The challenges of decarbonising heating of rural UK homes

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Abstract

In UK law, the country must reduce it's carbon emissions by 100% by 2050 in comparison to emissions produced in 1990 (UK Parliament 2008). Simply put the United Kingdom must reduce it's emissions to net zero by 2050. Domestic heating currently accounts for the largest proportion of CO2 emissions of the UK, where effort has been made to decarbonise improve UK housing stock. The vast majority of which are in urban and suburban environments. The work in this thesis comprises of understanding the current state and challenges to decarbonise rural homes, particularly remote home heating. Enabling lower emissions homes and heating in rural settings is more challenging and costlier due to various factors such as remoteness, lack of infrastructure, government awareness and other factors. This work is seeking to contribute to awareness and understanding of rural domestic energy access and the challenges in reducing household energy emissions in this setting.

This will be done by surveying rural residents and evaluating ***who*** lives rurally, and ***what*** sort of buildings they live in, five rural energy user groups are identified that can facilitate subsequent research in this thesis and beyond. 20 models are developed of a single rural home microgrid. Each using a different heating fuel or technology that is currently used in rural UK homes and low emissions technologies that could be used in rural settings in the future.

The 19 developed models are simulated across 6 different energy demand profiles. Three demand profiles are estimated, based on local heat degree days and building characteristics. Three more energy demand profiles are based on smart meter data using the earlier derived rural energy user groups, resulting in total 114 unique sets of results. Each model result is scored based on factors such as emissions, cost and energy efficiency. It is found that that heat pump based energy systems are the best scoring. The poorest scoring systems are those that electrolyse and generate hydrogen on location.

This thesis finishes by developing a home scale demonstration system using metal hydride material to store hydrogen gas in a solid state in a domestic energy system. In addition, a digital twin of this system is simulated and analysed alongside the 19 other microgrid models, resulting in 120 total model results

The purpose of this thesis is to develop and compare the current fuels and technologies used in rural domestic heating and power, to compile some of the challenges towards rural domestic net zero, and evaluate some low emissions technologies that could be considered and used in the future by rural residents and policymakers. And to demonstrate novel energy storage technologies that could be used in rural UK settings.

All to contribute towards a just transition to net zero and low emissions domestic energy to *everyone* no matter of socioeconomic ability. And to *everywhere*, whether from the city to the countryside or from the lowland to the highland.

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Chapter 1

Introduction

The United Kingdom (UK) has in law committed to reaching net zero *(a 100% reduction of greenhouse gas emissions compared to 1990 levels)* by 2050, according to the Climate Change Act 2008 (UK Parliament 2008). Currently, a fifth of UK emissions arise from heating buildings (H. Government 2021a). Greatly reducing building heating emissions will be critical in achieving net zero in the UK, as energy used to UK heat homes with gas can be up to five times the amount of electricity used in homes across the year (I. A. Wilson et al. 2013).

1.1 Background

Decarbonising heat is more challenging than decarbonising electricity, due to the wide variety of fuels and technologies used for domestic heating. In the UK natural gas dominates the domestic heating sector, where just under 80% of UK households consume natural gas as a heating fuel. The heating demand is weather dependent with greater demands at low temperatures. As a result there is a huge seasonal variation in heating (and therefore gas) demand with the greatest in the cold winter months and the least in the summer as seen in figure 1.1. This results in a large proportion of UK greenhouse emissions can be attributed to heating buildings and particularly domestic heating.

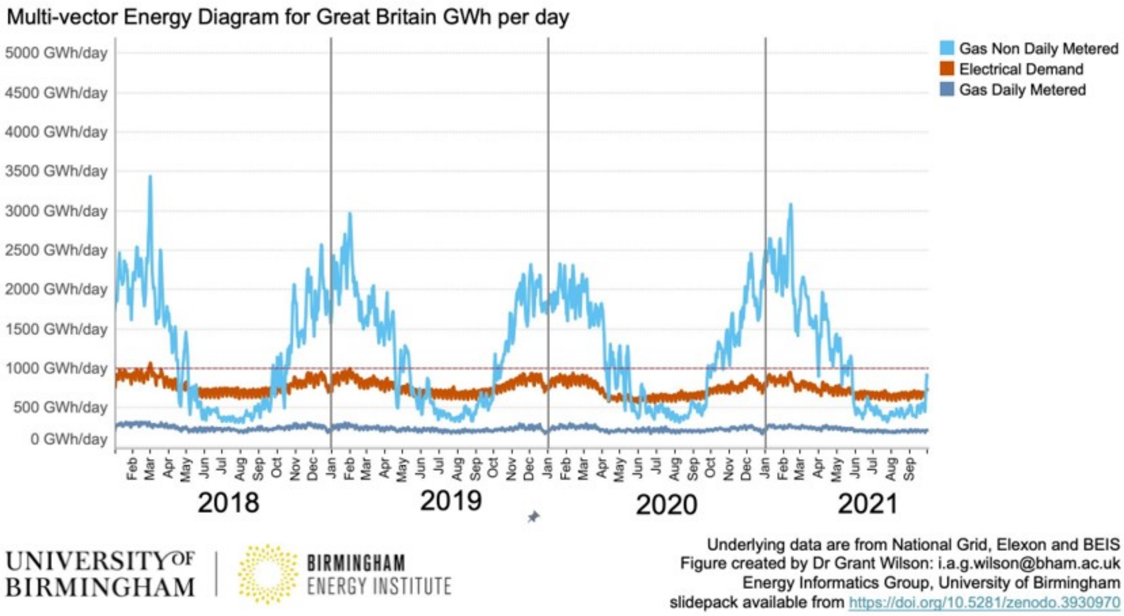


Figure 1.1: GB daily gas and electricity consumption, 2018 to 2021 (G. Wilson 2021)

There are two primary approaches to reducing emissions from domestic heating, one is to make buildings more energy efficient. The second approach of reducing domestic heating emissions is to directly replace the heating fuels and methods used in a home with lower emission fuels.

Homes can be made more energy efficient through measures such as installing insulation, double glazed windows and draught excluders, which effectively reduces the total annual energy demand of a home. This results in high upfront capital cost but long term operational cost savings, due to less energy being consumed to maintain the same level of heat in a home. Otherwise, emissions can be reduced by using lower carbon intensive heating fuels such as renewable electricity or renewable electrolytic hydrogen. Conversely the cost implications of this approach to reducing heating emissions results in often lower upfront capital costs and higher operational costs.

Defining the optimal low carbon energy system for a building, domestic or otherwise is keenly dependent on the existing building fabric and energy systems. The emissions and cost benefits will widely vary depending on this start point, consequently the low carbon energy system that can be achieved at a property will vary. Factors such as the building retrofit cost to improve energy efficiency, the emissions reduction, capital cost to remove old and install a new energy system, potential planning restrictions and the practicality of are among some of the considerations made when considering a building redevelopment project to reduce energy consumption and emissions. These factors are often key deciding factors that define the scope and scale of such a project as key requirements or limiting factors to the project.

There has been some research investigating various technologies and strategies enabling remote and off grid single home energy decarbonisation. Comprising of simulations and practical demonstrations of single home microgrids utilising the technology that is target of said research. There are limitations to some of the research here and discussed in the literature reviews in the subsequent chapters, such as limited to little comparison and analysis of different fuels, technologies, energy systems and the quality of the building fabric (how energy efficient the building is in retaining heat). This thesis seeks to address this gap of comparison between energy fuels and technologies with the comparative simulations discussed in chapter 5.

1.2 Switching to cleaner forms of energy

In order to meet UK net zero targets a combination of both, increasing building efficiency and switching to cleaner fuels is required. This requires individual consumer and government investment and support to achieve this. Aside from cost, key considerations to a large scale switch to low carbon domestic heating are other technical and social implications and measures required to achieve this. This has happened before in the 1960s, where a large energy fuel switch occurred. A key factor in the successful 1960 UK nationwide switch from town gas to natural gas was getting the public on board (Arapostathis, Laczay, and Pearson 2019). With the UK preparing for a second nationwide transition away from natural gas, a just transition should be ensured as this would also serve to get the public on board and enable a smarter transition.

In the landscape of the decarbonisation of UK housing stock and heating, rural and rural off gas grid housing are often an afterthought. In the UK and devolved governments policy about decarbonising off grid homes (homes not connected to the national gas grid), there is little policy attention or ”quick wins” in heat decarbonisation. With the resulting policy suggestion of implementing heat pump systems to enable low carbon heating.

In England and Scotland 17% of the population lived in rural regions, 32% of the Welsh population lives rurally and 32% of the Northern Irish population lives rurally (Vera-Toscano et al. 2024) in total across the UK 18% of the population live rurally. This is a significant fraction of the population which live in households which are much more diverse and varied in building composition, building age and heating fuels used than the remaining 82% of UK homes. Due to the diversity of UK off gas grid homes there is no “one size fits all” approach. Further analysis is needed to ensure greater focus is had in assessing the state of present day rural and remote domestic heating and evaluating some potential technological pathways to low carbon heating.

1.3 Aims and objectives

When considering this background to UK energy consumption and looking towards reducing emissions of UK homes due to heating and electricity, in particular rural homes. The aim of this research is develop an understanding of different fuels used to heat and power rural UK homes, with particular focus on off gas grid homes. Understanding the energy system change required to enable reduced emissions from rural homes which typically use various fuels with high emissions emitted. This achieved through the objectives of having techno-economic analysis of 20 different energy system scenarios in a rural UK home. Developing a profile of the energy system of a rural UK home and demonstrating in the lab a novel hydrogen energy storage technology modelled in the techno-economic analysis

1.4 Timeliness of this research

This research is timely in the context of UK and worldwide efforts towards decarbonisation and lowering emissions across all of society. Emissions form producing or consuming energy for use in a home is a major contributor. This research looking at decarbonising energy of rural, off gas grid UK homes is novel as there is minimal research published discussing and comparing domestic heating fuels. It will be a resource useful for stakeholders on all levels, homeowners, farmers, estate mangers, regional, national and international policymakers, industry and other researchers. It is important to make informed decisions when selecting an energy technology. This research focuses on a UK rural setting, Making the results presented broadly applicable to other comparable climates (northern Eurasia, northern North America and southern South America) and comparable economies. The methodologies discussed here can be utilised for any technology and any geography in the world.

1.5 Thesis overview

This thesis comprises of numerous key background, research and results chapters:

- Chapter 2 is the literature review, providing an overview of greater background to the challenges of energy access in rural UK, the policy background of UK and devolved governments towards domestic heat decarbonisiation and particular focus on rural and remote off grid dwellings. Other literature reviewed includes research of simulating and demonstrating measures and systems that can demonstrate homes that can provide power and or heat from gas and/or electric grids.

- Chapter 3 provides an overview of the methodology of this thesis and the individual research chapters as each have a distinct and separate methodology where the results of each project directly contribute to each other. The methodologies for each section are key extracts (in part or whole) of methodologies found in each research chapter.

- Chapter 4 looks at *who* lives rurally and off the gas grid by surveying rural residents. This is achieved by developing, distributing and analysing the results of a nationwide survey asking respondents to provide details about themselves, the energy systems in their homes and their views on sustainability. Understanding *what* is the technological and fuel compositions of their homes. Producing five user groups reflecting every type of rural resident for future modelling in this work and in future research seen in chapter 6.

- Chapter 5 comprises of computer modelling of domestic energy systems. *comparing* various rural off grid heating fuels and systems used presently, and low carbon alternatives such as heat pumps and hydrogen. Evaluating the results of the computer model according to various techno economic factors. Further discussing other qualitative factors that may influence the viability of one technology over the other. And why should the modern fuels and technologies analysed here be considered as alternative technologies to rural heating. Exploring the technical (e.g. efficiency), economic (e.g. operational and capital cost) and social factors.

- Chapter 6 follows on from the previous chapter re-computing the microgrid computer models with a new dataset of energy demand data sourced from smart meters that are developed according to the energy user groups produced in chapter 4. This chapter analyses and compares the results of simulations using metered energy demand data and estimated energy demand data.

- Chapter 7 demonstrated in the lab one technological solution to rural off grid heating with hydrogen gas and storing hydrogen in a solid state metal alloy. With the demonstration system comprising of a hydrogen elctrolyser and solid state hydrogen storage system. This work will find that household rural heating emissions can be greatly reduced compared to the traditional bulk fuels used for rural heating. The exact solution will vary depending on the user group modeled and other key quantifiable factors. Such as cost, and other qualitative factors (such as practicality of implementation) which are touched upon in this work but need further detailed investigation.

- Chapter 8 concludes this thesis collating and discussing all of the work researched and analysed in all previous chapters. Discussing how all the work relates to and are dependent on each other, discussing implications this work will can have on future decision making and other research, and discussing what future work can directly follow from this thesis.

Chapter 2

Literature Review

2.1 Introduction

This chapter examines and interrogates the current situation for rural energy use in order to establish the gaps in knowledge and research additions opportunity in this field. First establishing the context of the current domestic energy mix in the UK, with focus on domestic heating fuels, which accounts for a greater proportion of energy consumption in a UK home than power. Understanding UK and regional government policy towards decarbonising rural heating and identifying the gaps and opportunities in current policy. And an overview of current research on decarbonising remote and rural domestic energy systems. Exploring various low emission technologies, operating strategies and system configurations to enable an effective rural or remote domestic energy system for power and/or heat.

2.2 Domestic heating in the UK

2.2.1 Four nations, four heating fuels and technologies

How the UK heats its homes can be broadly put into four groups based upon fuel type and heating technologies.

1. **Grid gas heating.** By far the most widespread and common heating fuel with gas piped directly to homes

2. **Electricity.** Electric heating can come in various forms and technologies, such as Restive radiators, hot water immersion heating or heat pumps. This is often found in flats and apartments.

3. **Bulk fuels.** Fuels such as Heating oil, LPG, wood and coal. Typically found in rural remote homes where there is no gas grid.

4. **District heating.** These function with a heat network delivering hot water from a central communal boiler house to each building on the network, similar

to the national gas distribution grid. District heating networks have central communal boiler houses that generate heat from typically gas or other fuels. There are various examples of community district heating in the UK such as in Nottingham where over 5,000 homes are connected, with heat provided from a local waste incinerator (Enviroenergy 2024).

The national overview of heating fuels used in the UK reveals key insights in how the UK heats it's homes. Across the four home nations of the UK, the domestic heating fuels used also vary, both in variety and quantity of fuels used as seen in figure 2.1. There is a clear difference between the fuel mixes of Northern Ireland and the other three nations of England, Scotland and Wales. This is due to a GB-wide natural gas pipeline network that serves the majority of GB domestic homes.

In Northern Ireland only a third of domestic homes are served by a grid gas connection (Stewart and Bolton 2024). Half are served by bulk heating oil and the remaining fuels of domestic heating are served by electric heating (including heat pumps) and other bulk fuels such as LPG, coal, peat and wood. The domestic heating fuels used in the Republic of Ireland have a very similar composition to Northern Ireland.

In GB each home nation broadly composes similar proportions of the different fuels used with some variance of a few percentage points, however broadly in agreement with the total UK fuel mix. The variance of the GB nations fuel mixes reflect the geography and population represented in each nation. England composes of 84% of UK households, followed by Scotland (%9), Wales (%5) and Northern Ireland (%3). The type of fuel used can reflect the degree of urbanisation of the population of the nation. Urban regions typically are heated by grid gas, district heating and electricity, whereas rural regions typically are heated by bulk fuels or electricity.

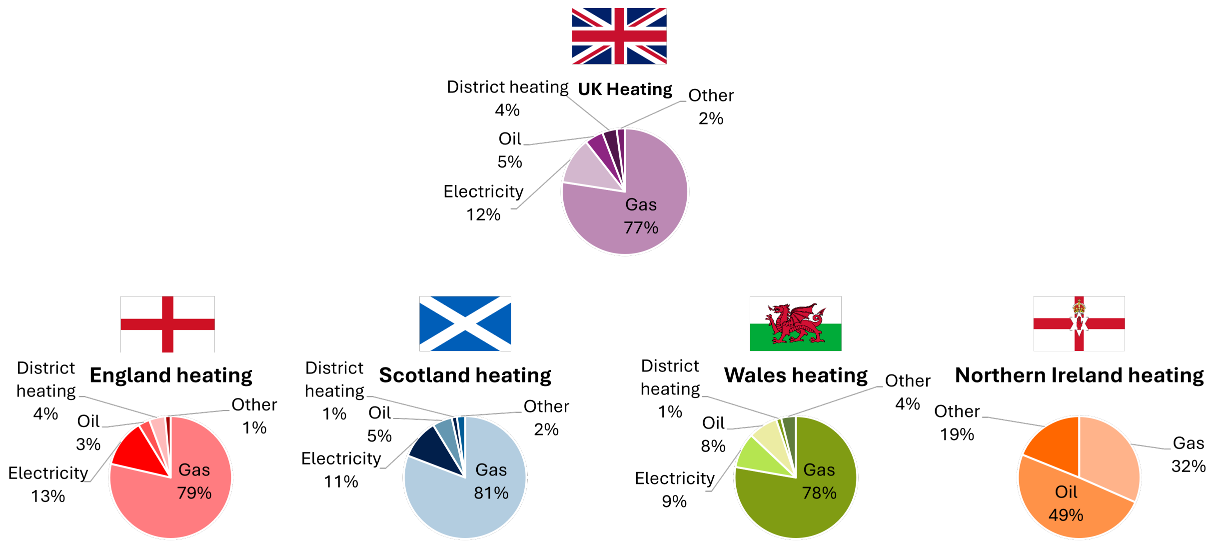


Figure 2.1: Domestic heating fuels used in the UK (top), England (far left) (Office for National Statistics 2021), Scotland (middle left) (Scottish Government 2020), Wales (middle right) (Office for National Statistics 2021), Northern Ireland (far right) (Stewart and Bolton 2024).
The "Other" dataset from Northern Ireland also includes electric heating, communal heating and no central heating.

2.2.2 The different ways homes are heated based on location

It is important to look at not only national, as this can help inform broader national or regional policies to decarbonising domestic heat, but also to look at the domestic energy landscape from a rural and urban perspective.

In the UK, the level of how urban or rural of a settlement you may live is a strong indicator of the heating fuels used in the home. Other implications can be deduced such as socio-economic factors such as fuel poverty, education level and access to public services. This work evaluates the current costs and emissions associated with heating rural homes. It also evaluates the costs and emissions that would result from switching rural homes to low carbon off grid domestic energy systems.

There is a rural/urban divide on heating homes in the UK. Over 77% of homes use gas from the national gas grid to heat their homes. In rural regions of the UK only 63% are connected to the gas grid compared to 81% of urban homes (Table 2.1). Fuels used to heat the remainder of homes include heating oil, electricity and fossil fuels (typically LPG, coal and other solid fuels).

Homes off the gas grid in urban areas typically use electricity for heating followed by communal district heating. Whereas rurally most off-gas grid homes are found, predominately use oil, followed by other fuels.

Off the gas grid homes in a rural setting using heating fuels such as oil and LPG will produce a larger share of emissions per household than the majority of homes using grid connected gas and electricity. This not just due to emissions directly associated with the use of the fuel itself, however also due to production and transport emissions.

Solely comparing urban and rural heating fuels, **a rural resident will produce 5% more emissions for the same unit of energy compared to an urban resident**, calculation presented in appendix C.1. These fuels have limited price controls unlike grid gas and electricity, making these fuels more sensitive to local

Table 2.1: Breakdown of heating fuels used in households in the United Kingdom including a rural/urban breakdown (Office for National Statistics 2021), (Scottish Government 2020),(Northern Ireland Housing Executive 2016), (Stewart and Bolton 2024)

Fuel	Grid Gas	Electricity [1 2 4]	Oil	Communal Heating [2]	Other [3 4]
Households	21,669,716	3,350,895	1,331,343	1,034,907	597,806
UK	77%	12%	5%	4%	2%
Urban UK	81%	11%	3%	4%	1%
Rural UK	63%	13%	18%	1%	5%

[1] *Includes heat pump figures for England and Wales*
[2] *excludes Northern Ireland, see [4] for electric heating in Northern Ireland*
[3] *Includes all other fuels such as: Dual fuel, solid fuel, tank or bottled gas, wood, B30K, bioethanol, biogas, biomass and liquid biofuel, Anthracite, coal and house coal, and smokeless fuel, Tank or bottled gas includes Liquefied Petroleum Gas (LPG).*
[4] *The "Other" dataset from Northern Ireland also includes electric heating, communal heating and no central heating.*

and global energy trends increasing the price volatility.

In April 2022 the price cap of grid gas and electricity has increased by 54% in the UK (Ofgem 2022) due to a global increase in gas and oil prices. In Northern Ireland the 2022/2023 energy crisis is particularly worse as 50% of the country relies on oil for heating. One consequence of the energy price increases in April 2022 brought over 2 million more households into fuel poverty* (UK Government and Department for Energy Security and Net Zero n.d.), bringing the total to over 6.2 million households. Even excluding recent energy cost increases due to external conflict, **a rural resident would typically pay 10% more for the same unit of energy compared to an urban resident**, calculation presented in appendix C.1.

Until 2016 the majority of those in fuel poverty were in rural areas, the shift of fuel poverty to an urban majority does not suggest a decrease in the proportion of fuel poor households rurally. Rather since 2018 there has been an increase in the proportion of fuel poor households overall from both urban and rural regions. Geopolitical events affecting the world energy markets such as the conflict in Ukraine serve as motivating factors to decarbonise heating and localised energy production. **Fuel poverty is defined as when after a household spends the required amount of energy to heat their home, they are left with a residual income below the official poverty line. In 2021 the UK government narrowed this definition to also require the household home to have an energy efficiency rating of D or below (UK Government and Department for Energy Security and Net Zero n.d.).*

Rural heating

In the UK, the majority of homes are connected to the national gas grid and hence use gas for heating. When breaking down gas connected homes between urban and rural, a variance from 77% of gas connected homes in urban settings (Table 2.1) to 63% in rural settings. Where non gas heating comprises of oil (18%) and electricity (13%) as the next two largest fuels used rurally.

Why do rural house holds require a higher amount of energy for heating in comparison to urban households? The UK has an old housing stock predominately designed with older housing standards and heating systems, with poorer standards of energy efficiency and emissions. This is particularly prominent rurally where there is a greater proportion of homes built before 1919 (28%) than in urban settings (18%) (Department for Environment 2024). These older homes have older and less efficient heating systems and poorer building fabric (1890s stone wall cottage vs. 2000s cavity wall insulated house). The thermal performance of the building fabric is quantified using U-values (thermal transmittance).

Lower U-values equate to higher heating efficiency as the building has greater thermal resistance, i.e. heat transfers through the fabric of the building at a lower rate. Older properties typically are built with a single solid stone or brick wall between the exterior and interior of the building with a typical U value between 2 and 3 (thegreenage.co.uk 2013).

Modern homes (from 1970 to 1999) are typically built with unfilled cavity walls. This comprises of having separate interior and exterior walls in a building separated by a gap (cavity) of air between the two walls. Providing a U value of 1 to 0.6, which is typical for a 1970s British terraced or detached home (thegreenage.co.uk 2013). This is the most common age group of English and Welsh homes (Valuation Office Agency 2021). New build 21st century homes with filled cavity walls typically have U values of 0.6 to 0.2.
Older solid single wall properties can most commonly be found in rural districts as often such related heritage characteristics are part of the aesthetic appeal of such buildings. But increased energy costs due to the inherent relative inefficient fabric of these buildings as well as the central heating systems used, compared to the median year of construction of UK homes (1970s). Furthermore, other factors, such as rural regions having lower levels of fuel poverty than in urban regions (11.7% rural fuel poverty and 13.5% of urban fuel poverty) (UK Government and Department for Environment Food & Rural Affairs 2022). However the fuel poverty gap, the amount of money required to bring a fuel poor home out of fuel poverty almost doubles from urban settings (£193) to rural settings (£388) and even more in remote rural settings (£501) (ibid.). These statistics highlight the more acute motivation to improve building heat efficiency and to decarbonise and modernise rural heating, not just for environmental benefits, also for economic benefits of reduced lifetime cost.

The UK government is beginning to address heat inefficiency and central heating with energy grants towards renewable heating, boiler replacement and home insulation (*Apply for the Boiler Upgrade Scheme: Overview - GOV.UK* n.d.). Yet these measures are often not enough to sufficiently cover widespread adoption as associated works can become cost prohibitive. Especially in rural regions where a more remote, older and more diverse housing stock requires greater costs to bring home heating system and efficiency to the minimum desired standard of Energy

Performance Certificate (EPC) C (Higney and Gibb 2024), (Martin 2023), (James Numminen 2022). Section 2.3 provides a further look at UK government policy to rural and domestic heat decarbonisation.

Off grid rural heating

A majority of these heating fuels are considered high carbon forms of energy that are clear targets for conversion to low/zero carbon technologies. This is the case at a large scale with coal and oil-based centralised electricity generation. Where most remaining power stations having closed down or converted to lower carbon intensive forms of electricity generation such as biomass and natural gas (powerstations.uk n.d.).

An increasingly higher proportion of power generation is derived from renewable energy sources of energy such as wind and solar. Recently there have even been some days of electricity generation from almost only renewable sources. At the time of writing (June 2024), 39% of electricity generated in the past year was from renewable sources followed by 29% from fossil fuels, 22% from nuclear/biomass and the remaining 10% importing energy from abroad via interconnectors (*National Grid: Live* n.d.).

