heat factor glass (N-W)	0.80		Window area (glass + frame) (N-W)	0.0	m^2	Solar heat factor blinds (N-W)	1	
Solar heat factor glass (roof)	0.80		Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	1	
f factor for light and heavy buildigs	0.85							
Internal heat gains								
Number of people	3.00	people						
Heat gain per person	117.00	W/person						
Fraction light power thermally released	1.00							
Lighten floor percentage	1.00							
Total Floor Area	96.00	m^2						
Light power per square meter	3.00	W/m^2						
Appliances power per square meter	3.00	W/m^2						
Building warm tap water demand								
Water density	1000.00	kg/m^3						
Daily average volume of warm tap water per person	0.10	m^3/day						
Daily average volume of warm tap water in building	0.30	m^3/day						
Maximum simulatenous flow rate	0.00	m^3/s						
Specific heat of water	4187.00	J/kgK						
Temperature cold water	10.00	°C						
Temperature hot water	50.00	°C						
Building electrical energy demand								
Ventilation								
Pressure drop	0.00	Pa						
Efficiency ventilator	0.70							
Power ventilator	0.00	W			h			
Lighting & Appliances								
Light power per square meter	3.00	W/m^2						
Floor area	96.00	m^2						
Appliances power per square meter	3.00	W/m^2						
Floor area	96.00	m^2						

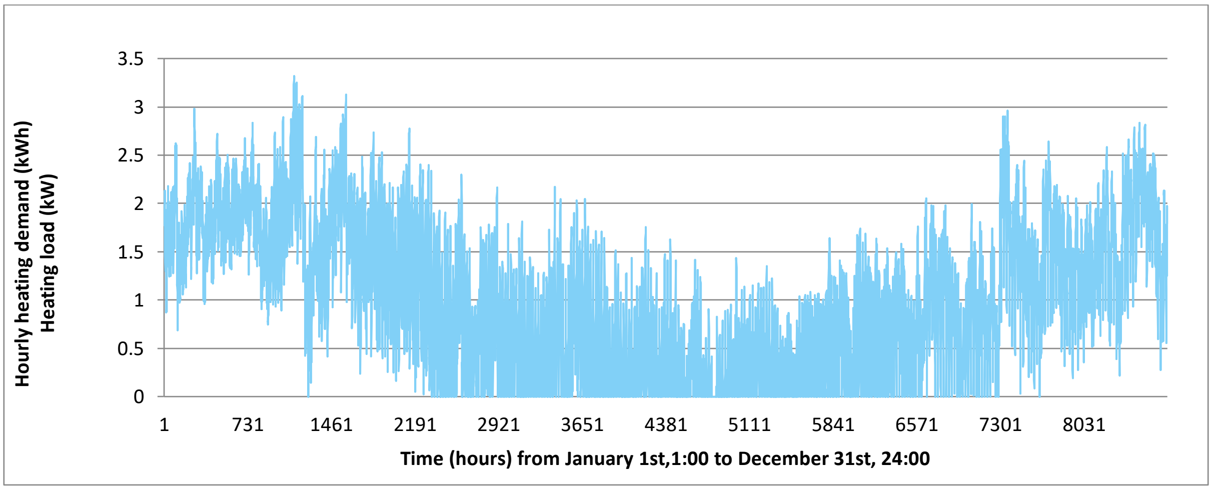
RESULTS

ANNUAL ENERGY DEMANDS AND NOMINAL POWERS

Year space heating energy demand	8,954	kWh
Year space cooling energy demand	0	kWh
Year hot water energy demand	5,094	kWh
Year electricity demand	2,521	kWh
Nominal power space heating	3.32	kW
Nominal power cooling	0	kW
Nominal power hot tapwater	16.75	kW
Nominal Power electricity	0.58	kW

* note on Nominal Power electricity:

In general the total connected load is much higher than this calculated Nominal Power. This is because appliance with a high power, but used only a few hours per year, are not accounted for here (e.g. an oven)



The result of Energy Demand Modeling for 5 typical buildings

Building Typology in the neighborhood 1,633.0

Building Data							Building Dimension			
Building Model in Real (Stock On Trent)	Building Model Tabula (English House)	Buildin g Typolo gy	Typica l Buildi ng	Tota l Floo rs	Total Housin g	Built in	Length	Width	Peopl e / house	Total Area (m2)
		Semi Terraced House	A	2	10	1945-1964	6	12	4	144.00
		Semi Detached House	B	1	3	1965-1980	9	6	4	54.00
		Semi Terraced House	C	2	6	1981-1990	8	8	5	120.00
		Terraced House	D	2	3	1965-1980	10	6	4	120.00
		Semi detached House	E	1	3	1945-1964	12	8	3	96.00

PER BUILDING

ORIGIN DATA TABULA			EXCEL MODELLING								
Heating Demand by Tabula			A (Base Case)			B (Light Renovation)			C (Ambitious Renovation)		
Base Case (kWh)	Light Renov (kWh)	Ambitious Renov (kWh)	Space Heating (kWh)	DHW (kWh)	Electricity (kWh)	Space Heating (kWh)	DHW (kWh)	Electricity (kWh)	Space Heating (kWh)	DHW (kWh)	Electricity (kWh)
40,493	15,538	13,810	41,687	8,490	3,781	13,412	8,490	3,781	10,642	8,490	3,781
12,312	7,479	5,060	17,791	6,792	1,418	7,450	6,792	1,418	4,736	6,792	1,418
17,184	12,432	9,948	23,557	8,490	3,151	15,052	8,490	3,151	6,490	8,490	3,151
26,568	13,740	11,280	29,609	6,792	3,151	12,596	6,792	3,151	9,275	6,792	3,151
24,941	9,888	8,832	35,261	5,094	2,521	10,572	5,094	2,521	8,954	5,094	2,521