The best solution with the UK's off gas housing stock is unclear and will be further investigated in this thesis. An effective insulation solution will typically require external or internal cladding for solid walled homes. External cladding can detract from the external appearance and appeal of a home, which can contribute to the value of a home. Given these complexities there is no definitive decarbonisation solution for the UK's off gas grid rural housing. Internal cladding reduces the livable space inside for occupants, the space of which may be valuable to the occupants, particularly in a small home. These insulation solutions may not be appealing options for the occupants and could be demotivating factors to unsure residents considering energy efficient measures, although technically feasible.

Alternatively, alongside or separately from insulating a home, there are various low or zero emissions heating system solutions available, such as heat pumps, biomass, solar thermal, hydrogen and electric heating. These can be used off gas grid in conjunction or separate from installing insulation. All of these represent a significant reduction or elimination of emissions with varying efficiency, feasibility and cost.

Heating fuels and technology

To evaluate rural, remote, domestic and off grid energy systems as chapter 5 will demonstrate of both present day and low carbon systems, an overview the current technological heating solutions and fuels used in rural off grid heating provides background to the later work in chapter 5.

Heating oil: Kerosene is the most prevalent oil used for heating. There is a varying range of performance of oil heating systems, with non condensing oil boilers are generally 60% efficient whereas modern condensing oil boilers are highly efficient at 95% (Power to Switch n.d.) comparable to modern gas boilers. Oil systems also require storage onsite generally in tanks ranging in storage capacity from 500-2000L with oil delivered by tanker typically a few times a year.

Bulk fuels: Coal, peat/turf and their derivatives are the primary bulk solid fossil fuels used in the UK for heating. These fuels are one of the most energy dense yet polluting fuels. Coal is used in fireplaces to heat rooms which often include back boilers to provide hot water.

LPG: Liquid Propane Gas (LPG) is similar to gas found in the national gas grid. The difference is there is no grid connection and all the gas is stored onsite in tanks. This method of delivery is similar to heating oil systems through delivery by tanker trucks or purchase of portable gas bottle cylinders. The portability of LPG gas in bottled or tankered formats makes this one of the most popular and accessible portable heating fuels used in various remote settings. Such as rural homes, caravans (static and movable), houseboats and camping.

Biomass: Is a broad term for fuels derived from organic matter such as wood, sugar cane, food processing residue, and manure. It is often not a zero-carbon source of energy at the point of use. Depending typically on the feedstock of the fuel, such as burning wood, bioethanol or other bio byproducts can reduce the emissions produced compared to fossil fuels for the same quantity of energy produced.

For home heating in the UK the primary biofuels used is wood (in the form of logs or pellets) and hydrotreated vegetable oil (HVO, a bio-oil), these fuels and others such as biogases can often directly replace a fossil fuel such as coal, heating oil or natural gas with little modification to the existing heating system.

Biomass heating systems are the secondary preferred heating system by UK government policy to reduce heating emissions in rural off grid buildings where heat pumps are not suitable (H. Government 2021a), (Scottish Government 2022a).

Electric heating: consists of various heating technologies that use electricity for heat. The primary technologies used are storage heaters, immersion heaters and electric boilers. Storage heaters consist of radiators installed in rooms across a house that contain heat retaining bricks that are heated up by electricity overnight on the cheaper night tariffs of electricity known as economy 7 and economy 10 (Which? N.d.). Electric boilers are comparable to gas, LPG and oil boilers, to provide on demand heat using a different fuel. Electric boilers can have a lower flow rate and take longer to reach the desired temperature than gas. A limiting factor with electric boilers is the electrical capacity of the building as electric boilers draw large amounts of power and may exceed the building limit.

Heat pumps: Are also another form of electric heating that is sometimes considered part or separate to other electric heating technologies. Heat pumps take heat from outside and pumping it inside via a heat exchanger and electric pump transferring that heat to the building via a heat transfer fluid. Simply described the most common type of heat pump (air source) operates with the same mechanism

to an air conditioning unit or refrigerator, only operating in reverse where an air conditioning unit expels the heat and pumps in cold air, a heat pump expels cold air and pumps in warm air.
The measure of performance of a heat pump is the Coefficient of Performance (COP), a ratio of heat produced and electricity used. The COP varies on the external heat sink temperature (the outside air for an air source heat pump or underground boreholes for a ground source heat pump) and internal heat demand of a building. A Typical COP for a UK home with a heat pump is 2.8, where 1kW of electricity produced 2.8kW of heat, equated to a performance of 280%. The running cost of a heat pump is dependent on the COP and the price of electricity used to power the heat pump.
There are various types of heat pumps that pump in heat in various forms and various formats. In the UK the most common types are air source, pumping in heat from air outside of the building. Ground source heat pumps on the other hand pumps in heat from the soil underground the building via heat transfer fluid.

Heat pumps can struggle in cold winter months, particularly air source heat pumps. The greater the temperature difference between the building interior and the building exterior, the greater the energy input is required to pump heat into the building. Heat pumps efficiency can drop quite rapidly in such weather conditions struggling to keep up the with the heat demanded. In these climates without effective insulation reducing the total energy required to maintain heat heat pump efficiency and running cost is comparable to gas boilers. This challenge in heat pump technology is still to be cost effectively overcome.

To make homes heat pump compatible and effective often requires installing insulation (and hence the EPC) to a minimum building efficiency standard. Which can entail replacing heat systems such as radiators, replacing with resized radiators or underfloor heating. Ensuring building insulation is installed to a minimum standard (EPC C) and having high levels of building air tightness.

All of these extra measures are desirable to increase building energy efficiency and reduced running costs, as well as the heat pump reducing running costs. However these additional measures compounds the cost of retrofit installation of heat pumps, in this UK in 2023/2024 it is considered to be in a cost of living crisis, making some or all of the possible energy efficiency measures unaffordable to many. The space required in the home for heat pumps is not just the heat pump unit itself but also require ancillary equipment such as hot water cylinders kept indoors to store the heat and hot water produced.

Climate and weather play a part in the effectiveness of a heat pump, particularly air source heat pumps. When the external temperature approaches the lower limits of the heat pumps temperature operating range the COP drops low.

Solar thermal: Heating consists of using solar panels or evacuated tube arrays and solar radiation to directly heat water that can be transferred to a hot water cylinder for conventional hot water use use.

Hydrogen: A zero carbon gas at the point of use in a boiler or in a fuel cell and can be low/zero carbon in production by through the method of electrolysis, using electricity to split water into oxygen and hydrogen. By using renewable produced electricity and water in electrolysis this can be considered as a green form of hydrogen.

Other methods of hydrogen production include steam methane reformation from natural gas, biomass sources and methods such as anaerobic digestion (Edinburgh Sensors 2017) which are cheaper but more carbon emitting. Each method of hydrogen production and the feed stock in the production is colloquially associated in the hydrogen sector a colour hydrogen as a quick indicator to the method of production and the emissions of that production method as seen in table 2.2. Hydrogen could be used as a drop in fuel for gas/oil/LPG heating systems, particularly remote regions of the UK.

Table 2.2: An overview of the "colours" of hydrogen according to method of production and associated emissions directly from hydrogen production, or from the manufacture of the hydrogen production plant

Colour	Feed stock	Conversion process	Process (detail)	Emissions kg CO2e/GJ H2	kg CO2e / kg H2	**kg CO2e / kWh**	Source
Black	Coal	Gasification	Coal Gasification		23.05	**0.6901**	**2021**
Grey	Natural gas (methane)	Steam reforming				**0.5049**	**(Howarth and Jacobson 2021)**
				81.5		**0.2934**	**(Gorski, Jutt, and Wu 2021)**
			SMR no CCS		9	**0.2695**	**(Global CCS Institute 2021)**
			ATR		8.25	**0.2470**	**(Global CCS Institute 2021)**
					Average	**0.3287**	
Blue	Natural gas (methane)	Steam reforming with carbon capture	ATR, average	23.4		**0.0842**	**(Gorski, Jutt, and Wu 2021)**
			ATR, best	10.6		**0.0382**	**(Gorski, Jutt, and Wu 2021)**
			SMR, exisiting (Quest)	53.8		**0.1937**	**(Gorski, Jutt, and Wu 2021)**
			SMR, best	13.2		**0.0475**	**(Gorski, Jutt, and Wu 2021)**
			SMR with CCS (90% capture)		1.69	**0.0506**	**(Global CCS Institute 2021)**
			ATR with CCS (94% capture)		1.3	**0.0389**	**(Global CCS Institute 2021)**
			Coal gasification with CCS (98% capture)		1.88	**0.0563**	**(Global CCS Institute 2021)**
					Average	**0.0728**	
Green	Renewably generated electricty	Electrolysis	Wind	3.3		**0.0119**	**(Gorski, Jutt, and Wu 2021)**
			Hydro	6.6		**0.0238**	**(Gorski, Jutt, and Wu 2021)**
			Solar	13.2		**0.0475**	**(Gorski, Jutt, and Wu 2021)**
					Average	**0.0277**	
Light green	Biomass	Gasification	Biomass gasficiation no CCS (EF gasifier)		0	**0**	**(Global CCS Institute 2021)**
			Biomass gasfication with CCS (EF gasifier)		-22.14	**-0.6629**	**(Global CCS Institute 2021)**
			Biomass gasficiation no CCS (FB gasifier)		0	**0**	**(Global CCS Institute 2021)**
			Biomass gasification with CCS (FB gasifier)		-16.1	**-0.4820**	**(Global CCS Institute 2021)**
					Average	**-0.2862**	
Yellow		Electrolysis	Electrolysis with grid power		22.21	**0.6650**	**(Gorski, Jutt, and Wu 2021)**
			Electrolysis with renewable electricity firmed by grid power		13.96	**0.4180**	**(Gorski, Jutt, and Wu 2021)**
					Average	**0.5415**	
Pink	Nuclear generated electricity	Electrolysis	Nuclear electricity electrolysis		0.4008	**0.0120**	**(*Carbon footprint of a nuclear power station equal to wind power — EDF* n.d.) (Schlömer et al. 2014)**
Red	Nuclear fission heat	Thermochemical	Hydrogen generated using heat from the nuclear fission process				**(DirectIndustry n.d.)**
Turquoise	Natural gas (methane)	Pyrolysis	Methane pyrolysis		0.91	**0.0272**	**(Howarth and Jacobson 2021)**

2.3 Heat decarbonisation policy in the United Kingdom

The only way to achieve net zero and domestic heat decarbonisation in particular is with national government policy. Policy can provide confidence and direction to encourage and enable industry and society to commit to technological change at a large scale. The government providing direction through policy is needed to ensure total societal heat emissions reduction. This has already happened before in the 1970s, where the government led and directed the national transition from coal based town gas to north sea based natural gas, which was cleaner, cheaper and safer than what preceded it (Arapostathis, Laczay, and Pearson 2019). This is now a similar moment in time where government policy and leadership is required to enable another great change of domestic heat decarbonisation.
The energy sector in the UK has changed since the 1970s to today, there is a multitude of fuels or technology to transition from and to trans ion to. There is a suite of heating fuels and technologies presently used which could be changed to fewer but still multiple low carbon heating solutions.

Today the energy networks are privately owned and operated where investment into the energy networks and coordination between networks is limited and uncoordinated for private entities to engage and invest in system change. Compared to publicly owned gas and electricity boards in the 1970s where system change can be a lot more coordinated and motivated by government. During the 1970s the regional electricity and gas boards coordinated with each other and led by central UK government in system planning and transition from town gas to north sea natural gas (ibid.). This past experience shows how central government can instigate system wide change over 8 years effectively.

The current disjointed privatised energy system in the UK makes such an effective

energy transition much more challenging due to competing interests and priorities as the public good and the environment is second to profits. Today similar change could be achieved by leveraging the energy regulator with greater enforcement powers to slow acting energy operators. By enacting further laws in parliament regarding the energy dearbonisation and pressuring and lobbying the investors of energy companies by government and civil society to assure system change happens.
Note:some policies mentioned below have changed by the time of publication.

The UK government has published a series of related reports on general energy decarbonisation and heat decarbonisation in particular. Also there is a legal requirement to achieve net zero emissions (compared to 1990) through the Climate Change Act 2008 (UK Parliament 2008) with particular reductions in emissions due to increasing amounts of renewable electricity generation coming online.

The Clean Growth Strategy (UK Government, Department for Energy Security and Net Zero, and Department for Business 2017) also outlined future decarbonisation pathways for the country and of various sectors. With possible policy measures to achieve this.
Regarding to decarbonising homes and heat, the Clean Growth Strategy highlighted this as the "most difficult policy and technology challenge". With short term actions such as a national roll out of smart meters and the then introduction of the Renewable Heat Incentive (RHI) policy. To help fund individual household installation of energy efficient and low carbon technologies.
One enacted policy is to ensuring all rental homes are upgraded to at least EPC Band C by 2030 to remain a rental property. The Clean Growth Strategy did not determine a preferred direction in decarbonising heat fuels such as grid gas.
In regards to off gas grid heat decarbonisation, there is little but still explicit mention of the tougher challenge of decarbonising heat at off gas grid homes. Suggesting the installation of heat pumps for all off gas grid new builds.

In 2018 the Clean Growth – Transforming Heating report (UK Government and Department for Business Energy and Industrial Strategy 2018) gave an overview of the of different pathways of future heating decarbonisation. Notably the inclusion of hydrogen and biogas for heating as different pathways to net zero reducing the scale of electrification needed and sole focus on electrification. This coincided with a consultation on encouraging low carbon heating for off gas grid homes, resulting in 2019 an announcement of a ban on gas and oil boilers in new build homes from 2025 (EDF Energy n.d.). This also suggested to retrofit off gas grid homes to heat pumps, based on a previous climate change committee recommendations in 2016 (Climate Change Committee 2016) and BEIS commissioned study (UK Government, Department for Business, and Delta 2018).

The 2020 Energy White Paper (UK Government, Department for Energy Security and Net Zero, and Department for Business 2020) following on from the Clean Growth strategy (UK Government, Department for Energy Security and Net Zero, and Department for Business 2017) and the Prime Minister's Ten Point Plan to lay the foundations for a Green Industrial Revolution (H. Government 2020). Looked at decarbonising all energy with significant focus on heating and buildings. With a first preference of electrifying domestic heating however still investing in hydrogen and other low carbon heating. Due to the anticipation of bottlenecks of the electric grid development, when considering the electrification of not just heating but transport and industry.

It is yet to be completely understood the scale of electric grid upgrade and increase in production of electricity to keep with the increasing demands of electrification. Particularly in a total electrification of heat and land transport scenario. Electrification is still the expected pathway for clean off grid heating as discussed in the heat and buildings strategy 2021 (H. Government 2021a), with a now closed consultation on the phasing out of fossil fuel heating in non-domestic buildings (BEIS 2021).

In 2021 when the UK hosted the COP26 climate conference, a series of reports concerning decarbonising heat were released from UK and devolved governments, building up momentum in heating decarbonisation policy.

The UK Hydrogen Strategy (H. Government 2021b) looked at heat, power, industrial and transport uses of hydrogen. With focus on developing green hydrogen production by using renewably produced electricity for various uses including off grid power backup and replacing natural gas in the gas grid.
The Heat and Buildings Strategy (H. Government 2021a) set out future policy and a timeline to achieve decarbonisation. The timeline sets out various heating policies and schemes currently in development over the 2020s, Presenting various stages of development from planning, funding and deployment. This includes introducing regulation in 2026 to start phasing out non gas grid fossil fuel domestic heating with an expected end of such existing heating in the late 2030s.

2.3.1 Devolved governments policy

The Scottish Government released the Heat in Buildings Strategy (Scottish Government 2022a) focusing on their plans on introducing low carbon heating and phasing out of new fossil fuel boilers on and off grid from 2025, with improving energy efficiency of homes through measures such as insulation, developing plans to convert natural gas supply to hydrogen and to develop low carbon heating and schemes to encourage homeowners to change their heating. The Scottish Government in this strategy indicates the aim for all rural off gas grid properties to be retrofitted with heat pumps and considers this as part of the 'low and no regrets' part of the strategy where early action can be taken.

The Welsh Government in 2023 published the draft Heat Strategy for Wales (Welsh Government 2023) and the completed document in 2024 (W. Government 2024), outlining its focus in heat decarbonisation. Where many Welsh regions are considered rural, the rural domestic heating policy focused on widespread heat pump adoption followed by biomass boilers for hard to electrify scenarios. This broadly follows UK and Scottish government policy direction. Other fuels and technologies such as hydrogen and heat networks are both described as tertiary solutions due to high investment cost, an immature industry around hydrogen technology and infrastructure in the case of hydrogen.

The Northern Ireland Executive in 2021 (Northern Ireland Executive 2021) also released an energy strategy looking at how to reduce emissions from all energy sectors including heat. As Northern Ireland relies on oil for heating over 67% of homes, heat decarbonisation is an obvious issue more so than elsewhere. However little vision or policy has been developed in this period since, particularly in a nation with per capita higher emissions heating compared to the other UK nations. This strategy mentions future plans to develop a decarbonising heat consultation in the next term of the Northern Irish Assembly, of which there have been political instability in the years between 2021 and 2024. Both the target dates of 2030 and 2050 for partial and complete decarbonisation in Northern Ireland are mentioned. A consultation on dearbonising Northern Irish heat has yet to be opened.
The UK and devolved governments have varied and related domestic heat decarbonisation policies. A trend is focusing primarily on heat electrification with heat pumps as the primary technology. Rural and off gas grid heat decarbonisation is more varied, with UK and Scottish governments providing clear direction and ambition on rural heating and the opportunities of incentivising the heating industry and retraining training the workforce to fulfill the energy transition.

In Wales and Northern Ireland policies have been developed much later or not yet at all for decarbonising domestic heat, following by example set by the UK and Scottish governments. This illustrates that there is a lack of ambition and/or resource by these governments towards low emissions heating, let alone rural and off gas grid heating. An advantage to this wait and see approach enables the smaller UK nations to learn and follow on from the what is successful from the larger nations, however this still showcases a severe lack of ambition in achieving net zero heating.

2.3.2 Current work on off grid rural heat decarbonisation.

Policy on decarbonising off grid gas heating is clear from the UK and Scottish governments; it is considered and worded as a “low regret”, which is not defined in the report, but can be assumed to be actions that have little alternative feasible technology and hence low downsides, *(H. Government 2021a), (Scottish Government 2022a)* approach to replace fossil fuel heating with heat pumps. This direction is rather established with research and demonstration of solely heat pumps in off gas grid settings (Green and Bradford n.d.) from over a decade ago, when heat pump systems were first promoted as green renewable heat systems with the Renewable Heat Incentive when it was announced in 2011.

Other low carbon technologies such as solar thermal heating and biomass boilers (Office for National Statistics n.d.) have been studied and promoted. All these technologies are technically feasible to heat a home. The Energy Systems Catapult (Energy Systems Catapult n.d.) and BEIS (UK Government, Department for Business, and Delta 2018) found so with heat pumps, exploring potential challenges with heat pump adoption being technical. Such as cold winter temperatures, replacing internal heat emitters (radiators), retrofitting insulation and potentially needing to replace wiring in the home and upgrading the fuse rating and electricity supply to the property. All of which can contribute to a ’hassle factor’ of a heat pump installation that may put off prospective homes. Due to this such challenges and implications of using other heating technologies should be considered and assessed.

A difficulty come across by the authors is that there is a gap in knowledge and more research is needed into the most suitable technologies for the off gas grid and rural domestic settings. Most of the policy sources examined explicitly focus on one technology study into comparing the pros and cons of such technologies. This is what the authors aim to achieve with this and further research. Some overview of the research into off grid and domestic heating technologies is examined later in section 2.4.3.

2.3.3 Policy summary

When looking in particular at the UK and its devolved governments energy and heat decarbonisation polices there are key trends can be identified. Firstly, policy looks at utilising established technologies where there are known and broadly commercially available. Primarily electric based heating such as heat pumps and biomass based heating, such as wood pellet boilers in scenarios that are hard to electrify.

There is acknowledgment that a wide scale system change to electrified heating will have an impact to the capacity of the electric grid. The implications of which are still yet not clearly known to the grid particularly when considered alongside other electrification measures such as vehicle electrification. Some research suggests in a total electrification of heat scenario with heat pumps and no other efficiency measures, requires a doubling of the UK electricity generation capacity (M. Zhang et al. 2022), (H. Government 2023). Finding that the peak electricity demand will increase from 96.6GW to 146.7GW.

The investment required for such an electricity grid capacity increase for heating alone is enormous and does require further consideration that an all electric domestic heating scenario (which comprises of 17% of UK emissions primarily through gas heating (H. Government 2021a)). Due to this the policy documents all show some willingness to other national heat decarbonisation pathways. Pathways such as a partial implementation of hydrogen gas grids and electrification.

A key area that is lacking policy detail relative to urban heat decarbonisation are rural and in particular off gas grid domestic heat decarbonisation. Approximately 10% of UK households that are off the gas grid and do not have gas or electric heating.
As discussed in section 2.2.2 this small minority is complex and diverse in terms of heating methods, the solutions and pathways to heat decarbonisation for this cohort will equally be varied in approach. The policy pays insufficient attention to the issue of decarbonising rural communities, making this vague and unclear. Two approaches seem to come from this, one is to heat pump electrify off gas grid homes. While this is technically feasible with sufficient investment and resources, it is not practical or accessible to many of the rural off grid housing stock or perhaps even the low voltage electric distribution grid.

The second suggested approach for off grid heat decarbonisation is implementing biomass boilers, likely with a wood pellet fuel as this is a readily available fuel with existing home heating products on sale. This approach could be seen as more of a half measure, a sign of government only targeting the policies of highest return of truly decarbonising UK housing stock. Wood biomass fuel is a low emissions fuel that is not subject to price regulation similar to grid gas or electricity.
There seems to be no indication that any lower carbon off grid heating fuel will be subject to any regulation or subsidy (akin to the subsidised red diesel). Such a subsidised fuel would provide market and consumer confidence investing in lower emissions heating fuel systems such as biomass wood pellets.

In the off grid heating space there is a variety of possible solutions that could have been explored by the policy. In chapter 6 this thesis investigates the suitability of several low to zero emissions technologies and their suitability for off gas grid dwellings in the UK. These technologies include looking at heat pump, biomass, hydrogen and other technologies to achieve this. Comparing and assessing the techno economic implications of each explored system through energy system micro grid modelling.

To enable model and assess each technology first a profile of rural energy user being modelled, which is developed in chapter 4 sets out survey work finding out and developing five archetypal rural energy users. The results of which is subsequently used in chapter 6 where techno economic modelling of 19 different fuels, technologies and configurations of a single home microgrid is assessed.

2.4 Research and demonstration of low carbon and rural off grid domestic energy systems

2.4.1 Heating decarbonisation demonstration projects in the UK

In the UK there has been research, demonstration and deployment into various forms of low carbon heat in the last few years. With research focus on hydrogen energy system optimisation, demonstration and implementation and heat pump deployment.
Hydrogen heating project HyDeploy (Isaac 2019) have demonstrated injecting hydrogen gas to an existing local natural gas grid to form a gas that is 80% natural gas and 20% hydrogen. Demonstrating that hydrogen gas can be used in existing homes and appliances with little to no modification (Keele University and Winalton, Gateshead). This informs the feasibility of introducing hydrogen gas to the national gas grid and in remote settings, as existing household appliances can be repurposed for hydrogen use and potentially retrofitted for 100% blend hydrogen use. In a total electrification pathway such appliances and systems may need replacing with electric only devices., increasing the total capital cost.

Hybrid heat pump projects that combine a heat pump and conventional boiler have been tested and demonstrated in various configurations, such as using various fuels such as natural gas, LPG (National Grid 2018) in the National grid FREEDOM project. This project developed and tested hybrid heat pump and grid gas/ off grid LPG boilers across 76 homes from 2016 to 2018. This project demonstrated the viability of heat pump hybrid systems in reducing emissions and costs to users, finding off gas grid users saving approximately 80% of cost compared to an LPG only heating system. As a follow on there is opportunity to explore and demonstrate hybrid systems with low carbon gases such as hydrogen and biogas.

2.4.2 Overview of low carbon and hybrid energy systems research

This section is a brief summary of research in which the techno-economic viability of low carbon energy systems is assessed. Focusing on the cost and technical feasibility of what combination of low carbon technologies are viable. With particular focus on the viability of hydrogen energy techniques.

The focus of industry and academia is developing small to mid-size hydrogen production and storage for electricity and transport. Focusing in developing a system that is energy efficient, cost effective and operate in an off grid setting (Also known as an island energy system disconnected from the national grid). With the aim of finding the best scale and size of system for hydrogen to be viable, competitive, and efficient.

Much of the research on domestic energy systems integrating hydrogen fuel cell electric systems into smart grids. With different energy generation and storage systems that are communally or individually optimised to best utilise available infrastructure and deliver the highest economic performance. (Nojavan, Zare, and Mohammadi-Ivatloo 2017) examined this looking at different pricing strategies with a smart grid of renewable energy and hydrogen storage, fulfilling residential and electric vehicle energy demand. As well as the techno-economic strategy an energy supplier may use for an electric vehicle battery and hydrogen storage energy management system. (Pan et al. 2020) looked in depth at developing a management algorithm of seasonal hydrogen storage charged by renewable electricity on a regional scale, with bi-level modelling finding a reduction in the cost of hydrogen production.