System Characteristic and managem	Base Case	Light Renov	us Renov		Base Case	Light Renov	Ambitious Renov		Base Case		Light Renovation		Wast			Base Case	Light Renov	Ambitiou s Renov		Base Case	Light Renov	Ambitiou s Renov		Base Case	Light Renov	Ambitious Renov	
Heting Supply Temperature	60	60	60	°C	-	60	60	°C		60		60		60	°C	60	60	60	°C	60	60	60	°C	60	60	60	°C
Return Temperature	40	40	40	°C	-	40	40	°C		40		40		40	°C	40	40	40	°C	40	40	40	°C	40	40	40	°C
Electricity Consumption																											
Lighting and Equipment	77,980	77,980	77,980	kWh	-	77,980	77,980	kWh		77,980		77,980		77,980	kWh	77,980	77,980	77,980	kWh	77,980	77,980	77,980	kWh	77,980	77,980	77,980	kWh
Efficiency of the grid	0.95	0.95	0.95			0.95	0.95			0.95		0.95		0.95		0.95	0.95	0.95		0.95	0.95	0.95		0.95	0.95	0.95	
Grid	82,085	82,085	82,085		-	82,085	82,085			82,085		82,085		82,085		82,085	82,085	82,085		82,085	82,085	82,085		82,085	82,085	82,085	
AC/DC Conversion Efficiency	0.95	0.95	0.95	kWh	-	0.95	0.95	kWh		0.95		0.95		0.95	kWh	0.95	0.95	0.95	kWh					0.95	0.95	0.95	kWh
AC/DC conversion	86,405	86,405	86,405		-	86,405	86,405			86,405		86,405		86,405		86,405	86,405	86,405						86,405	86,405	86,405	
FC electricity																											
Electricity consumption for Lighting and Equipments (grid assumption)	**86,405**	**86,405**	**86,405**	**kWh**	-	**86,405**	**86,405**	**kWh**		**86,405**		**86,405**		**86,405**	**kWh**	**86,405**	**86,405**	**86,405**	**kWh**	**0**	**0**	**0**	**kWh**	**86,405**	**86,405**	**86,405**	**kWh**
Energy Consumption (Domestic Hot Water)																											
Domestic Hot Water	191,881	191,881	191,881	kWh	-	191,881	191,881	kWh		191,881		191,881		191,881	kWh	191,881	191,881	191,881	kWh	191,881	191,881	191,881	kWh	165,297	165,297	165,297	kWh
Efficiency 1	0.85	0.85	0.85		-	3.58	3.58			0.85		0.85		0.85		0.85	0.85	0.85		0.37	0.37	0.37		3.5	3.5	3.5	
Energy consumption of Component 1	225,742	225,742	225,742	kWh	-	53,598	53,598	kWh		225,742		225,742		225,742	kWh	225,742	225,742	225,742	kWh	518,597	518,597	518,597	kWh	47,257	47,257	47,257	kWh
Efficiency 2	0.95	0.95	0.95		-	0.95	0.95			0.99		0.99		0.99		0.99	0.99	0.99		0.99	0.99	0.99		0.57	0.57	0.57	
Energy consumption of Component 2	237,623	237,623	237,623	kWh	-	56,419	56,419	kWh		68,407		68,407		68,407	kWh	228,022	228,022	228,022	kWh	523,835	523,835	523,835		82,907	82,907	82,907	kWh
Efficiency 3										0.70		0.70		0.70		0.70	0.70	0.70		0.70	0.70	0.70		0.99	0.99	0.99	
Energy consumption of Component 3										97,724		97,724		97,724	kWh	325,746	325,746	325,746		748,336	748,336	748,336		83,745	83,745	83,745	
Efficiency 4										0.95		0.95		0.95		0.95	0.95	0.95		0.95	0.95	0.95		0.70	0.70	0.70	
Energy consumption of Component 3										102,867		102,867		102,867		342,891	342,891	342,891		787,722	787,722	787,722		119,635	119,635	119,635	kWh
Efficiency 5										0.95		0.95		0.95										0.95	0.95	0.95	
Energy consumption of Component 3										166,336		166,336		166,336										125,932	125,932	125,932	
Energy Consumption for Domestic Hot Water	**237,623**	**237,623**	**237,623**	kWh	-	**56,419**	**56,419**	kWh		**102,867**		**102,867**		**102,867**	kWh	**342,891**	**342,891**	**342,891**	kWh	**787,722**	**787,722**	**787,722**	kWh	**125,932**	**125,932**	**125,932**	kWh
Energy Consumption (Space Heating)																											
Space Heating Consumption	806,194	316,282	214,251	kWh	-	316,282	214,251	kWh		806,194		316,282		214,251	kWh	806,194	316,282	214,251	kWh	806,194	316,282	214,251	kWh	745,918	292,635	198,233	kWh
Efficiency 1	0.950	0.950	0.950		-	4.31	4.31			0.95		0.95		0.95		0.95	0.95	0.95		0.37	0.37	0.37		4.3	4.3	4.3	
Energy consumption of Component 1	848,626	332,929	225,528	kWh	-	73,383	49,710	kWh		848,626		332,929		225,528	kWh	848,626	332,929	225,528	kWh	2,178,903	854,817	579,058	kWh	161,326	63,291	42,874	kWh
Efficiency 2	0.95	0.95	0.95		-	0.95	0.95			0.99		0.99		0.99		0.99	0.99	0.99		0.99	0.99	0.99		0.57	0.57	0.57	
Energy consumption of Component 2	893,290	350,451	237,398	kWh	-	77,246	52,327	kWh		257,159		100,887		68,342		857,198	336,291	227,806	kWh	2,200,913	863,451	584,907		283,029	111,036	75,217	kWh
Efficiency 3	-	-	-		-	-	-			0.70		0.70		0.70		0.70	0.70	0.70		0.70	0.70	0.70		0.99	0.99	0.99	
Energy consumption of Component 3	-	-	-	kWh	-	-	-	kWh		367,370		144,125		97,631	kWh	1,224,568	480,416	325,437		3,144,161	1,233,502	835,582		285,888	112,158	75,977	kWh
Efficiency 4										0.95		0.95		0.95		0.95	0.95	0.95		0.95	0.95	0.95		0.70	0.70	0.70	
Energy consumption of Component 4										386,706		151,710		102,770	kWh	1,289,019	505,701	342,565		3,309,643	1,298,423	879,560		408,411	160,226	108,538	kWh
Fuel cell efficiency for E+										0.95		0.95		0.95										0.95	0.95	0.95	
Fuel cell surplus										625,303		245,316		166,178										429,906	168,659	114,250	
Energy Consumption for Space Heating	**893,290**	**350,451**	**237,398**	kWh	-	**77,246**	**52,327**	kWh		**386,706**		**151,710**		**102,770**	kWh	**1,289,019**	**505,701**	**342,565**	kWh	**3,309,643**	**1,298,423**	**879,560**	kWh	**429,906**	**168,659**	**114,250**	kWh
Volume of Fuel									**Base Case**		**Light Renovation**		**nbitious Renovati**														
									30% H2	70% Gas	30% H2	70% Gas	30% H2	70% Gas													
Total Energy Consumption	1,130,913	588,075	475,021	kWh	-	133,665	108,746	kWh	489,573	791,639	254,578	411,652	205,637	332,515	kWh	1,631,910	848,592	685,456	kWh	4,097,365	2,086,145	1,667,282	kWh	555,838	294,591	248,800	kWh
Energy Content	10.6	10.6	10.6	kWh/kg	-	-	-	kWh/m3	33.3	10.6	33.3	10.6	33.3	10.6	kWh/kg	33.3	33.3	33.3	kWh/kg	33.3	33.3	33.3	kWh/kg	33.3	33.3	33.3	kWh/kg
Mass	106,690	55,479	44,813	kg	-	-	-	kg	14,702	74,683	7,645	38,835	6,175	31,369	kg	49,006	25,483	20,584	kg	123,044	62,647	50,069	kg	16,692	8,847	7,471	kg
Density	0.68	0.68	0.68	kg/m3	-	-	-	kg/m3	23.38	0.68	23.38	0.68	23.38	0.68	kg/m3	23.4	23.4	23.4	kg/m3	23.4	23.4	23.4	kg/m3	23.4	23.4	23.4	kg/m3
Volume	156,897	81,586	65,902	m3	-	-	-	m3	629	109,828	327	57,110	264	46,131	m3	2,096	1,090	880	m3	5,263	2,680	2,142	m3	714	378	320	m3
Water needed	-	-	-		-	-	-		132,317	-	68,805	-	55,578	-	L	441,057	229,349	185,258	L	1,107,396	563,823	450,617	L	150,227	79,619	67,243	L
Electricity needed	-	-	-		-	-	-							-	kWh	557,542	289,922	234,186	kWh	4,798,716	2,443,233	1,952,673	kWh	650,982	345,016	291,387	kWh