(Y. Zhang et al. 2017) modelled a hybrid hydrogen/battery storage system based of photovoltaic (PV) electricity generation comparing the two storage systems at different cost scenarios to power an apartment building. Finding that under different cost scenarios hydrogen is not the best but wins overall. (Y. Zhang et al. 2017)'s study is a useful tool in helping decide in the sizing and type of storage that may be needed although recommended only for Nordic type countries, expanding this for different climates and countries can be a useful tool.

(Li et al. 2017) examined the economics of producing hydrogen from curtailed renewable electricity or low cost electricity in China for different end uses of hydrogen. Finding that economics and technology level is not sufficient to be viable as PV generated electricity has driven the energy cost down as low as $0.11-$0.14/kWh. Making hydrogen uneconomic in the short term in China. However there is opportunity to be economical in such a low cost economy in the industrial and long distance road transport sectors. The technology cost being the major factor currently in developing economic cases and strategies as seen elsewhere. A difficulty with (ibid.)'s analysis is the ambiguity to the scale this modelling has been done gives little context to the results.

Similarly, (Marchenko and Solomin 2015) found that in their economic analysis of hydrogen energy systems compared to battery electric systems. The low efficiency and cost effectiveness of hydrogen technology at the time does not make hydrogen technologies yet viable, particularly for short term storage.

The literature discussed showcases some different research the hydrogen storage process into an integrated electricity system may work in such environments technically and economically. However this could be improved with further work to explo re the varying geographic and economic contexts that hydrogen for domestic energy systems could be best suited. This overview is beneficial in tracking the trends of the current high cost and relatively low efficiency of hydrogen technologies to electric technologies.

This section explores and emphasises additional considerations and factors that could make alternative low-carbon energy sources, such as hydrogen and other e-fuels, viable options in the low/zero carbon energy chain.

2.4.3 Domestic Off grid hydrogen energy systems, storage and power generation technologies.

This section looks at the research on remote and off grid domestic heat and power systems. Of most relevance are the remote systems in which hydrogen technologies are incorporated together with renewable power generation as this results in greater versatility..

There is currently a mature industry for off grid electric only energy systems. The work below explores if hydrogen technologies can aid in enabling effective off grid energy systems.
There are many commercially available systems to enable living electrically off grid in sparse regions, homesteads, on boats and in mobile homes. Despite the proliferation of commercially available off grid power systems this topic is being actively researched for the following reasons.

1. To investigate the performance and the integration of new technologies with existing energy systems
2. To optimise the operation of off grid systems for specific climates and use cases.
3. To optimise the configuration of energy systems in relation to scale, efficiency and cost.

Further investigating the strategies and technologies to enable off grid heating is key in Northern European and North American climates.

Improved and more effective technologies now truly enable effective and consistent low emissions off grid heating. Current research explores this particularly with hydrogen technologies integrated into an off grid energy system.

Literature of off grid energy systems.

(Viteri et al. 2023) reviewed the state of off grid energy and off grid hydrogen research finding some trends in hydrogen energy system research. Safety, making the case these novel technologies are as safe or safer than present systems. Storage, with a growing trend and interest in metal hydrate hydrogen storage systems over other more mature storage technologies.

In energy systems research the underlying energy demand data, the time series of electricity and heat demand for a given building, is typically estimated. This is derived often from a combination of weather data, national energy consumption data or building characteristics (such as such as floor space and number of windows).

Using real data from real users and buildings is relatively new, growing in the last decade in use both commercially and in research. There is often a variance between the estimated and actual energy demand profiles, in terms of both magnitude and in daily and seasonal trends. Using real data can further optimise energy systems modelled, reducing component sizing and adjusting energy management strategies to further increase efficiency and reduce cost. This may make using real energy demand data may be more ideal than using estimated data. (Jurasz et al. 2022) has modelled off grid energy systems with both estimated and real world load profiles. Finding that an energy system optimised to real energy demand data can find energy cost savings from 1.2% to 15%.

Simulations

An advantage of energy simulations is the ability to compare different energy system architectures, different configurations, fuels and technologies. The literature explores some of the research in simulating and modelling low carbon off grid domestic energy systems.

(Kahwash, Maheri, and Mahkamov 2021) investigates modelling a single off grid home in a generalised temperate northern hemisphere climate. Comparing three different heat and power energy systems with various levels of integration and technologies between the electric and thermal systems.

As a result, a higher utilisation of the renewable generated electricity, and the minimisation of utilisation (and size) of a backup diesel heat generator. Finding that system capital cost can be reduced by an integration of the electrical and thermal energy systems. Which in turn significantly reduces the operational emissions of this system.

In the Netherlands (Chamout et al. 2024) explored integrating hydrogen technologies (electrolyser, type IV composite material hydrogen gas tank and fuel cell) as the primary energy storage system in an electric off grid system. With the case study of a typical suburban/rural detached dutch home.

An interesting outcome from this work is the analysis of the water purification unit for the pure water required for the electrolyser. Modeling and analysing operational considerations and power impact of the water purifier. Other results such as the capital costs of the key renewable and hydrogen components used in this modelling is key. As costings for hydrogen system components at a domestic household scale is both expensive and difficult to quantify.

Looking further north at Nordic climates (Meriläinen et al. 2023) investigated a Finnish oil heated townhouse to model a retrofit off grid heat and power system with renewables and hydrogen storage. Looking at covering the heat demand in the cold nordic winters, heat recovered from the electrolyser and fuel cell fulfilling a high proportion of the winter heat demand. This showcases a technical viability of hydrogen off grid energy system in Nordic winter climates analysing various system interactions and sensitivity analysis on appropriate sizing of system components. Similarly to the findings of (53) this study also reported the high cost of a complete off-grid system.

(Dursun, Acarkan, and Kilic 2012) modelled hydrogen production from renewable sources in MATLAB-Simscape, comparing modelled results to experimental results. Finding close agreement between the simulated model and actual results, however finding an over estimation of double the rate of hydrogen production compard to the actual real life hydrogen production rate. This highlights a key space for opportunity for electrolysis and hydrogen storage in remote or off grid settings where concerns of efficiency are not a primary motivation. What is important is having an energy supply in remote settings. In these settings hydrogen systems should further replace diesel or petrol generators, which is becoming more commercially prevalent with hydrogen powered construction site equipment, powering remote television productions and most notably to the extreme-e off road electric racing series (Extreme-E, 2021).

In the UK companies such as GeoPura (*GeoPura: Renewable Energy Solutions, Green Hydrogen, Green H2* n.d.) and BOC (*HYMERA® Hydrogen Fuel Cell Generator — BOConline UK* n.d.) are bringing products to market to enable more remote power users that are more cost sensitive and more hesitant to technology change to switch from diesel electric generators to hydrogen electric generators. As the growth of hydrogen generators in this market would reduce system costs.

(Keiner et al. 2023) reviewed and simulated seasonal hydrogen storage for off grid or limited grid dwellings across various climates and regions, with comparisons to battery electric systems. A key finding was hydrogen storage is only suitable as a niche off grid energy storage solution for heat and power, with some suitability in Northern European Nordic climates. Where cost and efficiency are key barriers with hydrogen. They discussed possibility of sector coupling of residential and local industrial energy processes which could increase efficiency and reduce cost.

(Puranen, Kosonen, and Ahola 2021) looked at simulating adding battery and hydrogen storage to a grid connected, low energy rural home. With Photovoltaic (PV) solar panels installed to run the home essentially off the electric grid, only exporting electricity to the grid. Concluding that in northern climates with sunny summer months and dark winter months finding that seasonal hydrogen storage as well as shorter term battery storage can provide self-sufficiency to a finish home. As noted by (Puranen, Kosonen, and Ahola 2021), this home in the study has already installed energy efficient systems such as ground source heat pumps and underfloor heating to reduce the energy demand of the home.
A similar study of a more conventional home in a more moderate climate would be an ideal comparison to (Puranen, Kosonen, and Ahola 2021)'s study to see the suitability of hydrogen off grid systems in different climates.

These studies demonstrate that new build homes with the latest of energy saving measures can lead to off grid / reduced grid demand for energy. To build on this further similar research is required to investigate a broader cohort of building type and domestic energy user. Such as older and less efficient homes and buildings where retrofit measures will be required to decarbonise. The majority of homes that need to decarbonise there heating and energy consumption are already built. Research should not only be forward in looking at measures for new build construction measures but also look back further look at retrofit measures decarbonisation of domestic energy in existing homes.

An interesting finding by (Puranen, Kosonen, and Ahola 2021) highlighting difficulty of managing an off grid/energy storage system during periods of high peak usage, these may be periods where importing energy from the grid or a supplier is necessary. It suggests there may be a cost gap and installed capacity gap between being mostly self sufficient and totally self sufficient. Furthermore, there is opportunity to develop on (Puranen, Kosonen, and Ahola 2021)'s work with investigating heat recovery of hydrogen system components that yet have been investigated.

Demonstration systems

In Northern Spain (Maestre, A. Ortiz, and I. Ortiz 2024) modelled and then built a partially off grid solar and hydrogen home with a facility to export electricity. This work is interesting in building a demonstration system and accompanying model which both highlighted discuss parasitic energy demands from the compressor and dryer which affects the overall system efficiency. The effects to the end users in the pilot house providing tangible cost savings to their energy bills and emissions reductions. This could be furthered with more discussion on the cost and performance effects of hydrogen drying and compression stages of the process as no focus in this work on these parts of the system.

(Parra, Gillott, and Walker 2016) investigated developing a practical hydrogen storage and energy system generating hydrogen from renewable energy as well as a demand management system to generate electricity at optimal times. Excluding any energy or fuels for heating or air conditioning.

This project used a solid state material, magnesium metal hydride tanks, to store hydrogen instead of compressed gas tanks in the practical demonstration system. Solid state hydrogen storage is more space efficient than more common compressed hydrogen gas storage. This work found a round trip system efficiency of 47.5% for hydrogen storage systems have from electrolyser to storage to fuel cell. Making hydrogen energy systems less efficient for compared to battery electric systems, yet the hydrogen system efficiency is stated to be better than the Spanish electricity grid, although this figure is not stated.

From (Parra, Gillott, and Walker 2016)'s work of testing at scale different energy and hydrogen storage technologies, there is opportunity to further explore other technologies for energy storage such as different solid state hydrogen storage materials or other forms of storage in practice. These technologies

As well as testing in practice various other demand management strategies like (Nojavan, Zare, and Mohammadi-Ivatloo 2017), which modeled integrating hydrogen electyrolysers, fuel cells and plug in electric car batteries into an electric grid and electricity pricing. Whereas (Pan et al. 2020) similarly optimising hydrogen energy storage systems in a regional electricity grid system with renewable and geothermal sources of energy. These showcase some of the research in integrating hydrogen energy systems into the electricity system and the implications of electricity pricing when integrating energy storage and other technologies to the grid.

Using hydrogen storage for electricity and heat end use has been explored in numerous ways some of which has been highlighted above. With the particular opportunity focus on using renewable energy for local seasonal storage or to avoid curtailment of large-scale renewables and increase the useful yield of those resources is the space where hydrogen storage looks to be going. Investigating novel technologies that could be used in an off grid setting and the better optimisation of various technologies into one smart energy system.

2.5 Storing hydrogen in a solid state

This section looks at energy storage using hydrogen and specifically at use of solid state hydrogen storage. **Why?** Because the established or conventional method of storage is compressed gas bottles, where solid stage storage may have are advantages over compressed gas storage regarding safety.

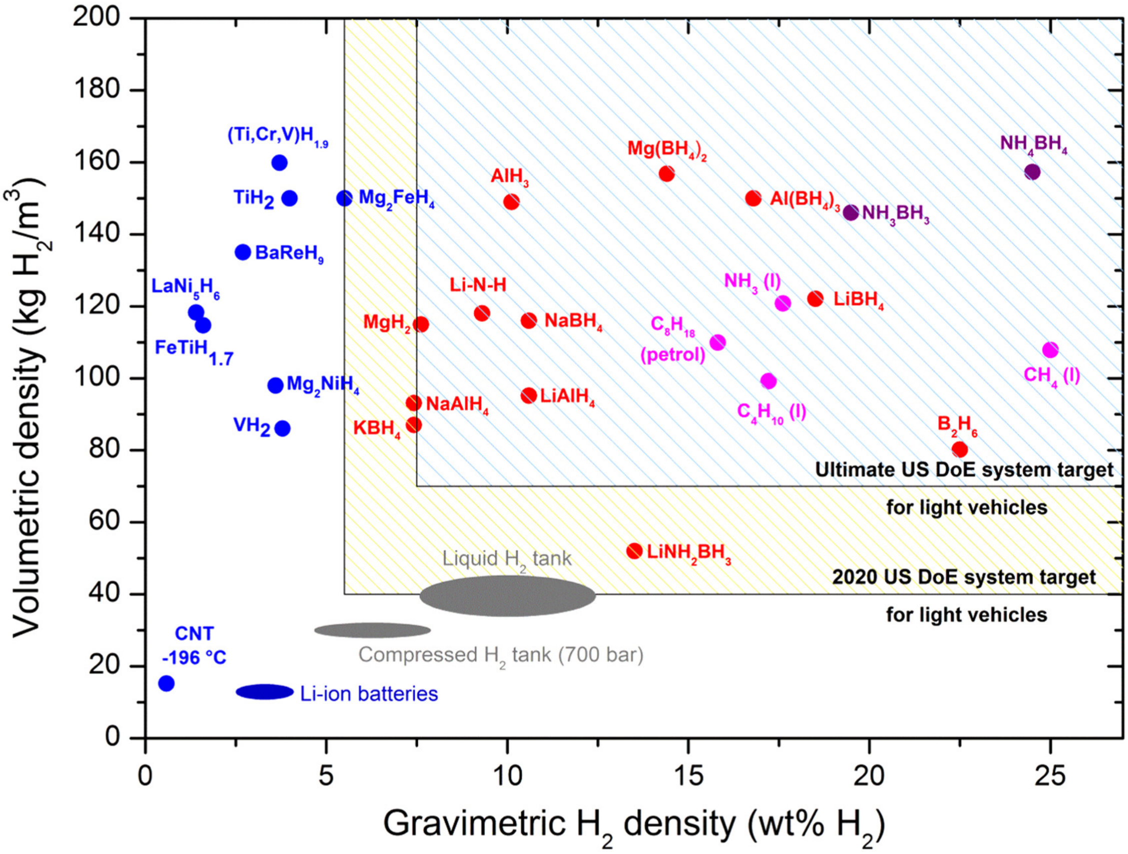


Figure 2.2: Selected hydrogen storage materials with their volumetric and gravimetric hydrogen densities. And other hydrocarbon fuels and the US Department of Energy targets for hydrogen storage are shown to compare. (Møller et al. 2017)

Solid state storage has an advantage at storing hydrogen at lower pressures, less than 100 bar in solid state storage compared to more than 350-700 bar for compressed gas storage. Solid state hydrogen storage materials (also known as metal hydrides) have a high volumetric density, that is for the cubic meter a metal hydride tank would store 2 to 3 times the same amount of hydrogen compared to a 700 bar compressed gas hydrogen tank (Møller et al. 2017).

The metal hydride composition is important in defining and fine tuning specific operational characteristics to obtain optimised system performance. Different metal hydride material compositions that have been researched have different conditions of activating the material and operational temperatures and pressures.

TiFe hydrides have been demonstrated for use since the 1970s in various use cases such as hydrogen vehicles, however recently it has been identified as usable in large scale stationary storage. To provide electric peak shaving for power companies in the US, or to store hydrogen as a byproduct of storing heat from a concentrated solar tower energy plant in Australia (Liu et al. 2023). In the 1980s NASA investigated using MgH2 and $LaNi_5$ aboard space stations for energy storage (Perry and Marshall 1988).
(Klopčič et al. 2023) reviewed a series of commonly known and researched metal hydrides. Such as magnesium hydride (MgH_2), which is a high capacity material (7.6wt%) however it extremely sensitive to oxygen and requires high temperatures (300C) and very low pressures (1bar) to desorb the hydrogen from magnesium.
The hydride Lanthanum Nickel 5 ($LaNi_5$) on the other hand has fast kinetics and well performing hydride at relatively low pressures (less than 100bar) and temperatures (less than 100C). However this material has a relatively low storage capacity at 1.4wt% and high material cost due to the La content which is a rare earth metal.

From this brief look at different metal hydride alloy compositions all have different key characteristics that can be utilised in different use cases and not just in recent years but for decades.

2.6 Summary

Something that has had some study as highlighted above is off grid hydrogen systems for remote communities where hydrogen could be used not just for electricity, but heating and transport as explored below, retrofitted into existing infrastructure. This overview of off grid domestic energy decarbonisation research feeds into the work presented in[section rural energy modelling], developing a micro grid energy systems model of a rural UK home. Comparing present day rural heating fuels to low/zero carbon alternatives such as heat pumps, and various iterations of hydrogen production, storage and delivery to site.

This review similarly relates to the work carried out in section 7 where a domestic scale solid state hydrogen storage tank system is developed and then tested.

Chapter 3

Methodology

Overall methodology of this thesis. And the methodologies specific to each chapter of research

3.1 Methodology overview

This thesis consists of three distinct projects and methodologies spread across four chapters which are all inter-related linking with each other. This chapter compiles the overall methodologies of each section and the relationship between all the chapters to produce a final thesis. The core chapters of this thesis are chapters 5 and 6 where an energy systems model is produced in the microgrid modelling software energyPro. The model consists of 19 iterations, each iteration with a different heating fuel or heating technology included in the model.

To compute the micro grid models an energy demand time series or electricity and heat consumption of the modelled home is required. Chapter 5 uses an energy demand time series from (Baumanis et al. n.d.[a]). The results of the micro grid models in energy pro is post processed to produce a ranking of best and worst scoring fuel in relation to the annual emissions and annual running cost. The post processing of the results is iterated in section 5.5 incorporating other characteristics for each model such as capital cost, efficiency and the proportion of energy consumed that is renewably generated within the micro grid from renewable sources.

Chapter 6 iterates upon this by using energy demand profiles derived from smart meter data from the (Smart Energy Research Lab and University College London n.d.). The characteristics of the user profiles used to produce the new energy demand time series is defined by the results of chapter 4.
Chapter 4 entails of an online survey sent to rural residents in the UK asking respondents regarding the energy systems used in their homes. The results of the survey is analysed to produce 5 rural domestic energy user profiles that encompass all types of rural dwelling. These 5 user profiles are used in chapter 6 to produce electricity and heat energy demand profiles from smart meter data which are representative of the 5 rural domestic energy user groups.

The methodology of chapter 7 entails the selection of a metal hydride material, the characterisation of the material and a green hydrogen demonstration system using the metal hydride material. The metal hydride material Hydralloy C5 is characterised using a sieverts apparatus. The apparatus is used to produce pressure composition isotherms (PCIs), which are used to mathematically derive the hydrogen storage capacity of the material. And at what temperatures and pressures the material thermochemically reacts with the hydrogen gas to store the gas within.

The metal hydride material is demonstrated in a green hydrogen demonstration system where hydrogen produced from an electrolyser is stored in the metal hydride and then discharged. The experimental system is replicated digitally in energyPro and compared as the 20th model of the simulations completed in chapters 5 and 6.

Figure 3.1 illustrates the relationship between each chapter of the thesis, how each chapter links to each other to produce one thesis. Also illustrating the progression of the project from the initial research project title of "Hydrogen for the sustainable built environment" to the final thesis title of "The challenges of decarbonising heating of rural UK homes".

The following sections of this chapter are extracts of the methodologies found in the respective research chapters.

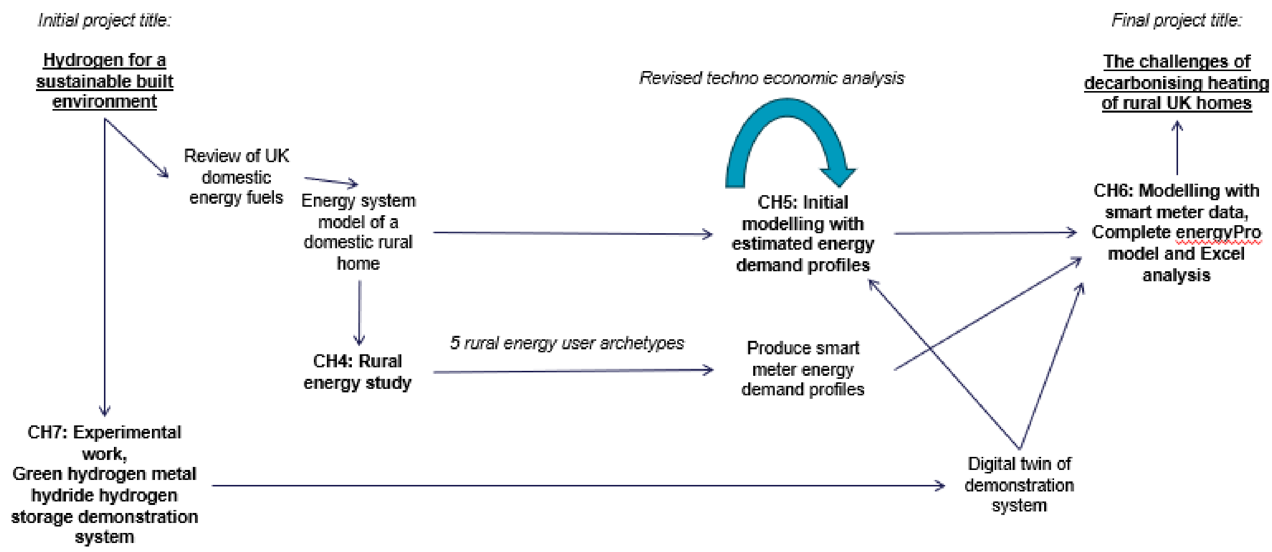


Figure 3.1: Structure and relationship between each chapter of work in the thesis

3.2 Methodology for chapter 4. Developing archetypal rural home profiles for future energy system modelling

This chapter centres on data and analysis from an online survey, comprising of 26 multiple choice questions related to rural energy accessibility. The topics covered by the questions were respondents demographics, location, attitude towards sustainability, the respondents home and the forms and methods of energy consumption in the home.

This survey was distributed online to over 500 parish councils or equivalent lowest level of local government across the UK, Isle of Man, Jersey and Republic of Ireland as seen in figure 3.2 for England. There are over 10,000 parish councils in England alone (National Association of Local Councils n.d.), selecting the appropriate parish councils to contact is first based on selected county council areas in the UK, and the subsequent borough or district council within a county.

First identified were counties that should be targeted to distribute the survey. Counties selected were those that have notable and substantial rural area or also have certain geography that would be beneficial to have responses from. Such as the English Peak District and Scottish Highlands where there are notable for their remote and rugged geography where energy access may be limited.

Once these counties were identified (such as Derbyshire, Lincolnshire and Highland), identifying the constituent district/borough councils (or equivalent) that make up the county was selected, based on the same criteria in selecting counties to target. Each district council is typically made up of tens of parishes.

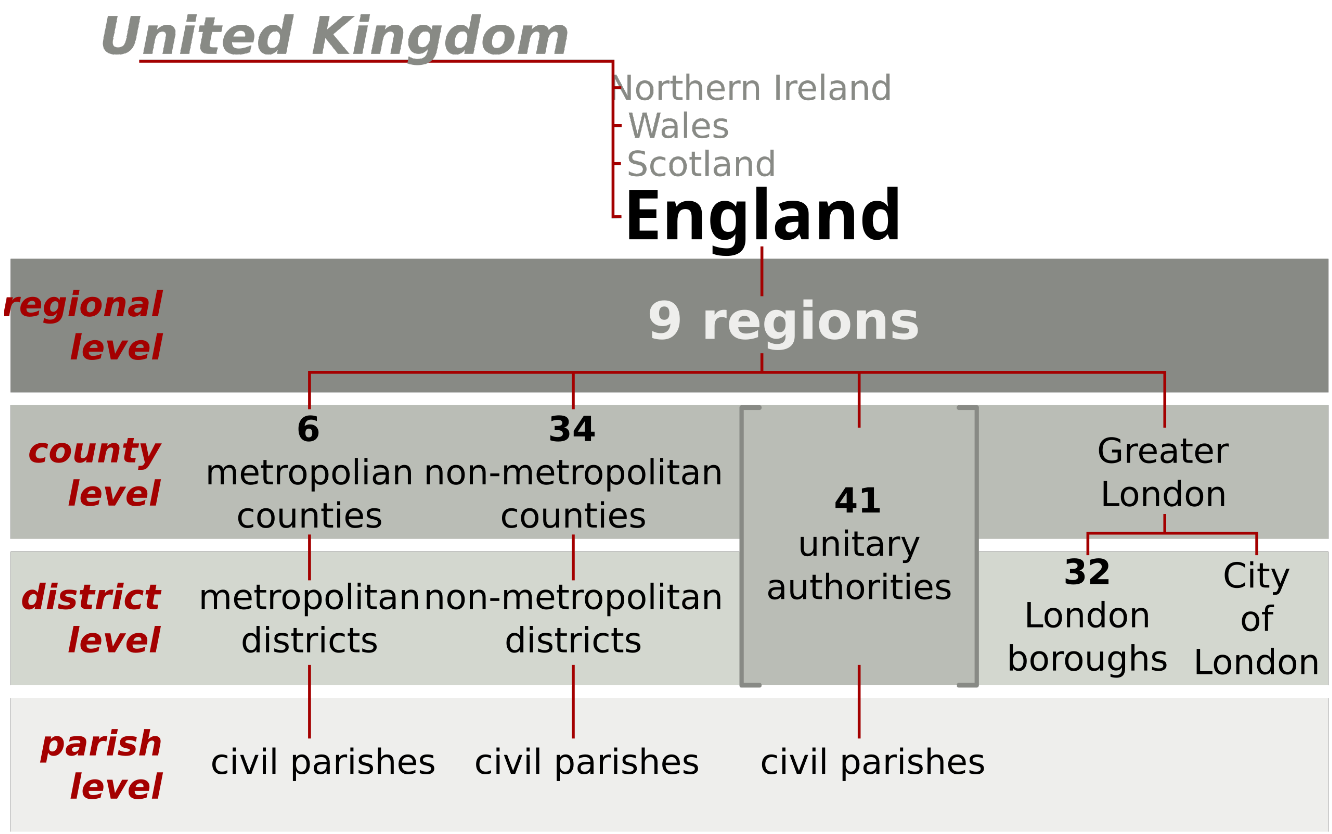


Figure 3.2: "England administrative divisions since 1995" by Marcin Floryan is licensed under CC BY-SA 2.0 (Floryan 2006)

The contact email sent out included a brief description of the rural energy access project and asking the recipient to fill out the survey linked in the email and to distribute the survey among their council and wider community. Due to the nature of this project involving outreach to the general public, this project and survey was approved by the University of Nottingham, Faculty of Engineering, Ethics Committee. Key considerations include access to personal data and respondents must consent to the collection of such data.

3.2.1 Survey questions

The survey was presented using a Google Form as this made it equally accessible to computer and mobile phone users. This also allowed the results to be exported with relative ease into MS Excel for processing.

The first 11 questions asked are primarily demographic questions to find out ***who*** the respondent is and what kind of household do they live in. Asking questions such as age, gender, employment status and the degree of working from home. Also asked in this first section are questions such as what kind of building (*What kind of home/building do you reside in?*) and geography (*What is the first half of your postcode (or equivalent)?*) the respondent considers themselves to live in. This first group of questions develop the background of ***who*** is responding and ***where*** do they live, to better understand and produce more effective solutions to these challenges through more in depth analysis. A copy of all the questions asked in the survey is found in appendix A.1.

Questions 12 to 16 are a series of multiple-choice questions that asks the respondents their attitudes towards the environment, sustainability and the cost of energy. These questions are asked to understand the attitudes of the respondents towards such issues, which often are motivations to adopting low carbon energy systems. This set of questions encourages respondents to begin thinking about the related topics in anticipation of the subsequent questions asked.

The final section of questions 17-27 are a series of technical questions asking the respondent to report key factors of their energy consumption such as the types of devices used in the home. What fuels are used for what application (power, heat, cooking or transport), how the fuels used is transported to their building and what sort of temperature is their thermostat set to throughout the year. These technical questions help build a profile of the archetypal homes and users that is later identified.

3.3 Methodology for chapter 5. Initial modelling with estimated energy demand profiles

3.3.1 Modelling methodology

This work is computed using energyPro, a block based microgrid modelling software to produce a model that compares energy conversion between numerous iterations of the system simulating electricity, heat and other fuel systems, with financial and economic modelling included.

The initial results produced include operating cost and emissions produced by various off gas grid heating fuels and technologies present and future that are modelled. The heat and electricity demand profile used for this model as seen in figure 3.3 is from (Baumanis et al. n.d.[a]) masters project website exploring energy modelling of buildings on the Isle of Gigha, which has since been taken down since downloading the data. However, an archive of the website on the WayBack Machine internet archive is listed for reference.

Three general heat demand profiles can be derived from this data; an old uninsulated home, an old home with retrofitted insulation and a new build home with insulation (Baumanis et al. n.d.[b]). The head demand profile includes DHW at certain times of the day (0400-0600 and 1500-1700) for 6 hours a day in total, the electric demand profile is for all appliances and excludes any secondary electric heating. A common electricity demand profile from the same source is used in all models, it is expected electricity demand profile for all appliances excluding electric heating. The final results of this model is presented in Table 3 in the existing fuels model and Table 6 later on.

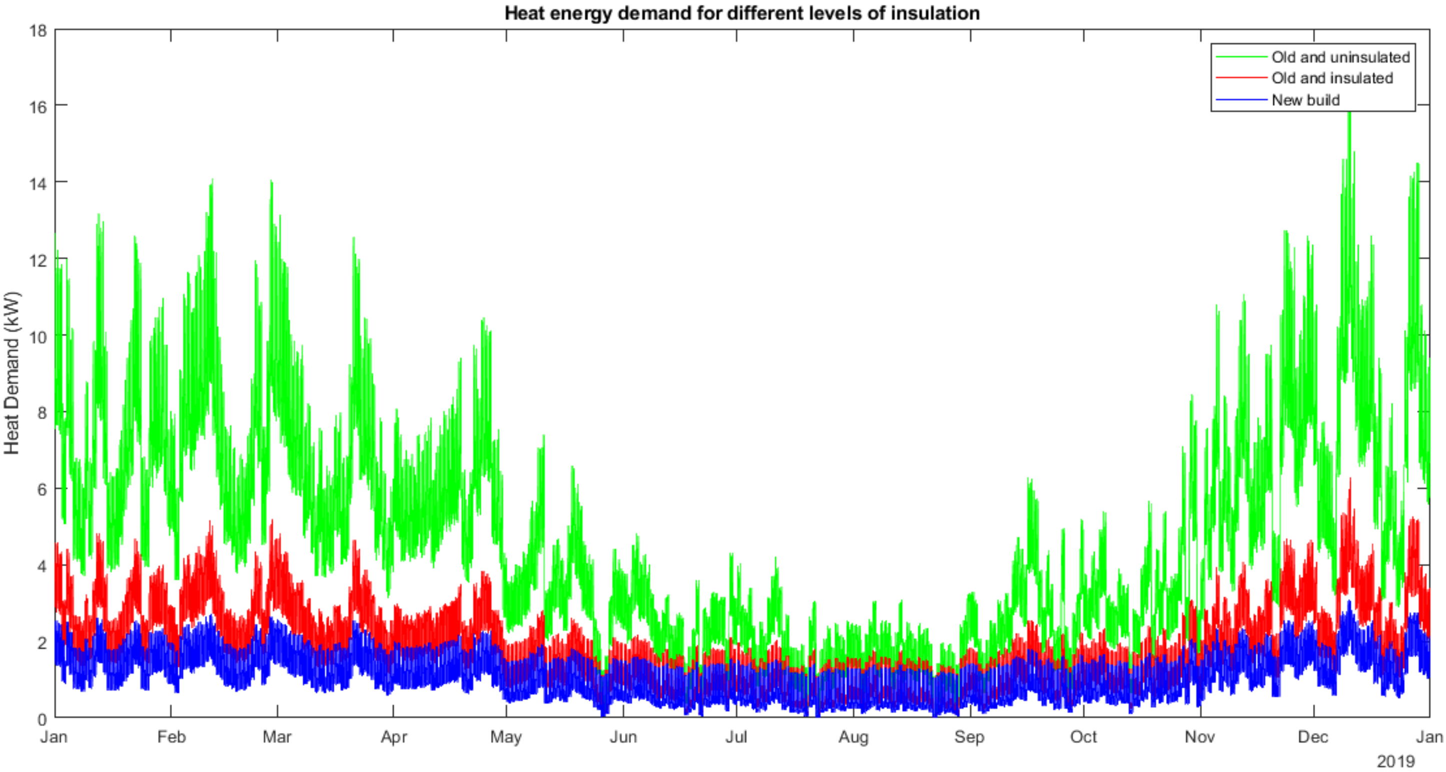


Figure 3.3: Heat demand profile across a year with different levels of insulation (Baumanis et al. n.d.[b])

3.3.2 Methodology of analysing results

To assess the results found according to different criteria, the methodology is a simple ranking of each result grouped into heat demand profile modeled separately assessing the annual cost and the annual emissions.

A ranking of 1-11 (as there are 11 fuels/technologies assessed), where 1 is the lowest annual cost or the lowest annual emissions and 11 is the highest annual cost or the highest annual emissions.
The final score is produced where the ranked scores of the annual cost and the annual emissions are added together. This method of scoring is useful to view the overall value of a certain fuel/technology. No weighting was applied to the annual emissions or annual cost scores as no appropriate weighting of each factor was decided. The weighting of different factors will vary depending on the context scenario and user of the data, who will find one factor more important than the other and hence weigh the results in that direction. The value of using this relatively simple ranking system allows comparison and combination of different metrics.

When the annual cost and annual emissions scores for each heat demand profile are added together this produces the results found in table 5.4. These results are useful as it provides a simple techno-economic assessment to find the optimal fuel/technology. This methodology is repeated for section 5.4 with a 1-8 ranking as there are 8 model versions explored.

3.3.3 Extended analysis scoring methodology.

An extended analysis was made iterating on earlier ranging methodology described in the previous section, which considers four factors* (operating emissions, operating cost, capital cost and system efficiency) whereas earlier work only assessed each of the models on two factors (operating emissions and operating cost). **Five factors* *for the renewable energy models including the proportion of energy consumed that is renewably generated within the microgrid.*

The method of analysing and evaluating has evolved from a simplistic numerical ranking of the worst performing and the best performing model iterations evaluated. Repeating this process for both factors being evaluated (Annual operational cost and annual operational emissions). Adding the two results together to provide a final score and re-ranking this to find the final result of all the model iterations being evaluated.

An issue with this methodology of analysis was that this did not account for the magnitude of the difference of the results between each iteration output. For example, table 5.6 in the Annual emissions column, Old and Uninsulated finds the highest carbon emitting result to be Green H2 FC (16,419 kg CO2e). The next highest emitting (and next lower ranked) result being Green H2 Boiler (9,997 kg CO2e) with a numerical difference in emissions of 6,422 kg CO2e.

Whereas the two lowest carbon emitting results of Biomass (1,094 kg CO2e) and Heat Pump (1,725 kg CO2e) have a difference of 631 kg CO2e, an order of magnitude between the two results but producing the same score with the original methodology of comparing the different systems. This newer method of assessing the same results attempts to account for the relative magnitude of the results in each category.

The extended results use the min-max statistical method to measure the spread of the results and produce a result from 0 to 1 where the best score is 0 and the worst score is 1. This allows a measure of spread between each result.

$$Score = \frac{x - minimum}{maximum - minimum} \tag{3.1}$$

This method of measuring spread was selected over others as with a zero to one produced this allows straightforward summation and comparison of other results and factors that have had a min-max method applied to them. For each model iteration assessed, adding all the min-max scores for all the elements assessed (capital cost, operational cost, operational emissions and system efficiency), will produce a final result that accounts for the magnitude of spread in all categories that are assessed.

3.4 Methodology for chapter 6. Modelling with smart meter data

This chapter develops on from the methodology from the previous chapter by using real energy demand data in the energyPro microgrid simulations. The real smart meter data is from the Smart Energy Research Lab (SERL), which is filtered and anonymised within the Secure Lab environment before export to be used in the microgrid model. Using python to 21 different energy demand profiles based on different characteristics of the home: GB EPC ratings (A, B, C, D, E, F, G, no EPC), Rural GB EPC ratings (A, B, C, D, E, F, G, no EPC), user profiles developed in chapter 4 Rural Energy Study, P01, P02, P03, P04, P05. This is seen in tables 3.1 and 3.2.

The resulting energy demand profiles from the filter is then averaged to produce a single set of energy demand time series. The Great Britain (GB) EPC energy demand profiles were developed by filtering the SERL dataset according to reported EPC (or lack of EPC).

The GB rural EPC energy demand profiles are filtered first by Lower layer Super Output Areas (LSOAs) that are considered rural at the 2011 census and then by EPC rating (or not). *2011 census results are used as the 2021 census results were not published at the time of the research being carried out.*

The rural urban classification varies between England, Wales and Scotland. England and Wales defines a rural area as a settlement area with a population of less than 10,000 (Bibby 2013). In Scotland an area and community is considered rural if there is a population less than 3,000 (Scottish Government 2022b).
The rural energy study responses energy demand profiles P01, P02, P03, P04 and P05 are produced based on the characteristics of each profile as defined in chapter

Table 3.1: Filters applied to the SERL dataset to produce the 5 archetypal rural energy user groups defined in chapter 4 Rural Energy Study.

Energy demand profile	Filters applied				Number of SERL particpants
P01	Rural GB	Semi Detatched /Detached home	Main heating fuel is Gas	EPC rating of C	68
P02	Rural GB	Semi Detatched /Detached home	Main heating fuel is Oil	EPC rating of C	47
P03	Rural GB	Semi Detatched /Detached home	Main heating fuel is Oil	EPC rating of D	67
P04	Rural GB	Detached home	Main heating fuel is Electricity	EPC rating of A, B or C	39
P05	Rural GB	Detached home	Main heating fuel is Gas or Electricity	EPC rating of D, E, F or G	237

Table 3.2: Filters applied to the SERL dataset to produce GB and rural GB EPC energy demand profiles.

Energy demand profile	Filters applied		Number of SERL particpants
Rural EPC A	Rural GB	EPC A	<10
Rural EPC B	Rural GB	EPC B	74
Rural EPC C	Rural GB	EPC C	385
Rural EPC D	Rural GB	EPC D	571
Rural EPC E	Rural GB	EPC E	257
Rural EPC F	Rural GB	EPC F	71
Rural EPC G	Rural GB	EPC G	19
Rural EPC N/A	Rural GB	EPC N/A	1017
Energy demand profile	**Filters applied**		**Number of SERL particpants**
GB EPC A	EPC A		<10
GB EPC B	EPC B		474
GB EPC C	EPC C		2488
GB EPC D	EPC D		3388
GB EPC E	EPC E		1191
GB EPC F	EPC F		187
GB EPC G	EPC G		47
GB EPC N/A	EPC N/A		5510

4 Rural Energy Study. Key attributes of each profile are used in each filtering the SERL dataset for each output.

The produced energy demand profiles are processed for export and checked by the UK Data Service to ensure no possible disclosures of personal information is possible before sending the exported data over email. The files are a half hourly time series in .CSV format. The data collected encompasses a 12 month period from September 2021 to August 2022. This time period was selected rather than one calendar year of 12 months as at the time of accessing the data this was the most

Table 3.3: Total energy consumption across the three energy user profiles P01, P04 and P05

Building heat profile type	Total heat demand (kWh)	Total electricty demand (kWh)
P01	15446	1804
P04	13925	4277
P05	14744	2916

complete and recent dataset available.

Using the derived archetypal user groups

Only three of the average energy demand profiles will be used in the micro grid models in energyPro, P01, P04 and P05. These energy demand profiles are used as they are based off the user profiles developed in chapter 4 rural energy study. When observing these energy demand profiles the typical peak instantaneous energy consumption is 6000 Wh when excluding outlier results.

Table 3.3 summarises the total electricity and heat demands for each demand profile. The differences between the different energy demand profiles finds that P01 has the lowest total energy demand and P04 with the highest total energy demand. Finding that there are similar magnitudes of gas (heat) consumption with an absolute difference of 1521kWh (10%), whereas the electricity demands observed for P04 is over double P01 and just under double of P05 with an absolute difference of 2473kWh (58%).

Figure 3.4: Gas (assumed to be heat) and electricity consumption profiles of P01, P04 and P05 energy profiles

3.4.1 Updating the microgrid models

The smart meter energy demand profiles that have been derived for user groups P01, P04 and P05 are applied to the microgird model used in chapter 5. Some of the models used are revised since used in the previous chapter to ensure that the successfully compute and in the correct method. This includes that models including energy storage correctly uses the energy stores implemented. Another set of revisions includes revising some of the green hydrogen models, reducing the quantity of electrolysers from a conservative over estimate to a smaller capacity.

This revision is made possible as there is a smaller magnitude of energy demand in the SERL data from the previously used energy demand profiles. Partially due to the SERL data recording energy consumption in half hourly intervals whereas the originally used estimated energy consumption profiles are hourly. The gas consumption profiles for P01, P04, and P05 are produced in figure 3.4.

3.5 Methodology for chapter 7. Experimental work

3.5.1 System description

The experimental system developed consists of an alkaline electrolyser producing hydrogen at 500 nL/h, hydrogen drying unit and central manifold. Where gas inputs and outputs to the Green Hydrogen metal hydride Store (GHS) are managed. The final component is the Green Hydrogen Store, where hydrogen gas was stored in an array of 5 1.44 L aluminium scuba tanks each containing 9072 g of AB2 alloy with thermocouples inserted that are charged and discharged by passing gas through a mass flow meter.

Figure 3.5: Diagram of the Green Hydrogen Store demonstration system

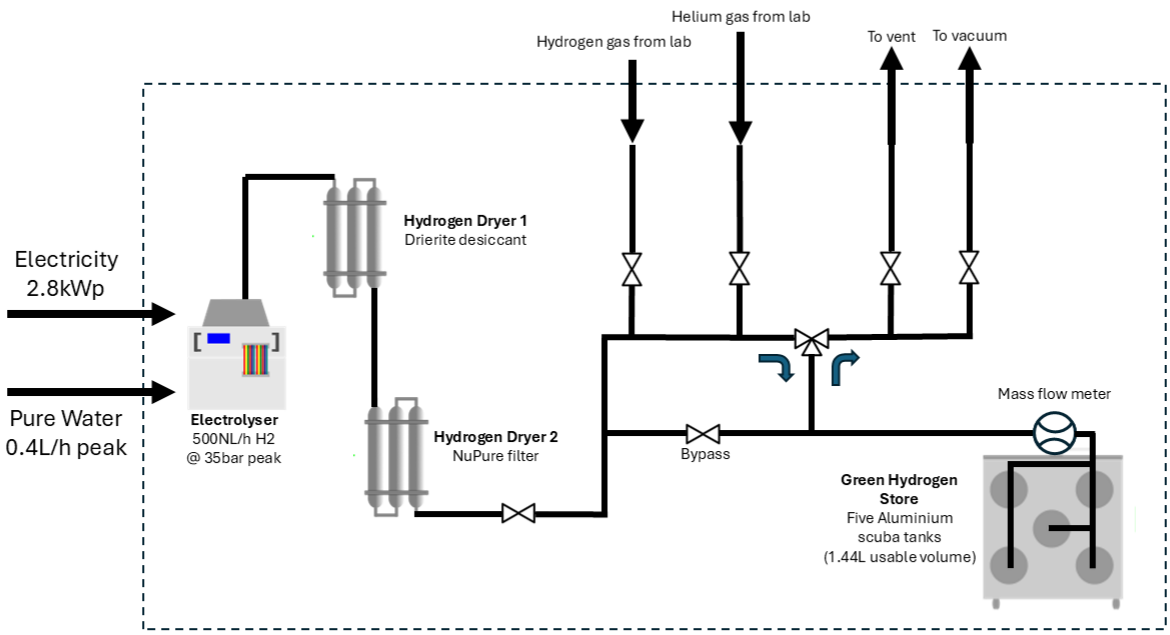


Figure 3.5 illustrates the input and output flows from the system boundary. With

electricity and water entering the system to supply the electrolyser. Hydrogen gas can also enter the system to operate the system without the electrolyser. The helium gas input is for leak testing the system whenever a major change to the system is had, such as removing one of the aluminium tanks. The external flows from the system are venting the hydrogen gas released from the GHS or venting via a vacuum pump.

Each of the five aluminium Luxfer scuba tanks have a thermocouple inserted within the vessel, with one vessel with a thermocouple attached to the exterior of the tank. The mass flow meter data is digitally captured and there are two pressure transducers in the system, one located of the left hand side of the three way valve, recording the pressure when charging the GHS. Similarly a second pressure transducer on the right hand side of the three way valve, enabling recording of pressure when discharging the GHS.

3.5.2 Metal hydride selection and characterisation

An important part of the system is the metal alloy material that will be used to store the hydrogen gas. Storing hydrogen gas in a metal alloy (also known as a metal hydride) occurs through the process of hydriding (charging the store) and dehydriding (discharging the store). For this hydriding and dehydriding process to occur the metal hydride alloy needs to be subject to hydrogen gas at certain temperatures and hydrogen gas pressures. The exact temperature and pressure varies according to the metal hydride used, for this demonstration system the hydride selected should be something that could be situated in a home. This means it should work at ambient temperatures and relatively low pressures (10-60 bar).

The metal hydride alloy Hydralloy C5 ($Ti_{0.95}$ $Zr_{0.05}$ $Mn_{1.46}$ $V_{0.45}$ $Fe_{0.09}$), which is an AB_2 alloy. Produced by GfE, this is a commercially available (there are few hydrides that are commercially available) and well known metal hydride material in hydrogen energy research and in broader industry. Hydralloy C5 (HC5) is known as a room temperature alloy, with the capacity to adsorb hydrogen at temperatures below 100C.

To validate the performance of the University of Nottingham's batch of HC5 a pressure composition isotherm (PCI) is taken of a 1g sample of HC5 on a sieverts apparatus. A sample with a mass of 1g is used as this is a typical capacity of sieverts apparatus used. The sieverts apparatus is a system used to test the properties of metal alloy hydrides for chemically storing energy such as hydrogen and ammonia. A PCI tests the capacity of a material to store hydrogen at various temperatures and pressures. The results of a PCI plot is used to generate a Van't Hoff Plot, a single line (and hence equation which can characterise the performance of a material at various temperatures and pressures. A Van't Hoff plot is produced by taking the natural log of the pressure at the midpoint of the plateau point at each PCI, against temperature in Kelvin and coefficients of the material's enthalpy and entropy with the ideal gas constant.

The Van't hoff plots of adsorption (figure 3.6) show the relationship of the temperature and pressure required for hydrogen to be adsorbed or desorbed from the hydride after the capacity has been determined by PCIs, in this case 1.8 wt%. The Van't hoff plots of adsorption are sufficiently similar between the experimental and literature results to use the data from literature to calculate the material properties of the batch of Hydralloy C5 used for adsorption and desorption. Both Van't hoff plots were manually calculated in Excel, the literature results use data from the literature PCIs.

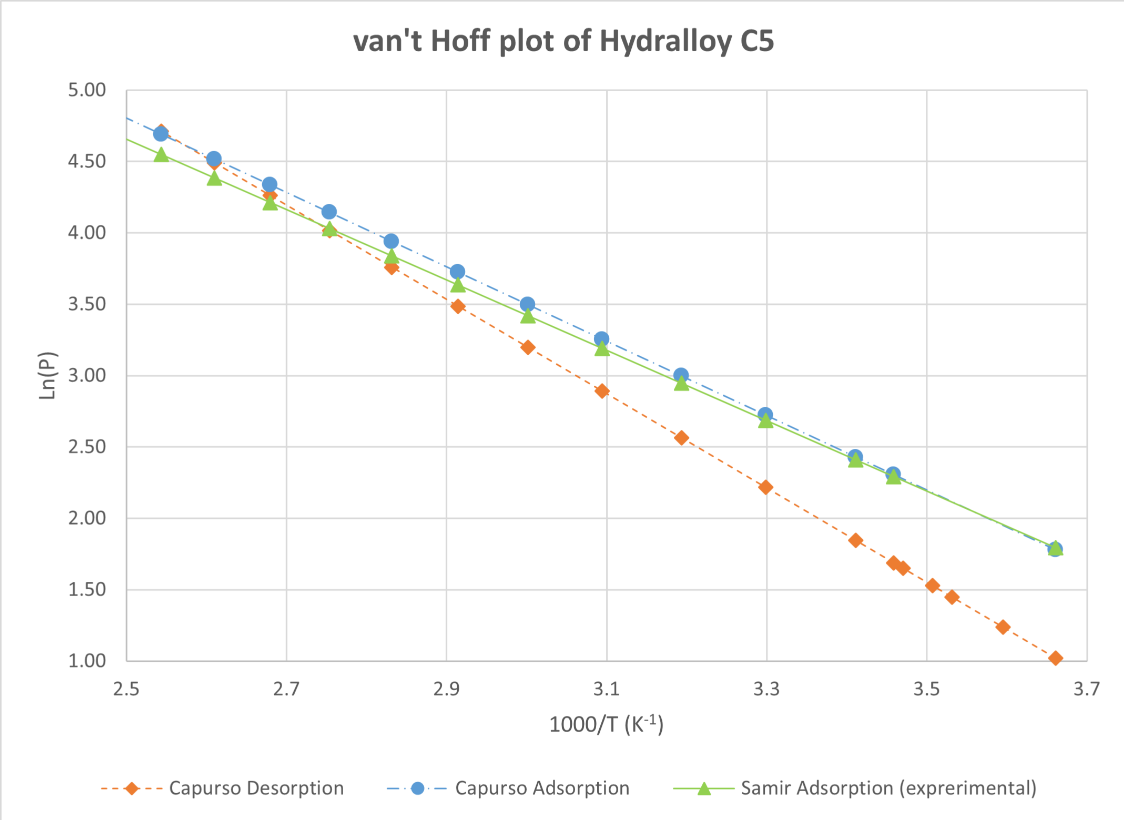


Figure 3.6: Van't Hoff plots of HC5 comparing the results of the UoN batch to literature (Capurso et al. 2016)

3.5.3 Construction of the GHS system

This demonstration system is comprised primarily of existing equipment present at the University of Nottingham hydrogen systems lab. Using a Pure Energy H-500 alkaline electrolyser from a previous project, re purposing a series of three buffer tanks as a large desiccant drying column (only two of the three tanks have Drierite desiccant within). An unused hydrogen purifier by NuPure follows the desiccant dryer down the line and next is a central manifold panel controlling the flows of hydrogen from the electolyser, the building and helium from the building into the store. There is facility to bypass the store to operate the electrolyser separately. Figure 3.5 illustrates the system.