Scenario 1. Natural gas grid boiler system

Payback year total system			
	CAPEX total	$	420,807
	CAPEX-investment cost	$	246,190
	OPEX	$	10,469
	Percentage OPEX to CAPEX	**%**	**2%**
	Fuel Costs	$	51,751
	Total LCOE	**$**	**0.36**
20 years			
	CAPEX 20 yrs	$/20 years	406,577
	opex 20 yrs	$/20 years	143,751
	Fuel costs 20 yrs	$	1,111,535
	generation 20 yrs	kWh	13,044,330
	LCOE manual	**$**	**0.13**
	TO REMIND		
	Natural gas price	$	0.09
	generation per year	$	588,075
	Natural gas price	$	51,751

Scenario 2. All-electric heat pump system

Payback year of system			
	TOTAL CAPEX	$	933,316
	CAPEX-investment only	$	766,401
	total renovation cost	$	85,036
	OPEX	$/ year	12,183
	percentage OPEX to CAPEX	**%**	**1%**
	LCOE total	$/kWh	1.05
	Electricity cost currently	$	0.34
	Generation of electricity needed	kWh	110,157
	Total Investment Cost BC	$	246,190
	Total Energy Cost BC	$	51,751
	Total Investment Cost Sc 2	$	851,437
	Total Energy Cost Sc2	$	37,453
	A	$	605,247
	B	$	14,297
	PBT = A/B	year	**42**
20 years			
	CAPEX 20 yrs	$/ 20 years	901,754
	opex 20 yrs	$/ 20 years	167,290
	total renovation cost	$/ 20 years	85,036
	generation 20 yrs	kWh	4,263,507
	LCOE manual	$	**0.27**

Scenario 3. Blending hydrogen and natural gas system

Payback year of system		
TOTAL CAPEX	$	1,304,753
CAPEX-investment only	$	881,695
Fuel Cost	$	36,225
OPEX	$	35,464
percentage OPEX and CAPEX	**%**	**3%**
LCOE total	$/kWh	0.85
Green H2 price per kwh	$/kWh	0.17
Natural gas price	$/kWh	0.09
Generation of Hydrogen Sc3	kWh	254,577.72
Generation of natural gas Sc 3	kWh	411,652.18
Total Investment Cost BC	$	246,190
Total Energy Cost BC	$	51,751
Total Investment Cost Sc 2	$	881,695
Total Energy Cost Sc2	$	80,327
A	$	635,505
B	$	-28,576
PBT = A/B	year	**-22**
20 years		
CAPEX 20 yrs	$	1,260,631
opex 20 yrs	$	486,984
Fuel costs 20 yrs	$	778,075
generation 20 yrs	kWh	14,554,690
LCOE manual	$	**0.17**

Scenario 4. Microgrid Hydrogen boiler System

Payback year of system		
TOTAL CAPEX	$	2,630,831
CAPEX-investment only	$	1,874,910
gridlines upgrade	$	54,000
OPEX	$	66,346
percentage OPEX to CAPEX	**%**	**3%**
LCOE total	$/kWh	**0.65**
Green H2 price per kwh	$/kWh	0.17
Generation of Hydrogen Sc3	kWh	848,592.00
Total Investment Cost BC	$	246,190
Total Energy Cost BC	$	51,751
Total Investment Cost Sc 2	$	1,928,910
Total Energy Cost Sc2	$	144,261
A	$	1,682,719
B	$	-92,510
PBT = A/B	year	**-18**
20 years		
CAPEX 20 yrs	$	2,541,866
opex 20 yrs	$	911,054
gridlines upgrade	$	54,000
generation 20 yrs	kWh	18,078,864
LCOE manual	$	**0.19**

Scenario 5. Hydrogen Waste-heat fuel cell system

Payback year of system		
TOTAL CAPEX	$	5,955,952
CAPEX-investment only	$	4,763,420
OPEX	$	93,670
percentage OPEX to CAPEX	**%**	**2%**
LCOE total	$/kWh	0.56
Green H2 price per kwh	$/kWh	0.17
Generation of Hydrogen Sc3	kWh	2,086,145
Total Investment Cost BC	$	246,190
Total Energy Cost BC	$	51,751
Total Investment Cost Sc 2	$	4,763,420
Total Energy Cost Sc2	$	354,645
A	$	4,517,230
B	$	-302,894
PBT = A/B	year	**-15**
20 years		
CAPEX 20 yrs	$	5,794,013
opex 20 yrs	$	1,466,147
gridlines upgrade	$	54,000
generation 20 yrs	kWh	40,333,690
LCOE manual	$	**0.18**