The hydrogen store itself was built initially for another research project which ended before being able to use the store built. Therefore work was carried out to ensure this equipment was safe to be repurposed for this project.

Loading and activating the metal hydride material

The metal hydride material is crushed from the 10 mm flake size as supplied to a 1-2 mm in diameter particle size. Before being loaded into the aluminium tank. The tank has a measured 1.8 L volume and only 1.44 L of Hydralloy C5 is filled into the tank. This leaves the tank to be 80% filled. A 20% headroom is left in the vessel as a safety measure for any expansion and thermal effect for the hydride, which can cause expansion and rupture of the storage vessel (Charlas et al. 2012). Hydralloy C5 can be crushed and processed in air if carried out quickly, which is what happened in this case.

To activate the hydride tank it is placed on another system in the hydrogen system lab as seen in figure 3.7. This panel operates by controlling the flow rate of hydrogen gas to and from the attached vessel. The activation process involves repeatedly charging and discharging the hydride tank with hydrogen gas at a 35 bar of pressure at a flowrate of 14 L/min at ambient temperatures. Activation is achieved when there is a temperature increase is the vessel during charging and a temperature decrease during discharging, which is captured by thermocouples withing the storage vessel and on the exterior. This activation cycle is repeated 10 times to ensure that a stable hydrogen capacity is reached.

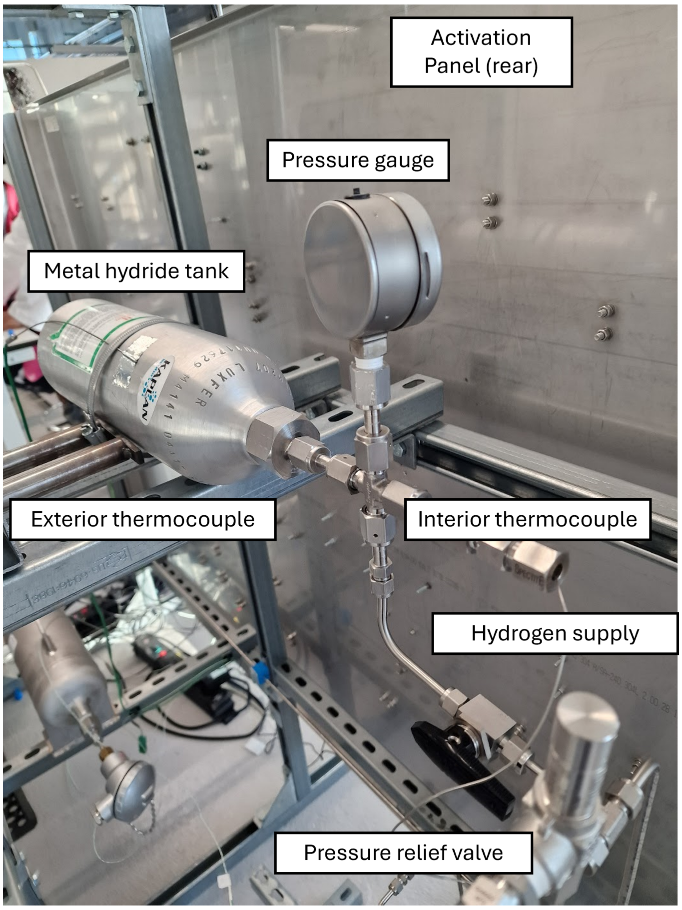


Figure 3.7: One of the GH2 Store's vessels filled with Hydralloy C5 in place on a different panel for activation.

Chapter 4

Developing archetypal rural home profiles for future energy system modelling

Understanding the current state of rural domestic energy consumption through a survey to rural residents asking about the energy systems in their homes

4.1 Introduction

In the UK, the way and form in which energy is consumed varies greatly depending on the location of the end user. In view of this, chapter 3 describes a survey designed based upon archetypal descriptions of rural UK homes energy systems and the occupant's energy related habits from this. This survey will produce archetypal descriptions of different homes and their energy access/technologies covering most possible combinations.

In the UK a minority of the population lives in rural regions. With 18% of the UK population living in rural areas, encompassing 91% of UK land area. The decarbonisation of homes and communities energy and fuel consumption is key to achieving a national transition to a low carbon society. Progress has been made towards this in decarbonising power with government backed research and investment to develop renewable electricity production through wind and solar. One result of this investment is some of the largest offshore wind farms in the world located in the UK such as the Hornsea One and Hornsea Two wind farms and the under construction the Hornsea Three and the Dogger Bank group of wind farms (A, B, C and Sophia). Work decarbonising and modernising the generation of electricity is ongoing, a greater and more complex challenge is decarbonising the generation of heat in buildings.

Heating in the UK consumes 44% of annual energy consumption (UK Government and Department for Business Energy and Industrial Strategy 2018) and produces 23% of all emissions (H. Government 2021a). 70% of buildings in the UK are reliant upon the national gas grid to meet their heating needs. Current government strategy is ambiguous and uncommitted, there is little certainty on the UK government's final decisions on what will be the preferred heat decarbonisation technologies and the government support towards this. One example of this is the delay delay on government approval of the hydrogen town trials (where all homes in a town would be heated with hydrogen) from 2023 where there was local backlash to the project and no hydrogen available to supply to the project. This project has been delayed to 2026, a date to when the government will decide the role of hydrogen to decarbonise heat (UK Government 2024). There is unclear policy to guide industry on investment in decarbonising heat, and opportunities to further research the challenges of implementing heat decarbonisation in buildings and scenarios considered hard to decarbonise such as rural and remote settings.

In researching domestic energy consumption there is importance to not only understand the patterns of energy consumption figures and trends, but also to understand the composition and fabric of the buildings in question. This includes the fuels (e.g. electricity and gas), energy conversion devices (e.g. boilers, radiators) and the level and composition of insulation of a building.
There is no standard or "typical" home in the UK and this is particularly true in rural areas. Factors such as the number of occupants, local weather patterns, age of buildings, and the construction fabric of building all contribute towards a diverse mix of end user energy demand usage. For this reason, when researching domestic energy consumption, in addition to data on energy consumption, it is also vital to understand the fabric of buildings. This provides a sufficient level of detail to research the costs and challenges of energy decarbonisation on a local level, and provide a more informed understanding of what is required to achieve this.

By producing a series of archetypes of UK rural homes that encompasses the diversity of UK rural homes and energy fuels/technologies used to heat and power homes a more representative breakdown of types of rural homes can be made. This thesis develops a series of rural energy user profiles based on factors such as location, demographics, current energy fuels used and building characteristics. The underlying data to develop these rural energy user profiles is an online survey developed as part to this research at the University of Nottingham distributed to parish councils across multiple districts in the United Kingdom.

4.1.1 Objectives

Rural energy is there focus of this research as there is limited understanding of the current local accessibility of energy. This is particularly evident when investigating the decarbonising of rural areas where there is a greater diversity in how energy is accessed and used in comparison to that of urban areas. There is a greater diversity in how energy is accessed rurally than urban.
Listed below are the objectives of the survey:

- Who lives rurally? - age, occupation, number of occupants
- What do respondents think about sustainability?
- What energy devices and other energy infrastructure is in the home?
- What fuels are used?

This work attempts to break down this diverse group of rural homes that may have varying levels of energy access into roughly analogous groups, to enable further insight which would be difficult to to obtain with out conducting a research survey of these groups in terms of the built environment and energy.

4.2 Survey methodology

The primary dataset used in this analysis was generated by an online survey comprising of 26 multiple choice questions related to rural energy accessibility. The topics covered by the questions were respondents demographics, location, attitude towards sustainability, the respondents home and the forms and methods of energy consumption in the home.

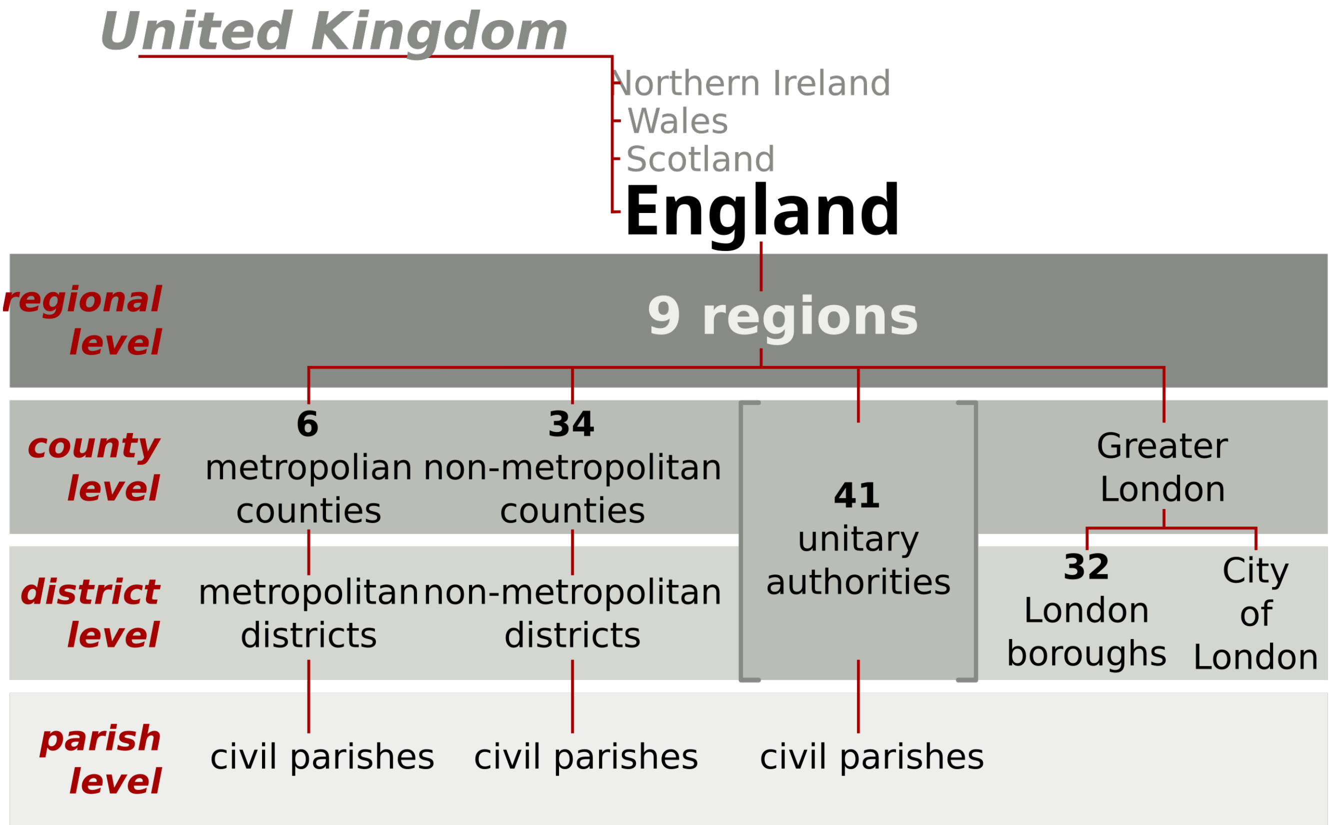


Figure 4.1: "England administrative divisions since 1995" by Marcin Floryan is licensed under CC BY-SA 2.0 (Floryan 2006)

This survey was distributed online to over 500 parish councils or equivalent lowest level of local government across the UK, Isle of Man, Jersey and Republic of Ireland. There are over 10,000 parish councils in England alone (National Association of Local Councils n.d.), selecting the appropriate parish councils to contact is first based on selected county council areas in the UK, and the subsequent borough or district council within a county.

First identified were counties that should be targeted to distribute the survey. Counties selected were those that have notable and substantial rural area or also have certain geography that would be beneficial to have responses from. Such as the English Peak District and Scottish Highlands where there are notable for their remote and rugged geography where energy access may be limited.

Once these counties were identified (such as Derbyshire, Lincolnshire and Highland), identifying the constituent district/borough councils (or equivalent) that make up the county was selected, based on the same criteria in selecting counties to target. Each district council is typically made up of tens of parishes.

The contact email sent out included a brief description of the rural energy access project and asking the recipient to fill out the survey linked in the email and to distribute the survey among their council and wider community. Due to the nature of this project involving outreach to the general public, this project and survey was approved by the University of Nottingham, Faculty of Engineering, Ethics Committee. Key considerations include access to personal data and respondents must consent to the collection of such data.

4.2.1 Survey questions

The survey was presented using a Google Form as this made it equally accessible to computer and mobile phone users. This also allowed the results to be exported with relative ease into MS Excel for processing.

The first 11 questions asked are primarily demographic questions to find out ***who*** the respondent is and what kind of household do they live in. Asking questions such as age, gender, employment status and the degree of working from home. Also asked in this first section are questions such as what kind of building (*What kind of home/building do you reside in?*) and geography (*What is the first half of your postcode (or equivalent)?*) the respondent considers themselves to live in. This first group of questions develop the background of ***who*** is responding and ***where*** do they live, to better understand and produce more effective solutions to these challenges through more in depth analysis. A copy of all the questions asked in the survey is found in appendix A.1.

Questions 12 to 16 are a series of multiple-choice questions that asks the respondents their attitudes towards the environment, sustainability and the cost of energy. These questions are asked to understand the attitudes of the respondents towards such issues, which often are motivations to adopting low carbon energy systems. This set of questions encourages respondents to begin thinking about the related topics in anticipation of the subsequent questions asked.

The final section of questions 17-27 are a series of technical questions asking the respondent to report key factors of their energy consumption such as the types of devices used in the home. What fuels are used for what application (power, heat, cooking or transport), how the fuels used is transported to their building and what sort of temperature is their thermostat set to throughout the year. These technical questions help build a profile of the archetypal homes and users that is later identified.

4.3 Survey results

The survey returned 229 responses, primarily from the English Midland and Scottish Highland regions of the UK. Also including some responses from Northern Ireland, Jersey and the Isle of Man that is not highlighted in figures 4.2, 4.3 and 4.4 due to the mapping software and postcode map only covering GB. The survey was distributed with focus on parishes in the English Midland and Scottish Highland areas of GB.

Geographic identification of respondents is limited to only the outward section of a UK postcode (e.g. SE16 or L7) consisting of two to four alphanumeric characters. This method of geographic mapping is used to avoid identification of individual respondents. A general location that would make identifying individual respondents locations not possible but still be able to provide a reasonable sized area where one geography (e.g. rural/urban) is consistent throughout, and help in identifying the type of energy access challenges had in the postcode area.

Figure 4.2: Map of Great Britain with postcode areas of only survey respondents from GB (Soares 2024)

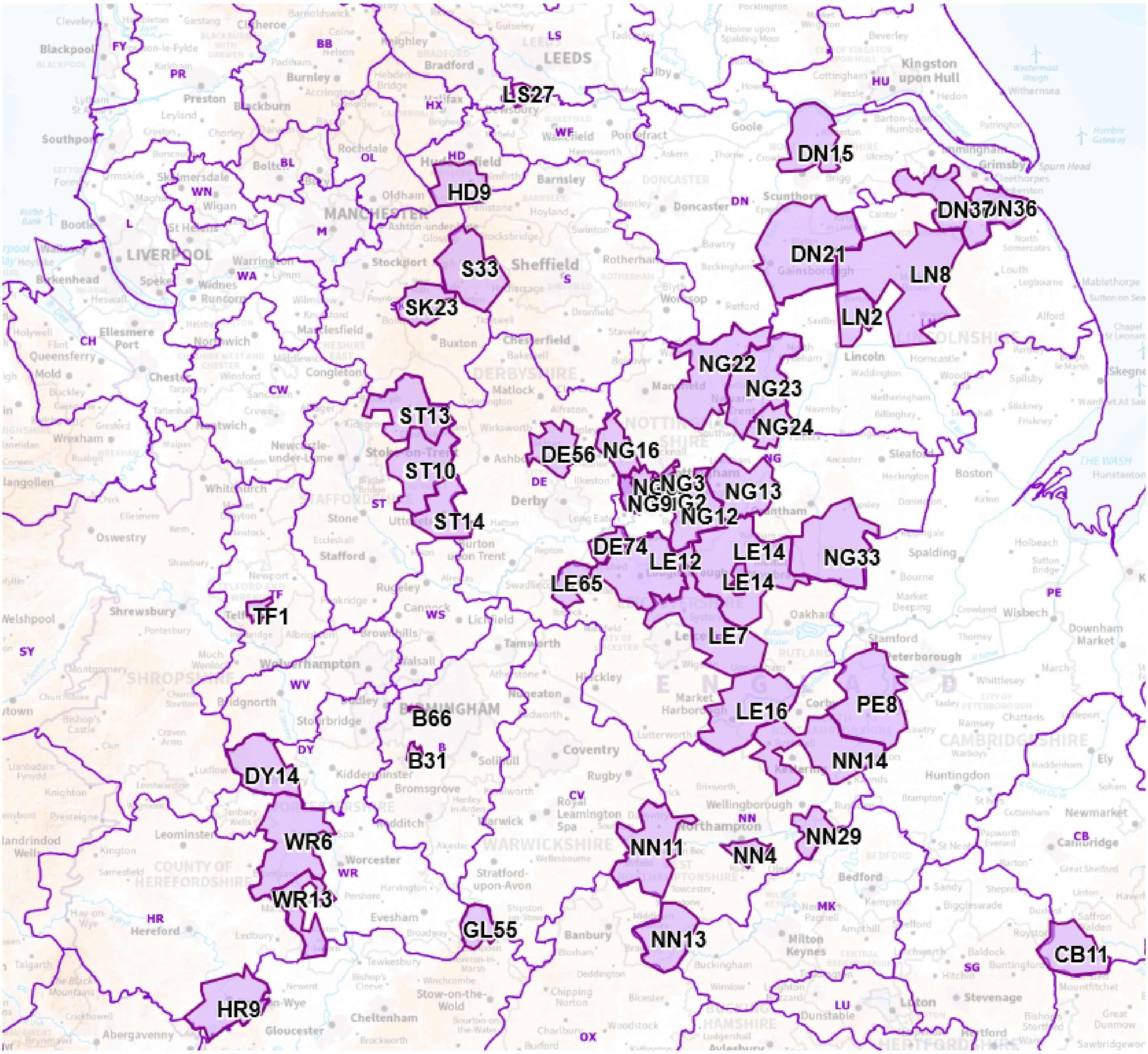


Figure 4.3: Map of the English Midlands with postcode areas of survey respondents (Soares 2024)

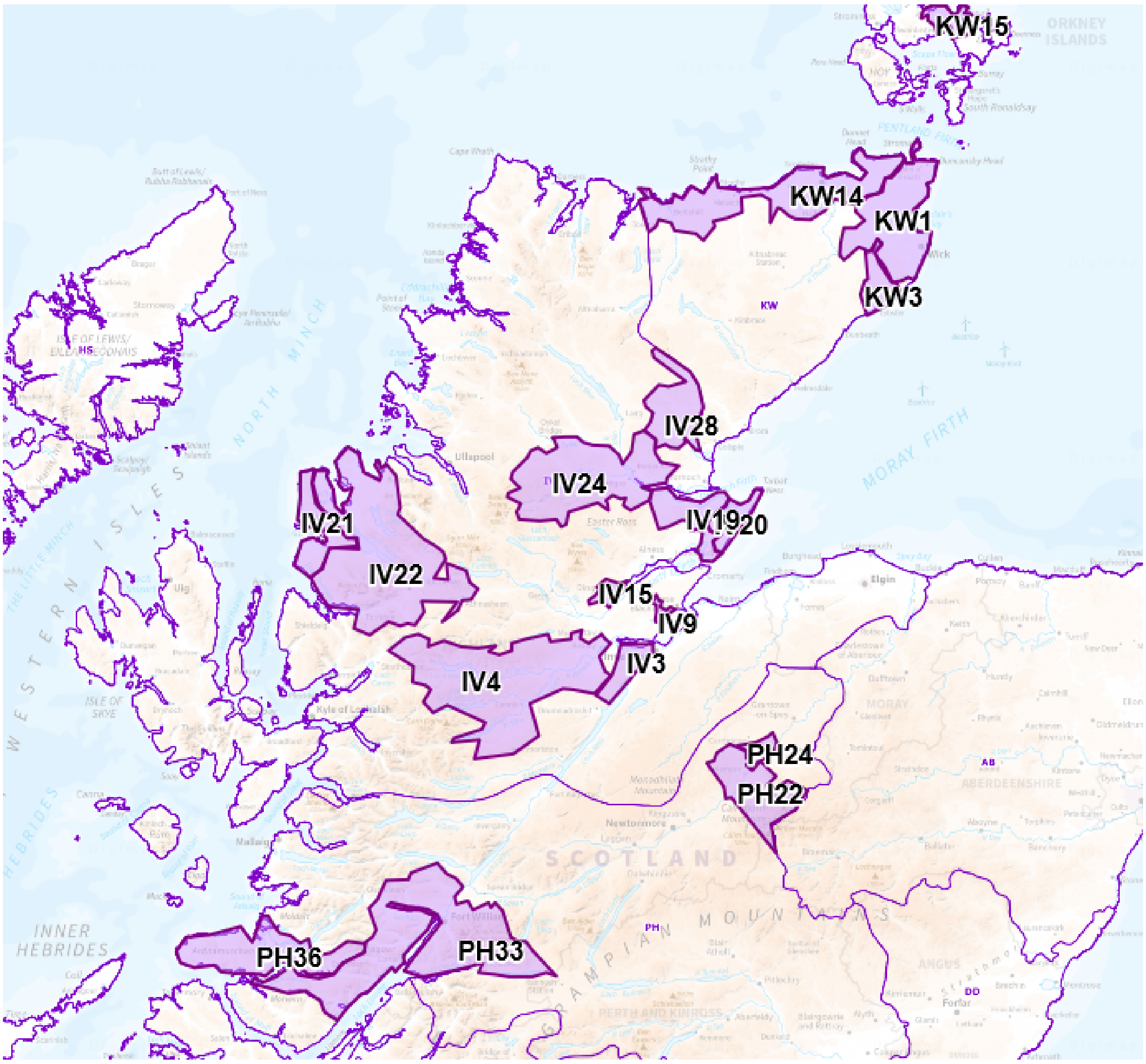


Figure 4.4: Map of the Scottish Highlands with postcode areas of survey respondents (Soares 2024)

4.3.1 Overall results

Using the survey data, and without applying a series of filters, it is possible to report who has responded to the survey and whether they live in a rural setting. Approximately 55% of respondents are male (45% female), 59% of occupants in respondents' homes are over the age of 44 and 78% of respondents live in a rural setting (village or smaller).

The overall trends of energy infrastructure and building fabric in the home finds over 85% of respondents report having some form of insulation, double glazing and energy efficient lighting, and 44% of respondents have a smart meter. 35% of respondents do not store energy in their residence. Those who do store energy report having a wood pile and/or hot water cylinder at over 40% each.
One result from this survey which is important to understand the fuels used in respondents day to day life. Figure 4.5 shows the response of what heating fuels are used by respondents. Finding that 56% of respondents use wood as a heating fuel closely followed by mains gas and electricity.

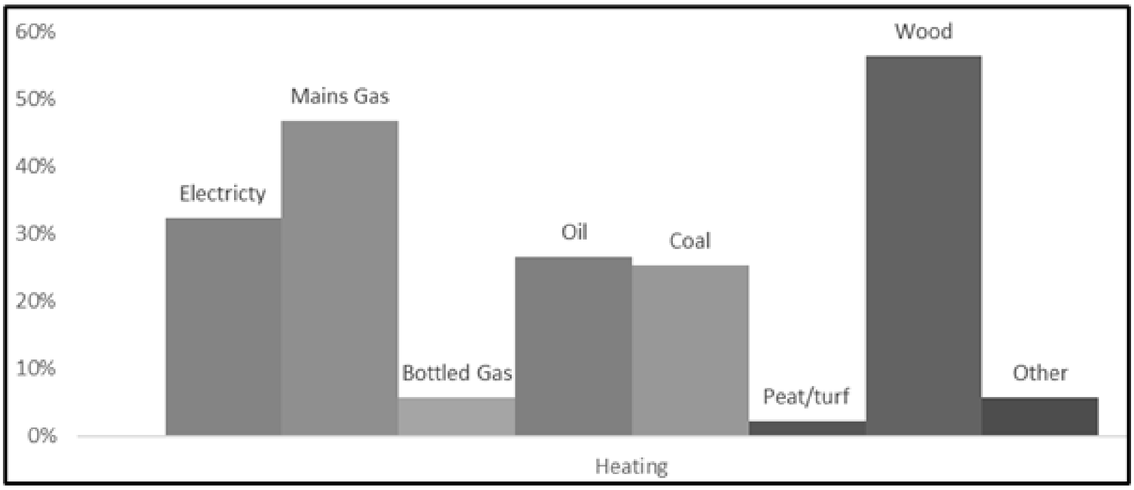


Figure 4.5: Results of Q19 from the survey ”What energy fuels do you use?”

4.3.2 Overall survey discussion

The results of the survey build a picture of who has responded to this survey, where they live, what energy infrastructure is in their home and what fuels they use in their home. To determine how representative the survey data is for rural dwellings in the UK. Results were compared with the 2022 Statistical Digest of Rural England (UK Government and Department for Environment 2022) derived from the 2011 Census will help validate how representative the results of the survey are in a national and rural context.

One marker looked at is population. By age over 50% of rural residents are above the age of 44 in national data, the survey results finds the figure for this age racket to be 59%. A comparable figure highlighting the general trend of the majority of rural residents being older in age.

Another marker is comparing the building types reported in the survey to (ibid.) finds that those reporting live in detached homes as a majority followed by semi detached and terraced homes in both datasets as seen in Table 4.1. The survey results output more building types than (ibid.). These additional building categories could be reduced to the four categories used by the four Department for Environment, Food & Rural Affairs (DEFRA) building category types, which could change the composition of building types present. This has not been done as this would change the composition of building types used in the survey.

Table 4.1: Comparing residential building types from (UK Government and Department for Environment 2022) and from the total survey results.

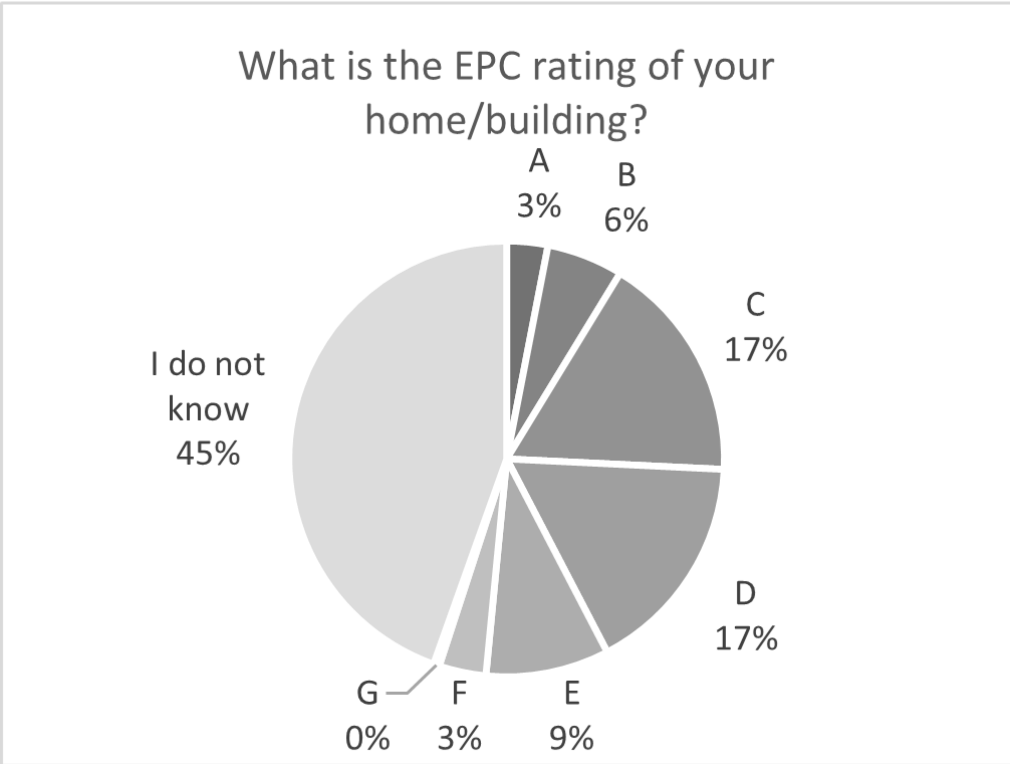
Building Type	DEFRA (Statistical Digest of Rural England 2022)	Survey
Flat	**7%**	**5%**
Bungalow		7%
Terrace	**17%**	**13%**
Semi detached	**31%**	**20%**
Detached	**45%**	**44%**
Farmhouse		6%
Other		5%

Energy Performance Certificates

A factor in understanding energy efficiency of homes and the possible measures to improve energy efficiency is the energy performance certificate (EPC). The EPC incorporates running costs, building insulation, heating technology and heating fuel to determine how energy efficient a home is.
45% of survey respondents did not know the EPC of their home as seen in figure **??**, highlighting the lack of public awareness of the energy efficiency of their own homes. When these ratings that are key to improving the energy efficiency of housing stock. Especially due to *(at the initial time of writing)* upcoming UK government legislation requiring new rental properties to have a minimum EPC rating of C by 2028, now pushed back to 2030 (Shilling and Simply Business 2024).

Of the respondents that responded knowing the EPC rating of their home, 46% of respondents have an EPC rating of C or better. This EPC rating is in line with research conducted by (Open Property Group, Department for Levelling Up, and Communities 2023) who reported that 40% of English homes have an EPC rating of C or better .

As the sample size of results is small, validation of the data is required to provide confidence that the data collected can be further analysed to develop archetypal rural users for future research.
Validation of the data was achieved by comparing survey findings to comparable figures found in the survey data to comparable figures from other sources. This has been achieved by looking at survey results for respondents age, building type and EPC rating of their homes. Comparing the results for these three categories to government figures on population and rural population in particular (Department for Environment 2024) have provided similar results, enough to assume that the data collected has captured a representative portion of the public, particularly rural



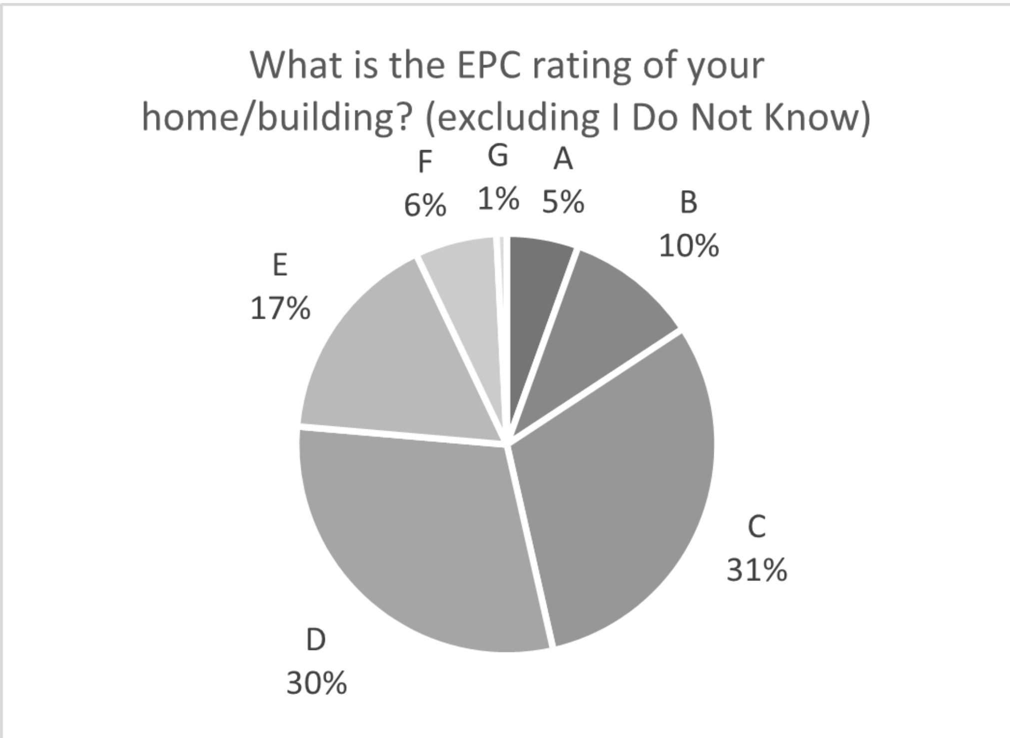


Figure 4.6: EPC rating of survey respondents homes (top) and excluding "I Do Not Know" (bottom).

residents.

4.4 Developing archetypes

To encompass the spread of different types of rural domestic energy user, a nuanced range of user archetypes are required to enable meaningful research to be conducted into the energy usage of rural residents. Five archetypal user groups derived from the results of the rural energy survey and are given in table 4.2. These five groups were selected primarily based on geography, access to the national grid and EPC rating. These criteria were used in the selection of the archetypes as they readily distinguish between the different groups of end users and are easily understood by the layperson.

The first two archetypes are complementary of each other focusing on rural village residents, where the majority of respondents originated from, with group P01 being village residents connected to the national gas grid and P02 conversely being village residents not connected to the national gas grid. The third archetype P03 looks at off gas grid respondents from sparse geographies, those who report to live communities smaller than a village (hamlet, farmhouse or other) not connected to the national gas grid.

The fourth and fifth archetypes are complimentary of each other being "Modern rural" P04 and "Old rural" P05. Where P04 focused on respondents whom report having an EPC rating of C or greater and report having some energy saving measures installed such as heat pumps electric vehicle (EV) chargers and smart meters. P05 looks at those reporting EPC less than C and excludes those with heat pumps or EV chargers. A key exclusion of both P04 and P05 are those who report that they do not know their EPC rating of their dwelling, which encompasses a majority of survey respondents.

Table 4.2: List of five archetypal rural energy users based on the survey results that use geography, connection to the national gas grid and reported EPC level as key filters.

Number	Key attributes	Key exclusions
P01	On gas grid, village only	city, town, suburb, hamlet, farm, other
P02	Off gas grid, village only	city, town, suburb, hamlet, farm, other
P03	Off gas grid, sparse only	city, town,suburb, village
P04	Modern rural (Village or sparse, EPC >= C, Insultation, energy efficient lighting, smart meter, heatpump or EV charging reported)	Excludes "I do not know my EPC"
P05	Old rural (Village or sparse, EPC <C)	Excludes "I do not know my EPC", Heat pump, EV charger

4.4.1 Five archetypes overview

Key results of each developed archetype will be presented here. A complete list of responses for each archetype will be presented in the appendix.

Group P01 comprises of a 60% majority of two person households and 56% are over the age of 54, 43% are retired. Over 60% live in detached buildings and the largest reported EPC rating is C. Regarding attitudes to the cost of energy 12% have no concern whereas 50% are sometimes concerned, however almost 75% of respondents sometimes take measures to reduce energy consumption and only 3% take no energy consumption measures.

All of group P01 report having a connection to the national gas grid, only 90% use gas for heating and 44% use gas for cooking. Other fuels used for heating and cooking are electricity, wood and coal. It can be inferred that a majority of P01 store energy at home in some form with Wood piles (46%), hot water cylinders (35%), coal stores (12%) and electric batteries (6%), whereas 41% do not store energy on site.

Group P02 has a slight female majority (53%) in contrast to P01 (46%) and the overall survey results with 57% of this group over the age of 54 where 45% are retired. 49% live in detached buildings where the largest reported group of EPC rating is C.

6% are not concerned with the cost of energy whereas 51% are sometimes concerned, only 8% of respondents in P02 have no interest in installing sustainable technologies in their residences. Fuels used in heating by P02 include wood (80%), oil (53%), electricity (43%) and coal (43%). The most common device used to provide hot water to the residence is an oil boiler (53%). Only 14% do not store energy in some form on site, of those who do the most common energy stores are wood pile, hot water cylinder and heating oil tank.

There are more varied heating systems in P02 compared to P01 with only 53% using central heating in P02 whereas 84% use central heating in P01 compared to other methods such as electricity and fireplaces.

Group P03 has a slight female majority (51%) and 54% of the group are over the age of 54. A majority of this group consider themselves to live in a hamlet (42%) followed by a single dwelling (29%) and farm (22%), where 39% of P03 live in detached homes and 24% in farmhouses.

EPC D is the most prevalent reported EPC rating (18%) followed by EPC E (11%).

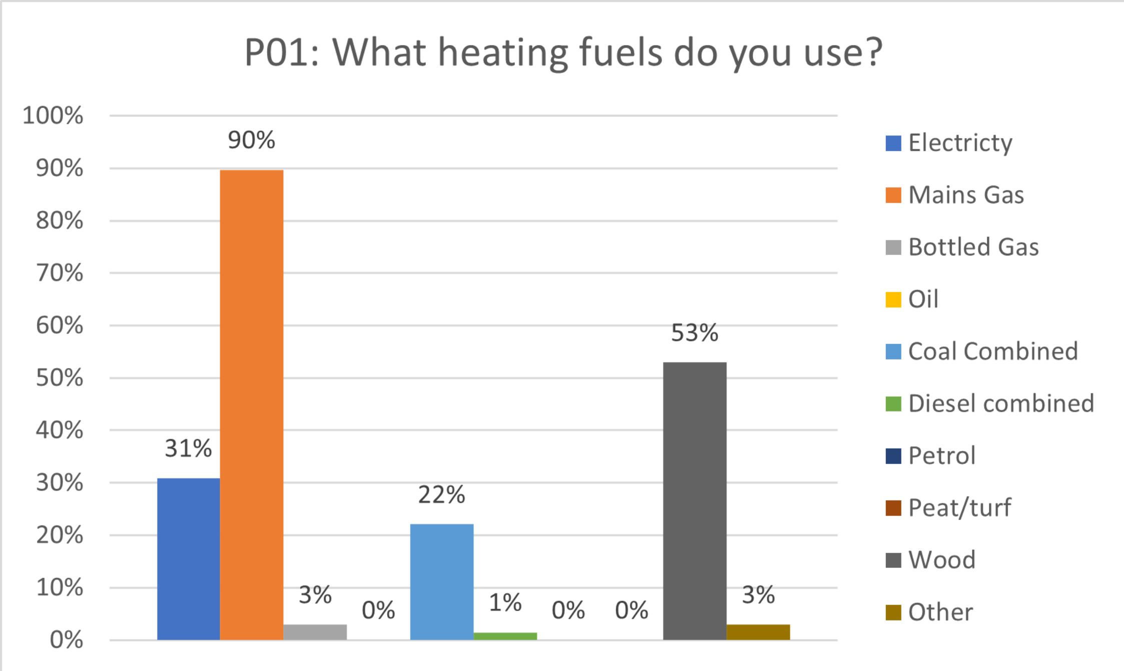
40% of P03 do not work from home for any proportion of their work, only 15% exclusively work from home.

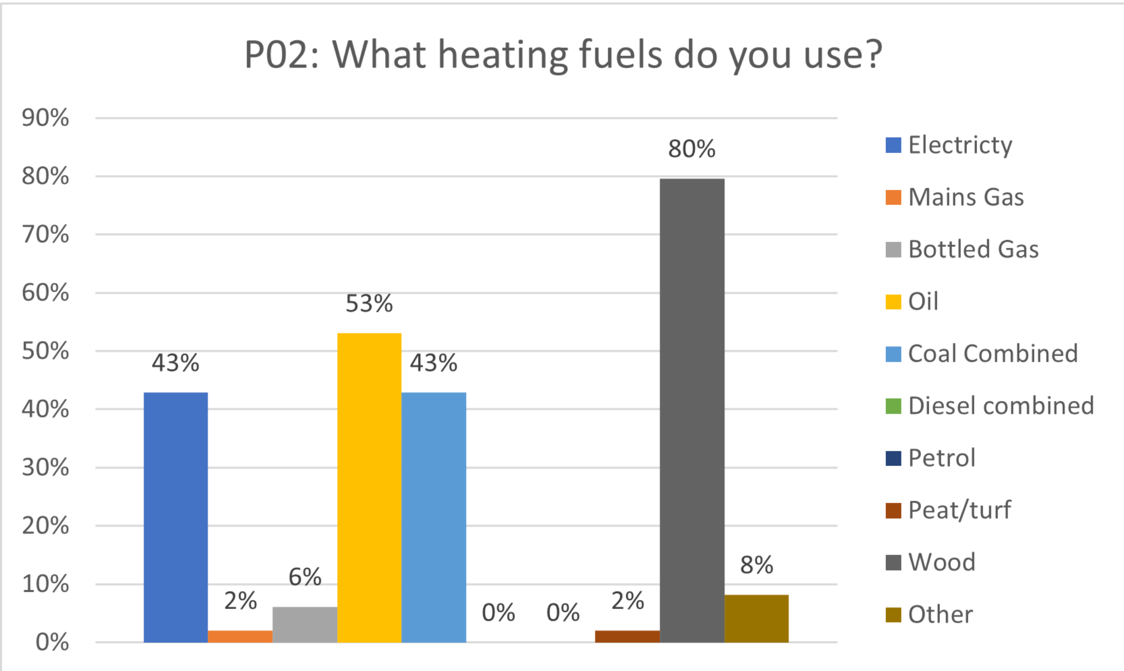
The fuels reported to be used for heating are wood (84%), oil (62%), electricity (33%) and coal (29%). Central heating is used by 56% of P03 as the principal method of heating. The primary stores of energy onsite are wood pile (69%), hot water cylinder (55%) and heating oil tank (53%), 11% report not having any form of energy storage on site. These reported fuels do not differentiate between primary and secondary heating fuels. Reflecting poor wording of the question given *What energy fuels do you use?*, a more appropriate question would be *What is your main source of heating?*

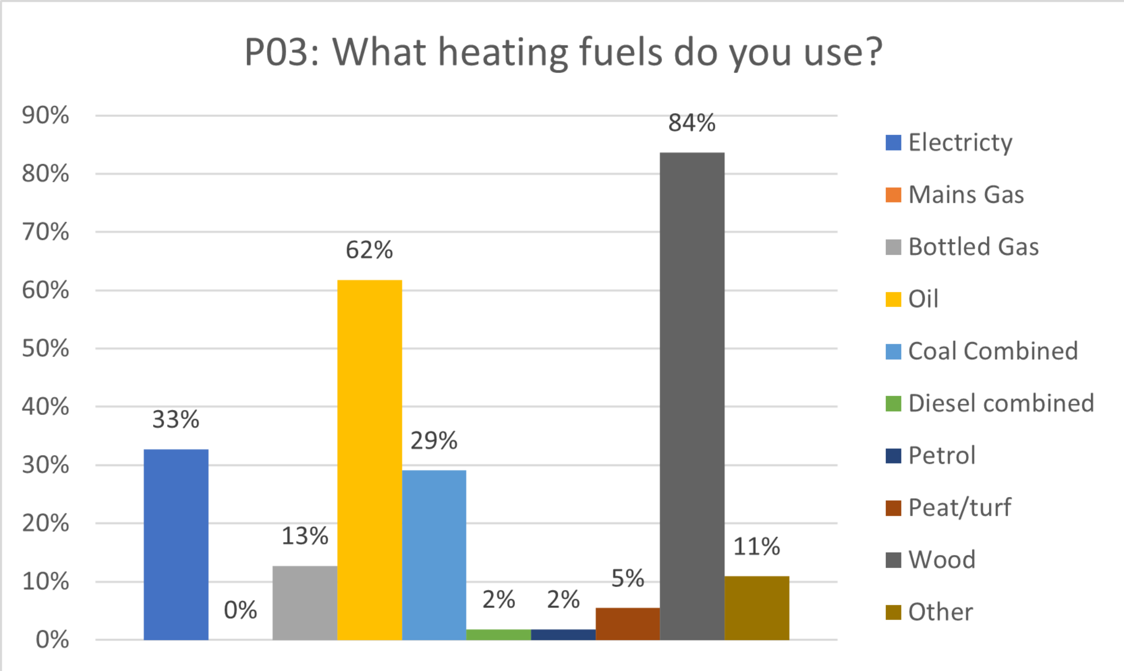
Group P04 "modern rural" encompasses any response with an energy saving measure installed up to and including heat pumps and EV chargers and if their EPC is greater or equal to C, the government ambition of the minimum EPC rating for housing.
This group comprises of a male majority (59%), largely of two person households (69%) and where 51% are above the age of 54, 46% are retired. Almost all respondents in P04 live in villages (90%) followed by hamlets (8%) and farms (2%), where detached homes are the most popular at 62%.

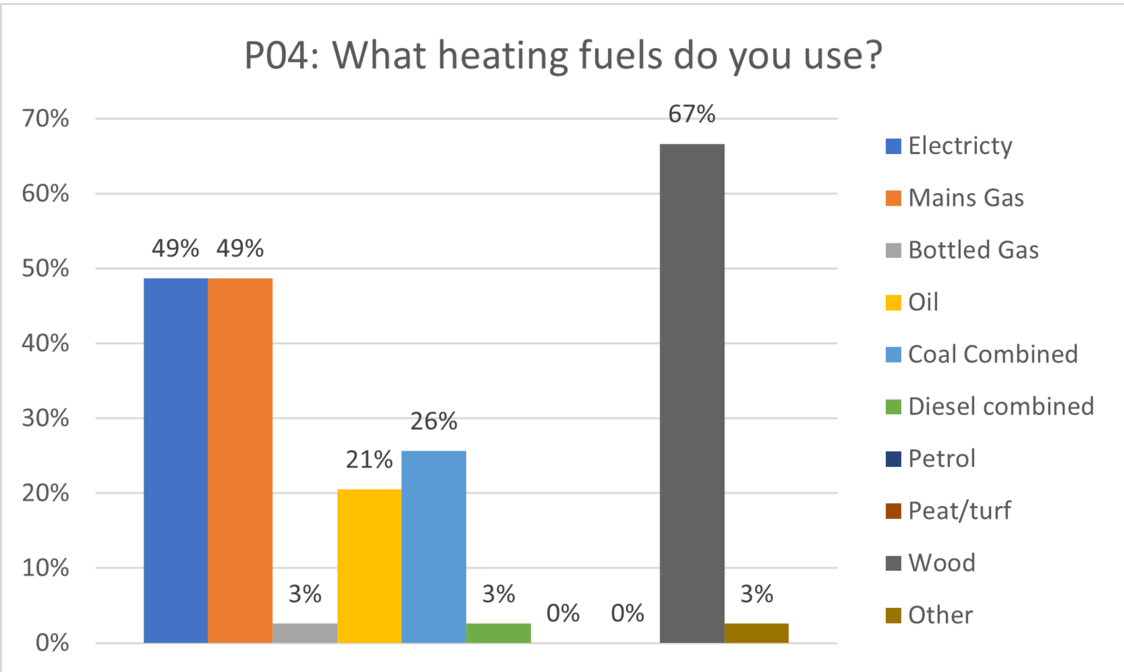
EPC C is most common (74%) followed by B (18%) and A (8%). Of the energy efficiency measures reported almost all respondents had some form of double glazing (100%), insulation (100%) and energy efficient lighting (97%). The uptake of heat pumps (21%) and EV chargers (10%) are relatively very low to other heating fuels and technologies reported in this survey. The heating fuels reported are wood (67%), electricity (49%), mains gas (49%), coal (26%) and oil (21%). The major heating devices reported is a gas boiler (51%), followed by oil boiler (21%) and heat pump (21%).

Group P05 covers rural residences who have a EPC less than C and do not have a heat pump or EV charger. 42% are over the age of 54, where the majority live in a village (61%). EPC D is most prevalent (46%) followed by E (40%). The energy fuels used for heating are roughly similar in uptake to each over other than wood as seen in 4.7. Similarly the main heating devices reported are the gas and oil boilers.


P01: What heating fuels do you use?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
90%
31%
3%
0%
22%
1%
0%
0%
53%
3%
Electricty
Mains Gas
Bottled Gas
Oil
Coal Combined
Diesel combined
Petrol
Peat/turf
Wood
Other


P02: What heating fuels do you use?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
80%
53%
43%
43%
6%
2%
0%
0%
2%
8%
Electricty
Mains Gas
Bottled Gas
Oil
Coal Combined
Diesel combined
Petrol
Peat/turf
Wood
Other


P03: What heating fuels do you use?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
33%
0%
13%
62%
29%
2%
2%
5%
84%
11%
Electricty
Mains Gas
Bottled Gas
Oil
Coal Combined
Diesel combined
Petrol
Peat/turf
Wood
Other


P04: What heating fuels do you use?
70%
60%
50%
40%
30%
20%
10%
0%
49%
49%
3%
21%
26%
3%
0%
0%
67%
3%
Electricty
Mains Gas
Bottled Gas
Oil
Coal Combined
Diesel combined
Petrol
Peat/turf
Wood
Other

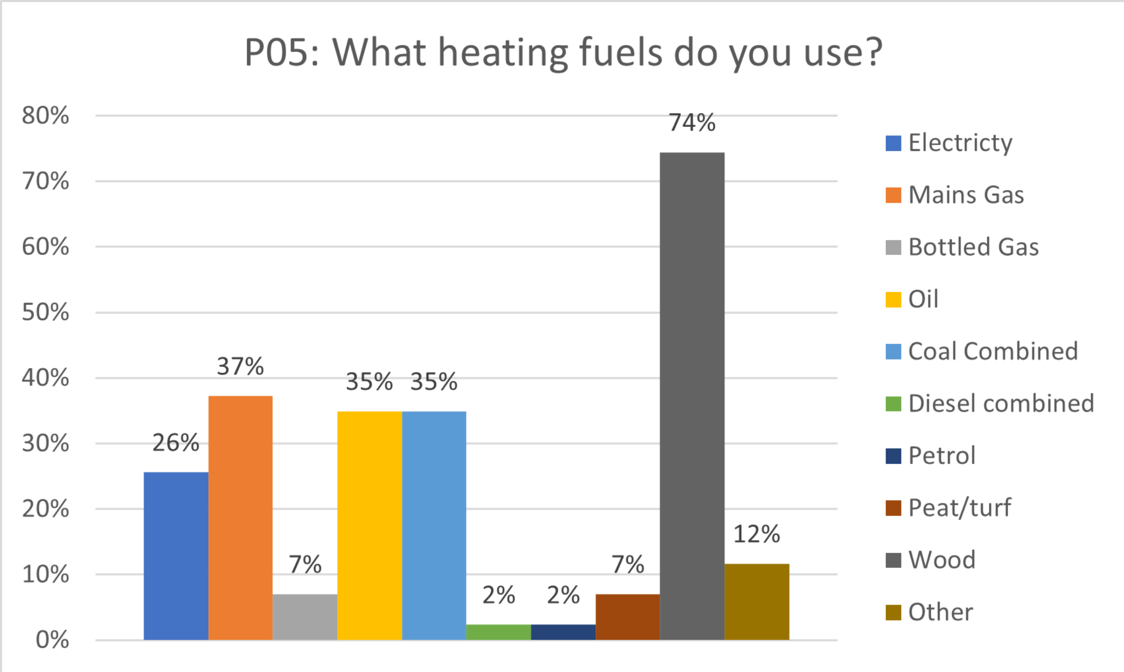


Figure 4.7: Heating fuels used by each archetype developed P01 - P05.
Multiple fuels can be selected by each respondent

4.4.2 Five archetypes discussion

Looking at the overview of the archetypes selected, with an overview of key figures for each of the defined archetypes. One observation was the prevalence of wood across all archetypes, suggesting wood being a popular secondary heating fuel in fireplaces. Suggesting a greater usage of secondary heating systems to meet the heating demand. Each of the identified groups are quite diverse in terms of fuels used, with generally positive attitudes and interest in addressing sustainability and installing sustainable technologies.