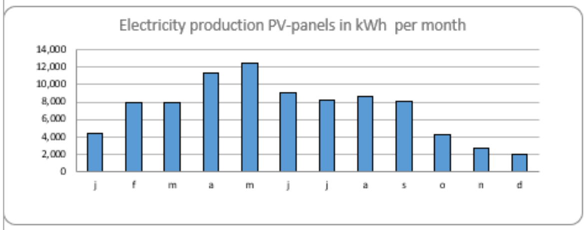
Scenario 6. Hybrid Hydrogen and heat pump system

Payback year of system		
TOTAL CAPEX	$	1,688,948
CAPEX-investment only	$	1,356,154
OPEX	$	32,760
percentage OPEX to CAPEX	**%**	**2%**
total renovation cost	$	85,036
LCOE total	$/kWh	0.95
Green H2 price per kwh	$/kWh	0.17
Generation of Hydrogen Sc3	kWh	248,800
Total Investment Cost BC	$	246,190
Total Energy Cost BC	$	51,751
Total Investment Cost Sc 2	$	1,441,190
Total Energy Cost Sc2	$	42,296
A	$	1,194,999
B	$	9,455
PBT = A/B	year	**126**
20 years		
CAPEX 20 yrs	$	1,638,690
opex 20 yrs	$	449,853
gridlines upgrade	$	54,000
total renovation cost	$	85,036
generation 20 yrs	kWh	6,518,576
LCOE manual	$	**0.34**

Scenario 1. Natural gas grid boiler system

Electricity production by Photo Voltaic (PV) panels

PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	330	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%

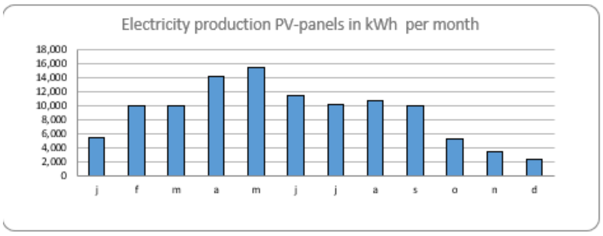


Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	4,350	0	0	0	0	0	4,350
f	8,006	0	0	0	0	0	8,006
m	8,006	0	0	0	0	0	8,006
a	11,369	0	0	0	0	0	11,369
m	12,430	0	0	0	0	0	12,430
j	9,115	0	0	0	0	0	9,115
j	8,190	0	0	0	0	0	8,190
a	8,591	0	0	0	0	0	8,591
s	8,048	0	0	0	0	0	8,048
o	4,200	0	0	0	0	0	4,200
n	2,703	0	0	0	0	0	2,703
d	1,961	0	0	0	0	0	1,961
year	86,970	0	0	0	0	0	86,970

Scenario 2. All-electric heat pump system

Electricity production by Photo Voltaic (PV) panels

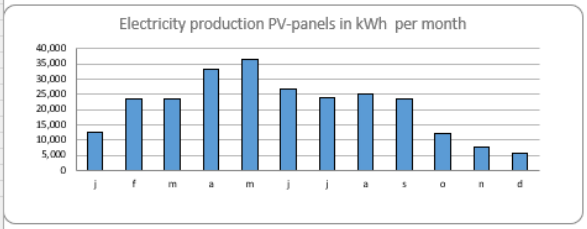
PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	413	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%



Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	5,444	0	0	0	0	0	5,444
f	10,020	0	0	0	0	0	10,020
m	10,020	0	0	0	0	0	10,020
a	14,229	0	0	0	0	0	14,229
m	15,556	0	0	0	0	0	15,556
j	11,407	0	0	0	0	0	11,407
j	10,250	0	0	0	0	0	10,250
a	10,752	0	0	0	0	0	10,752
s	10,072	0	0	0	0	0	10,072
o	5,257	0	0	0	0	0	5,257
n	3,382	0	0	0	0	0	3,382
d	2,454	0	0	0	0	0	2,454
year	108,844	0	0	0	0	0	108,844

Scenario 3. Blending hydrogen and natural gas system

PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	966	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%