This helps define a general final profile of each archetype by interpreting the top trends of each archetype area as;

- **P01** consists of mostly 2 person households over the age of 54 with an EPC of C. Mostly using grid natural gas to heat their homes using either gas or electricity to cook and have some form of energy storage typically most usefully in a hot water cylinder.

- **P02** typically consists of people aged over 54 in detached buildings with an EPC of C. the primary heating fuel used is oil with over half using an oil boiler with a large proportion of homes having a working fireplace for secondary heating with wood.

- **P03** mostly lives in a hamlets where a significant minority lives in detached homes followed by farmhouses. EPC ratings of D and E are common, where oil is the most common primary heating fuel.

- **P04** Almost all live in villages with a majority being 2 person households at a typical EPC of C. All have basic energy efficiency measures of double glazing, insulation and energy efficient lighting, very few have heat pumps or EV chargers. The primary heating fuels are either electricity or grid gas.

- **P05** finds the majority living in a village with a typical EPC of D and E, with no outright most common primary heating fuel across grid gas and oil when considering reported fuels used and reported heating devices used.

4.5 Conclusion and future use of this data

The data collected by this survey has been validated by comparing statistics from authoritative sources. Subsequently defining five key archetypal groups that generally encompass most types of different resident.

There could be improvements with the survey methodology as there are some questions asked that overlap asking similar topics and returning slightly different results for essentially the same question. Further rewording and focusing some questions for more targeted responses, such as further rewording some questions to specifically target particular responses. One example is rewording the question *What* *heating fuels do you use?* to *What is your primary heating fuels?* and an extra follow up question of *What other heating fuels do you use?* This would produce a greater detail of results and rely less on reading between the lines the entire set of responses by one respondent to estimate what the primary and secondary heating fuels may be it at all. With any survey-based research, this work could be improved by more responses will improve the quality of data received. More focused questions asking specifically what of the various heating fuels/technologies a respondents may use is the primary, secondary or even tertiary systems of heating.

The results from this survey and the identified archetypes will be used in subsequent work in chapter 6. To develop bespoke energy demand time series profiles of electricity and gas (heat) demand that can be associated to each of the five user groups developed. These energy demand profiles will be developed from a broader dataset of smart meter data collected by the Smart Energy Research Lab (SERL) (Smart Energy Research Lab and University College London n.d.).
Beyond this thesis this work could be beneficial for future rural energy research in topics such as domestic energy, energy infrastructure, demographics, fuel poverty and attitudes towards energy.

Chapter 5

Initial modelling with estimated energy demand profiles

5.1 Introduction

This section looks at developing a methodology of modelling a domestic micro-grid energy system to evaluate and compare various fuels and technologies that are used to heat and power rural and remote homes. Looking and selecting the micro-grid simulation software, energyPro and developing the subsequent methodology of analysis of the simulation results. There are 19 versions of the micro grid model developed. The first 11 model presently used heating fuels and systems such as Oil, coal and LPG bottle gas. In this first group some novel and lower emissions technologies such as heat pumps, grey and blue hydrogen systems are modelled.

The remaining 8 versions of the system explores a range low emissions technologies where each model version has a wind turbine, solar thermal array and solar photovoltaic array present. Evaluating low carbon heating technologies such as heat pumps, wood biomass and green hydrogen. Each of the 19 model versions are calculated against 3 different types of energy user relating to the level of insulation of the home. In total there are 57 results to analyse.[1]

5.2 Methodology

5.2.1 Modelling methodology

This work is computed using energyPro, a block based microgrid modelling software to produce a model that compares energy conversion between numerous iterations of the system simulating electricity, heat and other fuel systems, with financial and economic modelling included. Other modelling software was considered such as MATLAB Simulink and Homer Pro.

[1]This chapter was first presented as proceedings at the 15th International Green Energy Conference 2023, in Glasgow, UK.

MATLAB Simulink was not considered as although there is a high level of flexibility and detail in producing highly customisable models with bespoke algorithms and solvers. There is also not a dedicated library to a variety of energy system components and devices. Requiring much work to produce the required library of components that are compatible with each other in Simulink. For a larger and more detailed study, MATLAB Simulink would be ideal.
Homer Pro is a popular microgrid simulation software, however it is quite limited in functionality, in adding or tweaking custom modules and components. Also Homer Pro is good at modelling electricity only microgrids, yet limited when looking at heat systems and other fuel systems.

EnergyPro was selected due to its large library of system component modules and example models with the ability to simply customise existing modules. And the ability to have detailed modelling of electricity, heat and other fuels. There are some limitations, particularly in selecting or customising the operational solver and methodology in computing the model and no linking facility to external software such as MATLAB or python. These limitations were identified at the software selection phase and not seen as great impediments to completing the work.

The initial results produced include operating cost and emissions produced by various off gas grid heating fuels and technologies present and future that are modelled. The heat and electricity demand profile used for this model as seen in figure 5.1 is from (Baumanis et al. n.d.[a]) masters project website exploring energy modelling of buildings on the Isle of Gigha, which has since been taken down since downloading the data. However, an archive of the website on the WayBack Machine internet archive is listed for reference.

Three general heat demand profiles can be derived from this data; an old uninsulated home, an old home with retrofitted insulation and a new build home with

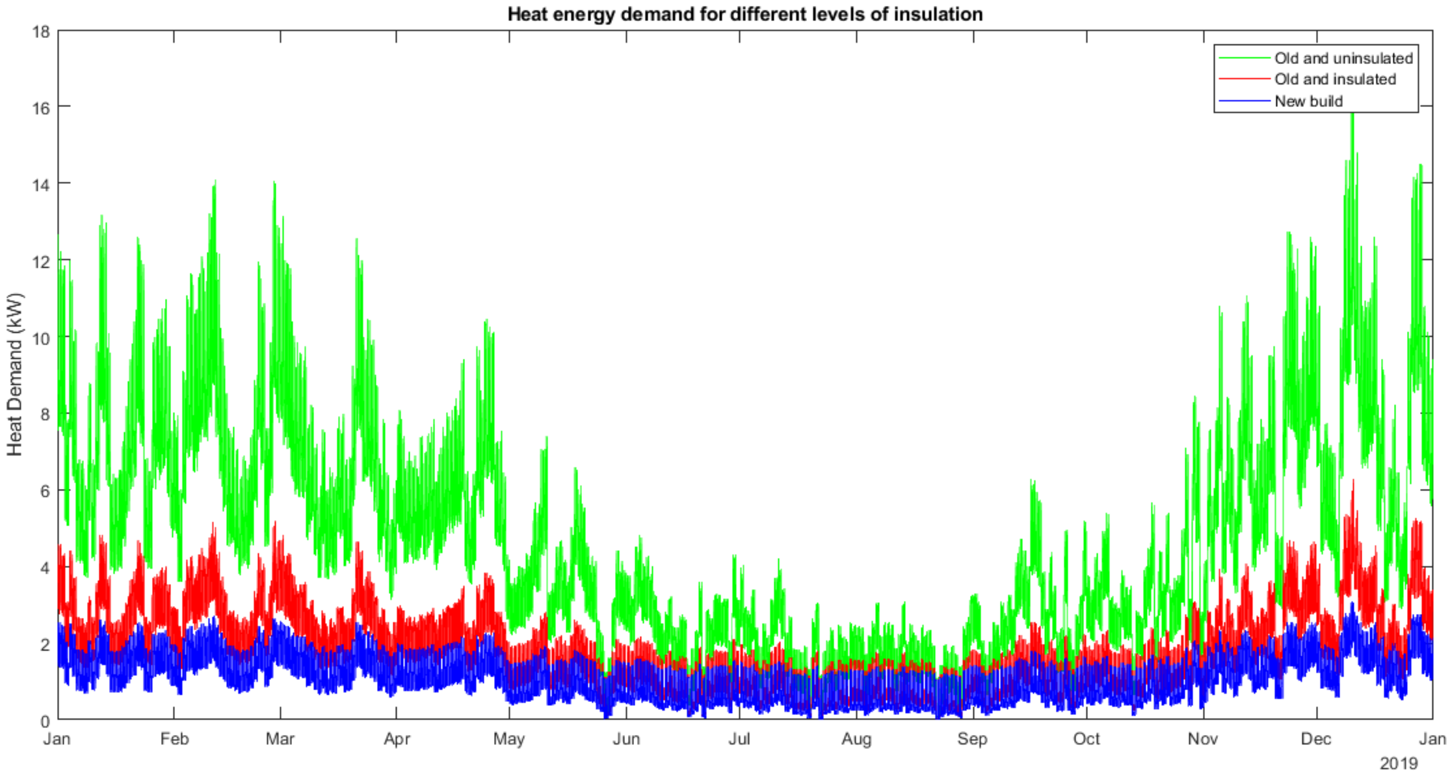


Figure 5.1: Heat demand profile across a year with different levels of insulation (Baumanis et al. n.d.[b])

insulation (Baumanis et al. n.d.[b]). The head demand profile includes DHW at certain times of the day (0400-0600 and 1500-1700) for 6 hours a day in total, the electric demand profile is for all appliances and excludes any secondary electric heating. A common electricity demand profile from the same source is used in all models, it is expected electricity demand profile for all appliances excluding electric heating. The final results of this model is presented in Table 3 in the existing fuels model and Table 6 later on.

5.2.2 Methodology of analysing results

To assess the results found according to different criteria, the methodology is a simple ranking of each result grouped into heat demand profile modeled separately assessing the annual cost and the annual emissions.

A ranking of 1-11 (as there are 11 fuels/technologies assessed), where 1 is the lowest annual cost or the lowest annual emissions and 11 is the highest annual cost or the highest annual emissions. This analysis provides a simpler view of the results found in table 5.3. However comparing the two tables highlights a limitation to using this simple ranked analysis, the varying magnitude of raw result compared to the corresponding ranked value.
The final score is produced in table 5.4 where the ranked scores of the annual cost and the annual emissions are added together. This method of scoring is useful to view the overall value of a certain fuel/technology. No weighting was applied to the annual emissions or annual cost scores as no appropriate weighting of each factor was decided. The weighting of different factors will vary depending on the context scenario and user of the data, who will find one factor more important than the other and hence weigh the results in that direction. The value of using this relatively simple ranking system allows comparison and combination of different metrics.

When the annual cost and annual emissions scores for each heat demand profile are added together this produces the results found in table 5.4. These results are useful as it provides a simple techno-economic assessment to find the optimal fuel/technology. This methodology is repeated for section 5.4 with a 1-8 ranking as there are 8 model versions explored.

5.3 Existing fuels model

The existing fuel model used comprises of eleven versions using different fuels and associated technology to supply sufficient heat and power. All eleven versions are run three times each with a different heat demand profile as previously described. The inbuilt MILP solver that is included with energyPro (emd.dk n.d.) has been used to compute the models.

Table 5.1: Emissions and costs per unit of energy used in each fuel/technology in the existing fuel model

Fuel/Technology	Emissions (kg CO2e/kWh)	Cost (p/kWh)	Source
Mains Gas	0.21	3.64	(BRE, Garston, and Watford 2023)
Heating oil	0.298	4.94	(BRE, Garston, and Watford 2023)
House coal	0.395	5.58	(BRE, Garston, and Watford 2023)
Dry wood log	0.028	5.12	(BRE, Garston, and Watford 2023)
Grey Hydrogen	0.5049	9.57	(BOC n.d.) Cost £49.97 per bottle of hydrogen when data was captured (Howarth and Jacobson 2021)
Electric boiler	0.136	16.49	(BRE, Garston, and Watford 2023)
LPG Bottle	0.241	9.46	(BRE, Garston, and Watford 2023)
Electric Tank	0.136	16.49	(BRE, Garston, and Watford 2023)
Heat Pump	0.136	16.49	(BRE, Garston, and Watford 2023)
Storage heater	0.136	16.49	(BRE, Garston, and Watford 2023)
Blue hydrogen	0.042	9.57	(BOC n.d.) Cost £49.97 per bottle of hydrogen when data was captured (Howarth and Jacobson 2021)

The fuels used in the model use energy and emissions data from the UK government GHG conversion factors for company reporting (BEIS 2022) and the Standard Assessment Procedure (SAP) 10.2 (BRE, Garston, and Watford 2023), where unit costs of fuels are used. This model and its results only calculate operational costs associated with the unit cost of the fuels used, which within the price may include transport, labour, taxes and other costs (Ofgem 2022), (Howarth and Jacobson 2021). Some limited financial modelling of annual maintenance for some technologies is included based off online accessible quotes from boiler/heat pump service providers.

The model uses “modules” to graphically represent each device in the energy system such as boilers, wind turbines and solar PV devices, which can be modified with technical information analogous to real devices. The modules modelled are mostly real-world devices with the technical information for them found online where possible. Each model version was sized for the “Old and uninsulated” heat demand profile, this allowed for the same models to be used with the other heat demand profiles that have a lower demand. As there was no modelling of fuel, electricity or heat storage other than the heat pump, immersion and storage heater versions of the model as heat storage are key elements of these systems.

Central heating and direct hot water demands are combined to develop the heat demand profile. The effect temperature can have on the performance on certain devices is not calculated other than for heat pumps. Temperature heat degree days is used to compute the heat demand profiles (Baumanis et al. n.d.[b]).

This model compares the approximate annual operating cost and environmental impact of different fuels that are typically used in off gas grid homes. Included in this analysis of rural off gas grid heating fuels are other adjacent fuels and technologies that are relevant to be included. Such as Mains (grid) natural gas, the most common form of domestic heating providing a point of comparison with most, whilst future possible solutions to rural domestic heating such as hydrogen and heat pumps.

The capital costs of the component used in all of the microgrid models are listed in table 5.2. The majority of figures are real capital costs from commercially available products (including the installation costs where available). Some devices are not commercially available online, particularly the hydrogen electrolyser and fuel cell are placeholder values that are estimated. such as the hydrogen technologies as these are not mass market products with costs relatively unknown and unstable for these use cases. These figures for hydrogen electrolysers and fuel cells are derived from enquiries to fuel cell and electrolyser manufacturers and previous University of Nottingham procurement of such devices.

Table 5.2: Capital costs of devices used in modelling. Includes installation cost where data is available. If no capital cost is found an estimate is made.

Baxi 624 Combi Boiler 20% hydrogen ready	£ 2,787.50	Solar photovoltaic 3kW	£ 6,400.00
Baxi 624 Combi hydrogen Boiler 20% hydrogen blend	£ 3,037.50	SD6 6kW freestanding wind turbine	£ 24,000.00
Baxi 624 Combi Boiler LPG 24kW	£ 2,788.34	Electrolyser Pure Energy H2 500 (900g/day @500NL/h)	£ 4,945.00
Worcester Bosch Greenstar Heatslave II 25/32 Combi oil boiler	£ 7,513.68	Electrolyser @ UoN RAD 50kg/day (100kW)	£ 875,000*
Electric Boiler Strom SB21C combi 3phase 21kW	£ 2,750.00	Fuel Cell HyPm XR12 (12.5kW)	£ 100,000*
Vittoria Biomass pellet Boiler 19kW	£ 3,995.99	(Hot water) RM Cylinders Stelflow Direct Unvented Cylinder 300Ltr	£ 2,125.00
Heat Pump WB 7000i AW 5kW	£ 7,742.44	Biomass pellet store	£ 2,100.00
Multifuel Fireplace 14kW rated hot water coal/wood log	£ 3,299.00	Compressed hydrogen gas store (BOC bottles)	£ 779.17
Two kW Electric space heater	£ 21.99	Heating oil tank	£ 2,874.00
Storage heater Dimplex QM150	£ 2,209.00	Coal store	£ 372.00
Immersion heater 3kW	£ 59.66	LPG tank	£ 779.17
Evacuated solar collector 20 tube Joule Acapella	£ 4,000.00	Biomass (dry log) storage	£ 372.00
* Placeholder values used in the modelling. They are vastly underestimated			

5.3.1 Results

The existing fuel model results can be found in table 5.3, where figures on annual bill and annual emissions for each iteration of the model. The highest operational costing iteration was “Electric immersion tank” for two levels of insulation (Old and uninsulated/Old and insulated) with “Electric boiler” being highest cost for the (new build) heat demand.

The middle costing fuel across all heat demand types are LPG bottle gas, the lowest costing fuels/technologies is heat pump and mains gas. Excluding mains gas, the lowest cost off grid fuel is found to be oil for the “old and uninsulated” heat demand and “heat pumps” for the insulated and new build demands respectively.

The results for annual emissions found the same rating for all three heat profiles, “grey hydrogen” having the highest emissions, electric storage heater having middle scoring emissions. “Dry wood log” having the lowest annual emission for the uninsulated heat demand and heat pump for insulated and heat pump demands. Although the annual emissions figures between “dry wood logs”, “heat pump” and “blue hydrogen” are all relatively similar in emissions.

Table 5.3: Results of existing fuel energy model comparing the energy bill and emissions of different fuels or technologies.

Model version name	Annual running cost (£)			Annual emissions (kg CO2e)		
	Building heat profile type			Building heat profile type		
	Old and uninsulated	**Old and insulated**	**New build**	**Old and uninsulated**	**Old and insulated**	**New build**
Mains Gas	2,565	1,627	1,360	9,575 *anomalous result*	4,162	2,624
Oil	3,025	1,759	1,395	13,314	5,673	3,479
Coal	3,912	2,125	1,602	21,795	9,141	5,442
Wood	3,666	2,025	1,546	2,120	1,222	960
LPG Bottle	4,917	2,517	1,824	10,798	4,685	2,920
Electric boiler	7,316	3,494	2,377	5,893	2,741	1,820
Electric Tank	7,547	3,533	2,361	6,158	2,847	1,880
Storage heater	5,732	2,589	1,854	6,618	3,070	2,006
Heat Pump	3,432	1,549	1,313	2,619	1,066	872
Grey Hydrogen	5,002	2,535	1,835	22,153	9,139	5,441
Blue hydrogen	5,002	2,535	1,835	2,431	1,336	1,024

5.3.2 Discussion

It was found that all heat demands used exceed the national typical domestic consumption values of 2,900kWh of electricity, 12,00kWh of gas and 4,200kWh of economy 7 electricity.
All the above results include cost and emissions for both electricity (which is the same for all model versions) and heating with various fuels. As the heat demands explored non average homes using local weather conditions and building fabric to develop a heat demand profile can explain this deviation from the national average. Annual emissions results find that “dry wood logs” and “heat pumps” are the lowest carbon emitting fuels/technologies across different heat demands.

Heat pumps are some of the least polluting fuel/technology due to high efficiency. Wood logs are also low emitters due to the low emissions per kWh as seen in table 5.1, whereas other transformed forms of solid wood fuel such as wood pellets are over double the emissions of wood logs.
Electric storage heating was found to be approximately middle emitting fuel and grey hydrogen the most emitting fuel, due to the energy intensive process of producing hydrogen via steam methane reformation.

The lowest scoring (and hence best in terms of combined emissions and running cost) fuel/technology across the three heat demands modelled in table 5.4. Finding “wood” and “heat pump” fuels/technologies the lowest scoring technologies. Heat pump did not score lowest across all heat demands, only the retrofit insulated and new build heat demands. This was not expected as heat pump technologies have a high effectiveness ranging from 200% - 400%.

The result is due to the operating principles of a “heat pump”, most simply explained that it is the most effective (efficient) when the temperature difference from the exterior heat source (e.g. the outside air in an air source heat pump) to the interior. This is most prevalent in air source heat pumps which rely on external ambient temperatures (engineeringtoolbox.com n.d.), (Maritime Geothermal Ltd. 2017) and are the majority of installed heat pumps in the UK. Due to the high heat demand of the “Uninsulated” heat demand profile Figure 1 a large amount of energy is required to sustain the heat demanded to reach the same levels of temperature and comfort required.

From this “existing fuel” model, mainly looking at various commonly used off grid fuels and technologies that can be found today. Lower to middling carbon emitting fuels such as “blue hydrogen”, “heat pumps” and “wood” are found to have low to middle emissions and annual bills, particularly so when combining the cost and emissions results of table5.3 as seen in table 5.4. “Wood” fuel scoring low sometimes beating out heat pumps was an unexpected result.

Wood is considered a biomass fuel with moderate emissions and moderate energy content that can be cheaply bought at scale, resulting in the low combined score. However, there are practical issues with wood not factored in these results, such as its bulky nature affecting the transportability of this fuel, large storage space and handling of logs required into a boiler. Physical challenges of using wood logs can be alleviated if using wood pellets into a biomass boiler which reduces bulkiness to transport, handle and store but increases overall emissions and cost due to the processing of wood logs into smaller pellets.

This model only looks at annual operating cost (OPEX) and emissions, it does not look at the capital cost and emissions from purchase, transport, and installation of the heating systems. Incorporating calculations of economic and carbon payback time if purchased at the time of writing (2022/23) would undoubtedly modify the

Table 5.4: Ranked result of different heating fuels when combining the ranking for cost and emissions of each technology/fuel for the existing fuels model. *Half marks are due to models being tied with the same rank result.

Technology/fuel	**Old and uninsulated**	**Old and insulated**	**New build**
Mains Gas	8	9	9
Oil	11	12	12
Coal	15	16	16
Wood	5	6	6
LPG Bottle	14	14	14
Electric boiler	14	14	15
Electric Tank	16	16	15
Heat Pump	6	2	2
Storage heater	15	15	15
Grey Hydrogen	18.5*	17.5*	17.5*
Blue hydrogen	9.5*	10.5*	10.5*

result found here, there results are nonetheless important when considering long term system planning.

These results are still informative in assessing and comparing the day to day, year to year running costs and the resulting emissions impact from present and future off gas grid heating fuels/technologies. This can inform further research and decision making on energy decarbonisation of places with limited energy infrastructure or where it is difficult to install.

5.4 Renewable energy systems model

When looking at low carbon energy systems, micro generation and hybrid heat and power systems are keenly pushed by government to encourage local level decarbonisation. Local distributed electricity generation through installing small wind turbines, solar panels and solar thermal devices on a community or home basis reduces dependence on external sources such as grid electricity and delivered fuels. Reducing the operating costs of energy systems but requiring higher capital expenditures by individual users. Onsite energy storage is a key of part of enabling effective renewable distributed generation. As the ability to export excess electricity generated will not always be feasible and sizing renewable devices to only the consumer's consumption may not be cost effective in utilising the renewable energy resources present.

There may not be the local demand for the energy produced or the local low voltage grid may not have the capacity at that time or require upgrades to sustain the exported locally distributed energy. The form of which energy storage may take is varied such as batteries, pumped storage and hydrogen.

The following renewable energy model will explore some combinations of renewable energy generation, energy storage and heat and power production with the aim to minimise the quantity of energy imported (hence lowering the annual bills and emissions). While supplying sufficient heat and power.

Exploring low carbon technologies for off grid heat and power hydrogen technologies such as electrolysers, fuel cells and hydrogen boilers in this model. Each version of the model has the same sources and magnitudes of renewable energy; a 6kW peak wind turbine, a 3kW peak solar photovoltaic (PV) panel and a $2m^2$, 1.2 kW peak evacuated tube solar thermal array. These sizings of 3kW peak for a solar PV array for this model was selected as this is a common recommended sizing for a small 2 bed home in the UK (greenmatch.co.uk 2024), where in the UK a typical average domestic PV installation is 3.5kW peak. A 6kW standalone wind turbine sizing was selected as this is a common and small size for a full standalone wind turbine on a rural domestic property with land to install available (HIESS 2025), with various examples of rural UK communities using 6kW wind turbines to proveide energy (SD Wind Energy 2025). The size of the solar thermal array selected is based on the evacuated tube solar thermal arrays used at the University of Nottingham Creative Energy Homes. Also included throughout every version is an electric grid connection for import and export of electricity.

A hot water cylinder in sized as 300L singularly or multiples depending on the technology used. Wind, temperature and solar radiation data is used to develop energy production trends of the renewable energy devices based on CFSv2 weather data, which can be downloaded through a facility in the modelling software.

There are various hydrogen based technologies modeled in this set of models, it is key to highlight the “green” hydrogen based technologies are more accurately. But less concisely described as electrolysed hydrogen on site that uses a mix of grid electricity and locally, renewably generated hydrogen. In this work it is more concisely referred to as “green” hydrogen but this is not the most accurate description of this. All model versions were sized for the highest heat demand (Old and Uninsulated) and all manage to provide sufficient heat that is demanded. All other methodology and data used are the same used in the existing fuels model.