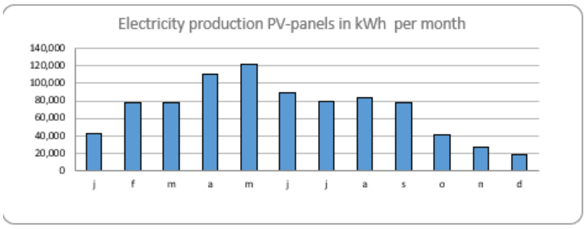


Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	12,734	0	0	0	0	0	12,734
f	23,437	0	0	0	0	0	23,437
m	23,437	0	0	0	0	0	23,437
a	33,281	0	0	0	0	0	33,281
m	36,385	0	0	0	0	0	36,385
j	26,681	0	0	0	0	0	26,681
j	23,974	0	0	0	0	0	23,974
a	25,149	0	0	0	0	0	25,149
s	23,559	0	0	0	0	0	23,559
o	12,295	0	0	0	0	0	12,295
n	7,912	0	0	0	0	0	7,912
d	5,740	0	0	0	0	0	5,740
year	254,584	0	0	0	0	0	254,584

Scenario 4. Microgrid Hydrogen boiler System

Electricity production by Photo Voltaic (PV) panels

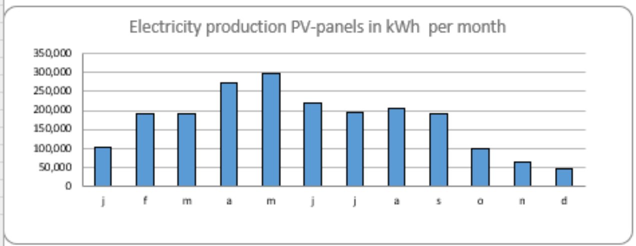
PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	3220	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%



Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	42,446	0	0	0	0	0	42,446
f	78,124	0	0	0	0	0	78,124
m	78,124	0	0	0	0	0	78,124
a	110,935	0	0	0	0	0	110,935
m	121,285	0	0	0	0	0	121,285
j	88,936	0	0	0	0	0	88,936
j	79,914	0	0	0	0	0	79,914
a	83,829	0	0	0	0	0	83,829
s	78,529	0	0	0	0	0	78,529
o	40,984	0	0	0	0	0	40,984
n	26,372	0	0	0	0	0	26,372
d	19,133	0	0	0	0	0	19,133
year	848,612	0	0	0	0	0	848,612

Scenario 5. Hydrogen Waste-heat fuel cell system

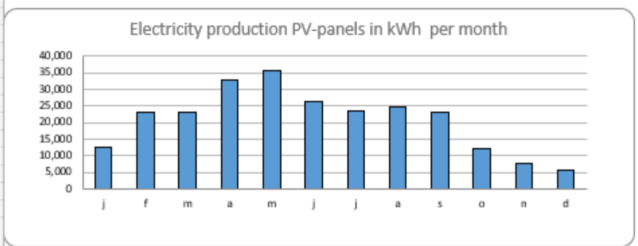
PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	7920	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%



Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	104,401	0	0	0	0	0	104,401
f	192,155	0	0	0	0	0	192,155
m	192,155	0	0	0	0	0	192,155
a	272,860	0	0	0	0	0	272,860
m	298,315	0	0	0	0	0	298,315
j	218,750	0	0	0	0	0	218,750
j	196,559	0	0	0	0	0	196,559
a	206,189	0	0	0	0	0	206,189
s	193,153	0	0	0	0	0	193,153
o	100,806	0	0	0	0	0	100,806
n	64,865	0	0	0	0	0	64,865
d	47,061	0	0	0	0	0	47,061
year	2,087,268	0	0	0	0	0	2,087,268

Scenario 6. Hybrid Hydrogen and heat pump system

PV-system	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	S	30	950	20%
PV-system 2	S	50	0	12%
PV-system 3	HOR	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%



Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	12,523	0	0	0	0	0	12,523
f	23,049	0	0	0	0	0	23,049
m	23,049	0	0	0	0	0	23,049
a	32,729	0	0	0	0	0	32,729
m	35,783	0	0	0	0	0	35,783
j	26,239	0	0	0	0	0	26,239
j	23,577	0	0	0	0	0	23,577
a	24,732	0	0	0	0	0	24,732
s	23,169	0	0	0	0	0	23,169
o	12,092	0	0	0	0	0	12,092
n	7,781	0	0	0	0	0	7,781
d	5,645	0	0	0	0	0	5,645
year	250,367	0	0	0	0	0	250,367

Scenario 1. Natural gas grid boiler system

(1) Natural gas grid system				
Process	**Demand**	**Value**	**Grand Total**	
	kWh	**g/kWh**	**1 year (kg)**	**20 years (kg)**
Pipeline Construction and gridline installment	180	1070.00	193	193
Natural gas production	588,075	4.98	2,929	2,929
PV Solar for electricity demand	86,405	69.10	5,971	5,971
Air emissions	588,075	274.40	161,369	3,227,379
Total (kg)		1418.48	170,461	3,236,471

Scenario 2. All-electric heat pump system

(2) All electric heat pump system				
Refrigerants use and leakage	108,746	163.00	17,726	354,512
Manufacturing, Equipment and installation	108,746	17.19	1,869	1,869
Heat pump operation	108,746	15.25	1,658	1,658
PV solarfor electricity demand	86,405	69.10	5,971	5,971
Upgrading insulation renovation	2,970	730.00	2,168,100	2,168,100
Total (kg)		994.54	2,195	2,532

Scenario 3. Blending hydrogen and natural gas system

(3) Hydrogen and natural blended system				
Construction and gridline installment	180	1070.00	193	193
Natural gas production	411,652	4.98	2,050	2,050
Air emission	411,652	274.40	112,957	2,259,146
Electrolysis process, and compression	254,578	6.40	1,628	1,628
PV solar for electricity demand	86,405	69.10	5,971	5,971
PV solar for hydrogen production	254,578	69.10	17,591	17,591
Total (kg)		1493.98	140,390	2,286,579

Scenario 4. Microgrid Hydrogen boiler System

(4) Microgrid hydrogen system				
Pipelines upgrade	180	1320.00	238	238
Construction and gridline installment	180	1070.00	193	193
Plant operation and construction	848,592	20.29	17,218	172,179
Electrolysis process, and compression	848,592	6.40	5,428	108,559
PV solar for hydrogen production	848,592	69.10	58,638	58,638
PV solar for electricity demand	86,405	69.10	5,971	5,971
Air emissions	848,592	0.00	0	0
Total (kg)		1234.89	87,684	345,776

Scenario 5. Hydrogen Waste-heat fuel cell system

(5) Cogeneration hydrogen fuel cell system				
Plant operation and construction	2,086,145	20.29	42,328	42,328
Fuel Cell Operation	2,086,145	2.48	5,174	5,174
Electrolysis process, and compression	2,086,145	6.40	13,344	13,344
PV solar for hydrogen production	2,086,145	69.10	144,153	144,153
Air emissions	2,086,145	0.00	0	0
TON (kg)		75.50	204,998	204,998

Scenario 6. Hybrid Hydrogen and heat pump system

(6) Hybrid hydrogen heat pump system				
Plant operation and construction	248,800	20.29	5,048	5,048
PV solar for hydrogen production	248,800	69.10	17,192	17,192
PV solar for electricity demand	86,405	69.10	5,971	5,971
Refrigerants leakage	248,800	163.00	40,554	811,088
Manufacturing, Equipment and installation	248,800	17.19	4,277	4,277
Heat pump operation and maintenance	248,800	15.25	3,794	3,794
Electrolysis process, and compression	248,800	6.40	1,591	1,591
Fuel Cell Operation	248,800	2.48	617	617
Upgrading insulation renovation	2,970	730.00	2,168	2,168
Air emissions	248,800	0.00	0	0
Total (kg)			81,213	851,746