Table 5.5: Overview of renewable energy model versions.

Model version name	**Description**
Mains Gas (reference)	Mains natural gas and boiler + hot water cylinder + renewables
Biomass (wood log)	Biomass boiler + hot water cylinder with immersion heating boost + renewables
Green hydrogen boiler	Hydrogen boiler + hot water cylinder + renewables
Immersion heater and hot water cylinder only (Electric Tank)	Immersion heater + hot water cylinder + space heater boost + renewables
Green hydrogen fuel cell	Electrolyser + hydrogen store + fuel cell + hot water cylinder + renewables
Heat Pump	Heat pump + hot water cylinder + immersion heating boost + renewables
Green hydrogen hybrid heat pump	Electrolyser + hydrogen store + hydrogen boiler + heat pump + hot water cylinder + renewables
Bottled grey hydrogen hybrid heat pump	Hydrogen bottle + hydrogen boiler + heat pump + hot water cylinder + renewables

5.4.1 Results

The results of the renewable energy model as seen in Table 6 has been processed exactly like the existing fuel model using the same heat demands, producing figures for approximate annual energy bill and annual emissions. A negative figure for annual bills indicates money earned from exporting excess renewable electricity is greater than money spent on unit costs of energy used.

From this the lowest energy bill was found to be “biomass” for uninsulated buildings, and bottled hydrogen hybrid heat pump for insulated buildings and heat pump for new build buildings. Both of which earned a net income from exporting excess electricity. Mid-range cost technologies was found to green hydrogen hybrid heat pump for all building heat profile types. The highest operating cost technologies was found to be green hydrogen fuel cell system.

Looking at annual emissions “biomass” was the lowest for the uninsulated and newbuild building heat demand types with heat pumps the lowest for the insulated heat demand. Approximately middling emission technologies was found to be immersion heated water for all building heat profile types. Highest emission technology was found to be “green hydrogen fuel cell” system.

Table 5.6: Results of renewable energy model showing the annual energy bill and annual emissions broken down by building type and technology.

Model version name	Annual running cost (£)			Annual emissions (kg CO2e)		
	Building heat profile type			Building heat profile type		
	Old and uninsulated	**Old and insulated**	**New build**	**Old and uninsulated**	**Old and insulated**	**New build**
Mains Gas	284	-650	-916	8,928	3,540	2,010
Biomass	266	-687	-987	1,094	597	427
Green H2 Boiler	10,742	3,867	1,374	9,997	4,538	2,492
Electric Tank	5,411	1,153	-83	5,264	2,227	1,329
Green H2 FC	14,823	6,306	2,955	16,419	8,922	5,272
Heat Pump	1,554	-520	-821	1,725	571	452
Hybrid HP GH2 Boiler	3,221	-226	-470	3,127	780	706
Hybrid HP Bottled H2	1,169	-437	-725	5,227	996	967

5.4.2 Discussion

The results found in table 5.6 show that there is a significant difference between the highest and lowest values calculated. Approximately one order of magnitude, the largest values coming from the "green hydrogen fuel cell" and boiler technologies. If the green hydrogen (onsite hydrogen electrolysis) technologies were to be removed all results would approximately fall within the same order of magnitude.

Why is there such a relatively high economic and emissions cost to the electrolysed hydrogen technologies? This model has a fixed supply of renewable energy from three sources, wind, solar PV and solar thermal, of which wind and solar PV can provide a combined 9kW peak supply of electricity. Renewable energy is intermittent by its nature and can be coupled up with energy storage systems, such as batteries and electrolysers (which produce "green" hydrogen) to store energy generated that is surplus to demand and would otherwise be exported.

Exporting electricity back to the grid can often be unfeasible in the UK due to grid capacity issues and long multiple year queue for the electricity disributed network operator (DNO) to implement any application for new grid connections. Hence the appeal of energy storage. This model did not couple electrolysers to periods when renewable power was generated (due to challenges doing this with the software) and was simply connected to the electricity grid. Finding performance data on electrolysers is challenging as these are not widely available products that can be simply purchased.

Performance data used to model electrolysers are based off electrolysers found at the University of Nottingham. A small alkaline electrolyser (Pure energy H-500, comparable in size and scale to the Enapter AEM electrolyser EL4 (*AEM Electrolyser EL 4 - Enapter* n.d.)) used in a lab with approximately 58% efficiency producing approximately 900g/day at 500NL/hr. And a large electrolyser (based upon the ITM electrolyser at the University of Nottingham that supplies hydrogen the Research Acceleration and Development (RAD) building) with an approximate 82% efficiency producing approximately 60kg/day.

These devices were scaled up and down in size to produce an approximately sufficient production capacity that would be indicative of the current spread of electrolyser technology available that would be used in such scenario as found in this model.

High emissions and high costs for the green hydrogen energy systems are due to not coupling hydrogen production with excess electricity produced, relying on imported electricity which has a financial and emissions costs associated. Highlighting that such a system should be only used when there are other factors that limit the feasibility of other technologies with lower costs and emissions.

Future modelling will be done on coupling and scaling renewable energy to local use to minimise import and export of electricity. The bottled hydrogen hybrid heat pump model used the same grey hydrogen cost and emissions data as in the existing fuels model, finding it comparable in operating cost and emissions to a sole heat pump system.

Looking at the heat pump and hybrid heat pump systems, the green hydrogen hybrid has the greatest cost and emissions. The “Mains gas”, “Biomass (wood)”, “Heat pump” and “Immersion heater and hot water cylinder only (Electric tank)” model versions are the same as similarly named model versions in the existing fuel model. Other than with the inclusion of wind, solar PV, solar thermal and hot water cylinder devices. These inclusions produced an average 82% cost reduction (based on export of electricity costing the same as import) and 42% emissions reduction. When using the simple ranking methodology as described in earlier, producing re-

Table 5.7: Ranked result of different heating fuels when combining the ranking for cost and emissions of each.

Model version name	**Total score**		
	Old and uninsulated	**Old and insulated**	**New build**
Mains gas	8	8	8
Biomass	2	3	2
Green H2 Boiler	14	14	14
Electric Tank	11	11	11
Green H2 FC	16	16	16
Heat Pump	6	4	5
Hybrid HP GH2 Boiler	8	8	8
Hybrid HP Bottled H2	7	8	8

sults in table 5.7. Finding “biomass (wood)” to have the lowest combined score across all building heat profile types closely followed by heat pump systems. Middle ranking scores found by the “green hydrogen hybrid heat pump” and high scores by “green hydrogen fuel cell” as seen in 5.7. The high total scores for the green hydrogen models reflect the limitation in the current modelling where hydrogen generation is directly linked to renewable electricity production on site and system efficiencies. Resulting in continued draw of electricity from the electric grid which have associated costs and emissions per unit of electricity, which reflects the relative inefficiencies of hydrogen technologies relative to electric technologies. Hybrid heat pump / hydrogen systems where hydrogen boilers are secondary heating devices where the heat pump cannot meet all demand, achieve similar combined scores to mains gas.

The “mains gas” model, which is used as a control to compare the results had to homes connected to the gas grid, has an average score of 6 across the different heat demand profiles. With a score higher than “biomass” or “bottled hydrogen hybrid heat pumps”, suggesting that there is scope to find off gas grid heat and power alternative systems that are not solely reliant on heat pumps.

The renewable energy model can be improved upon with further detailing and sizing of devices at the renewable, storage and heat generation stages of the model, particularly with modelling more useful utilisation of renewable energy into energy storage systems such as battery and hydrogen. This will go with further detail on limitations on the electric grid connection. Often electricity suppliers out limits on how much electricity can be exported due to not having strong enough local low voltage infrastructure for distributed generation. Particularly in rural regions which is often a key motivation for onsite and local energy storage.

One conclusion from is modelling is the opportunity for further research hybrid technology heat systems. Where a secondary energy system could be used more usefully in conditions where the primary energy system is worse performing and the cost/emissions implications of this. Further work can be had on the economic modelling with further detail on electric export costs and capital costs looking at current prices for the technologies modelled and the possible payback periods of operating different systems. More importantly developing a more detailed ranking and scoring system of the various technologies modelled. Looking particularly at incorporating other key factors that will change the score a technology achieves such as capital costs, utilisation of technologies, government incentives to adopt low carbon technologies and carbon taxes.

5.5 Extended analysis of model results.

This section was originally proceedings at the 15th International Green Energy Conference 2023, in Glasgow, UK. Subsequently extended analysis of the computed results from the energyPro models with a different method of analysing the model results and incorporating other techno economic factors such as: capital cost, system effectiveness and the proportion energy consumed that is renewably generated.

5.5.1 Extended analysis scoring methodology.

The extended analysis considers four factors* (operating emissions, operating cost, capital cost and system efficiency) whereas earlier work only assessed each of the models on two factors (operating emissions and operating cost). **Five factors for the renewable energy models including the proportion of energy consumed that is renewably generated within the microgrid.*

The method of analysing and evaluating has evolved from a simplistic numerical ranking of the worst performing and the best performing model iterations evaluated. Repeating this process for both factors being evaluated (Annual operational cost and annual operational emissions). Adding the two results together to provide a final score and re-ranking this to find the final result of all the model iterations being evaluated.

An issue with this methodology of analysis was that this did not account for the magnitude of the difference of the results between each iteration output. For example, table 5.6 in the Annual emissions column, Old and Uninsulated finds the highest carbon emitting result to be Green H2 FC (16,419 kg CO2e). The next highest emitting (and next lower ranked) result being Green H2 Boiler (9,997 kg CO2e) with a numerical difference in emissions of 6,422 kg CO2e.

Whereas the two lowest carbon emitting results of Biomass (1,094 kg CO2e) and Heat Pump (1,725 kg CO2e) have a difference of 631 kg CO2e, an order of magnitude between the two results but producing the same score with the original methodology of comparing the different systems. This newer method of assessing the same results attempts to account for the relative magnitude of the results in each category.

The extended results use the min-max statistical method to measure the spread of the results and produce a result from 0 to 1 where the best score is 0 and the worst score is 1. This allows a measure of spread between each result.

$$Score = \frac{x - minimum}{maximum - minimum} \tag{5.1}$$

This method of measuring spread was selected over others as with a zero to one produced this allows straightforward summation and comparison of other results and factors that have had a min-max method applied to them. For each model iteration assessed, adding all the min-max scores for all the elements assessed (capital cost, operational cost, operational emissions and system efficiency), will produce a final result that accounts for the magnitude of spread in all categories that are assessed.

5.5.2 Evaluating system efficiency

An additional metric that has been assessed is total system efficiency. This figure is found by evaluating the ratio of the total energy demanded by the end users (heat and power) by the total energy consumed by the system.

The total consumed energy comprises of any total amount of energy or fuel imported into the system, or any energy that is renewably generated. This does not include any other transformations of energy occurring within the microgrid system, such as hydrogen electrolysis.

5.5.3 Evaluating capital cost

Values for the capital cost are calculated based on the cost of the real costs required to purchase and install each major system component. An assumption was made that for each energy system and fuel modelled, capital costs are calculated from the approximate retail cost of key components of the domestic energy system that are modelled. These include solar panels, boilers, hot water cylinders, other fuel storage vessels and other devices where appropriate. As much as possible costs are gathered from real devices used in the modelling rather than devices with comparable technical requirements. These costs are captured at the time of developing this extended analysis in winter 2023.

5.5.4 Evaluating the proportion of energy consumption renewably generated (renewable energy system models only)

This metric is used to evaluate how much of the energy consumed is renewably generated in the microgrid to produce heat and electricity, also accounting for excess generated electricity that may be exported back to the national grid. No other fuel than electricity can be exported in this series of models. This is evaluated in equation 5.2 by the ratio of the total energy generated from renewable sources such as solar PV, wind turbines and solar thermal and the total energy consumed by the total system. The total energy required is derived in equation 5.3 where each imported or exported fuel or electricity has a cost per unit of energy where the unit cost of exported electricity is the same as imported electricity from (BRE, Garston, and Watford 2023).

$$\%\ of\ energy\ self\ sufficiency = \frac{electricity\ generated + solar\ thermal\ heat\ generated}{total\ energy\ required} \tag{5.2}$$

$$\begin{aligned} total\ energy\ required = electricity\ imported + other\ fuel\ imported + \\ electricity\ generated + heat\ generated - electricity\ exported \end{aligned} \tag{5.3}$$

This is a valuable metric to include in the analysis of the renewable energy models as one aim of installing devices that renewably generate energy is to reduce the consumption of imported energy to the property and become more self-sufficient.

5.6 Results and discussion

The min-max normalised scores for each metric for each model iteration are summed together to create the overall score for each model iteration. For the existing fuels model there are 33 iterations (Eleven different microgrid/fuel systems across three levels of building insulation).

The renewable energy model has 24 results (Eight different microgrid/fuel systems across three levels of building insulation). For each different model alongside the total min-max score for each iteration a number rank is assigned with 1 being the lowest scoring and 33 (or 24) being the highest scoring. This can be seen in figures 5.2 and 5.3 showing on the Y-axis the relative spread of the min-max normalised scores compared to the sequential rank of each model iteration. The X-axis is a sequential ranking of each technology according to the score generated. This high-iights the limitations of the previous ranking methodology found in sections 5.3.1 and 5.4.1 where the relative spread is not accounted when presenting the results of the different models. These figures provide an overview of both the effects of both the heating technology used and the level.

The level of insulation can affect the relative score. Finding solid and liquid fuels

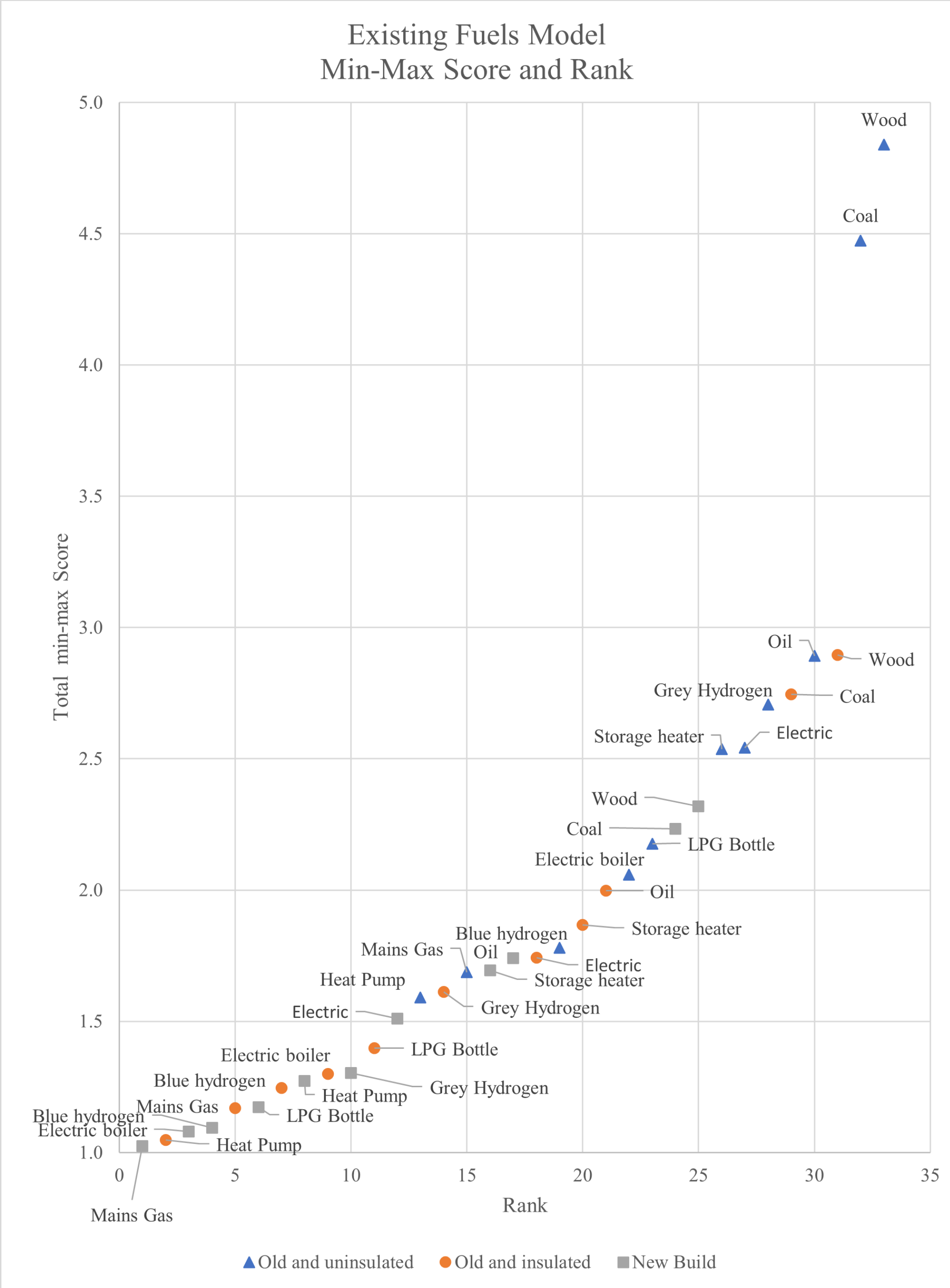


Figure 5.2: The total min-max normalised score for all 33 iterations of the existing fuels model across three different levels of insulation showing the relative spread of the scores of the iterations.

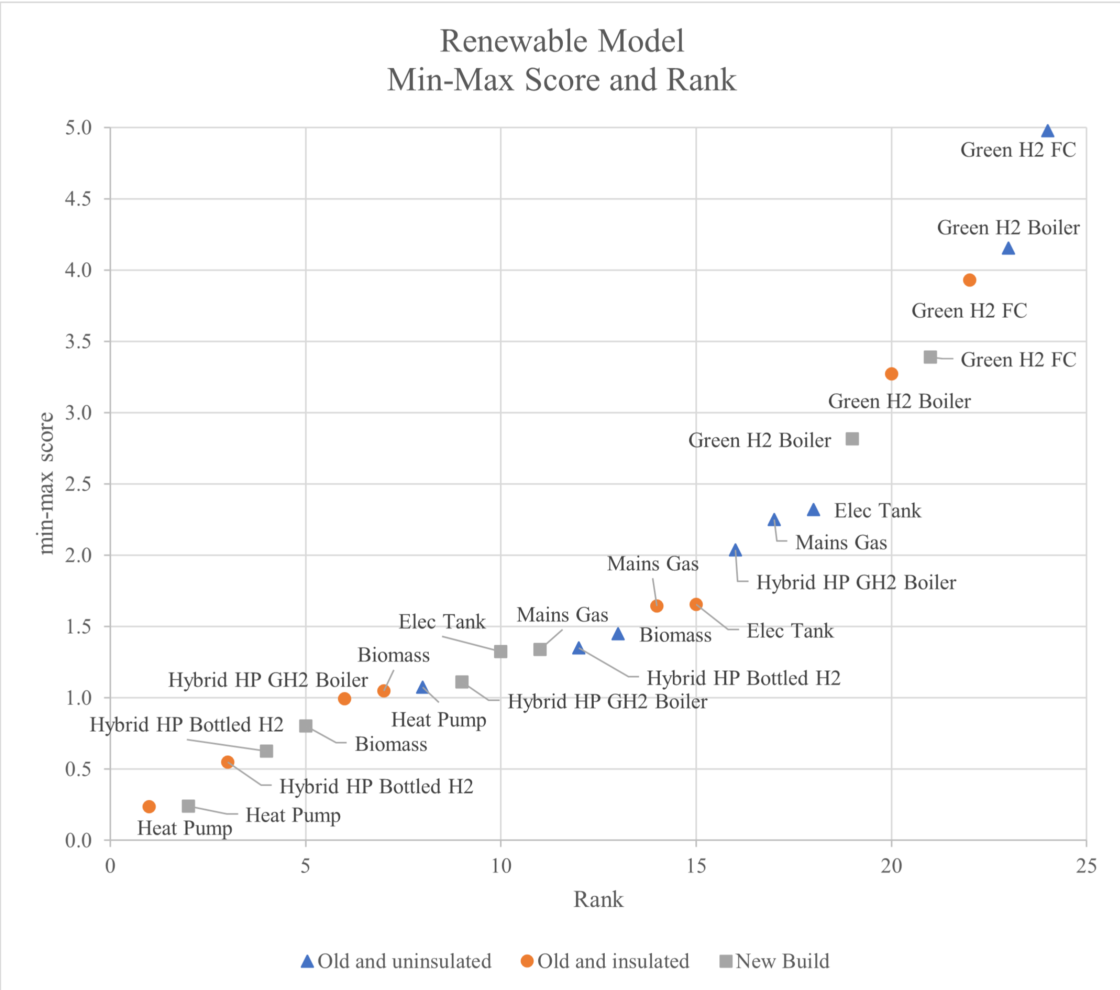


Figure 5.3: The total min-max normalised score for all 27 iterations of the renewables model across three different levels of insulation showing the relative spread of the scores of the iterations.

such as coal, wood and oil consistently scoring the highest in figure 5.2, primarily due to the relatively high emissions of such fuels and high capital cost of not just a fuel boiler. However also onsite hot water storage contributes highly in the capital costs of most systems which include a hot water cylinder or multiple cylinders.

Low capital cost systems in the existing fuel model such as Mains Gas, LPG, Hydrogen and Electric Boiler do not include hot water cylinders. Lower scoring systems in the existing fuel model such as Heat Pump, Hydrogen and Mains Gas achieve this due to relatively lower emissions and relatively higher overall system efficiencies.

In the renewable model results as seen in Figure 5.3 the highest scoring systems are the Green Hydrogen systems at any level of insulation. This is due to the extremely high cost of purchasing enough electrolysers to achieve this model and satisfy the energy demand without refining the actual necessary required electrolyser capacity when the model was created. This is not at all realistic.

Electrolysers however are extremely expensive with an approximate cost of €15,000 for a 1.8kW electrolyser producing 1kg a day. Ascertaining reasonable costs and specifications are difficult for hydrogen systems as there are virtually no products that can be bought ready to use, due to not having matured sufficiently as a product market yet. Table 5.8 highlights the calculated capital costs or each model iteration, where any iteration involving hydrogen production has significantly higher costs at an order of magnitude greater.

This highlights the immaturity of cost of hydrogen electrolyser technology and the immaturity of selecting the appropriate device for the constructed models. Adding challenges in reasonably constructing microgrid models and associated costs. From this analysis and modelling, any local green hydrogen production on a household level is grossly unfeasible solely due to cost, regardless of using grid electricity or local renewable electricity. Future sensitivity analysis on constructing more realistic green hydrogen microgrids may mitigate this.

Table 5.8: Capital costs for the existing fuels model (left) and the renewable energy model (right).

Existing fuels model		
Model Iteration	**Number of key components**	**Capital cost**
Mains Gas	1	£ 2,787.50
Oil	2	£ 10,387.68
Coal	5	£ 11,573.16
Wood	6	£ 11,632.82
LPG Bottle	2	£ 3,567.51
Electric boiler	1	£ 2,750.00
Electric Tank	7	£ 8,103.13
Storage heater	10	£ 11,045.00
Heat Pump	6	£ 15,763.92
Grey Hydrogen	2	£ 3,816.67
Blue hydrogen	2	£ 3,816.67

Renewable energy model		
Model Iteration	**Number of key components**	**Capital cost**
Mains Gas	5	£ 39,312.50
Biomass	10	£ 48,865.31
Green H2 Boiler	10	£ 1,659,216.67
Electric Tank	10	£ 38,910.63
Green H2 FC	10	£ 1,756,179.17
Heat Pump	9	£ 46,571.42
Hybrid HP GH2 Boiler	9	£ 547,529.11
Hybrid HP Bottled H2	7	£ 48,084.11

The lowest scoring results in the renewable model are found to be heat pump based with heat pump and hybrid heat pump hydrogen systems. This is primarily due to the low operational emissions, low running costs and high efficiencies of such systems. High efficiencies are typically due to the use of heat pump technologies.

5.6.1 Extended methodology quality

The initial methodology of analysing the microgrid model's results was limited in the weighting the spread of results, which in this extended analysis was improved by measuring spread between the minimum and maximum results for a given attribute. This measure of spread works successfully and provides better results than the previous method. However a limitation is found when measuring the spread across results over various orders of magnitude such as in table 5.8. Where the magnitude of spread between the minimum and maximum is so large that measuring and analysing the spread of intermediate values are challenging. This updated methodology does provide further analysis and sensitivity in the different attributes that can be used to assess a system.

5.6.2 Comparing original and extended results

The total number of model iterations across the across the existing fuel and renewable energy models, across three different types of building and insulation is 57. After applying this new method of analysis to measure the spread of results, it finds that 46 of all 57 model iterations have changed their ranking, an 81% change.

Demonstrating that 81% of the rank has changed because of this extended analysis, highlighting the improved value in having weighted analysis over various other key attributes. The method of assigning a rank to each result provides limited scope for analysis, hence why the extended methodology uses a different method of assessment. However, to compare between the two methods assigning a rank to the extended results allows comparison between the two sets of results.

5.6.3 Existing fuels model comparison

Notable trends in the change in rankings between the original and extended analysis of the existing fuels model (Table 5.9) finds a consistent drop in ranking of the solid and liquid fuels (wood, coal and oil). This is due to the higher capital cost of these systems compared to gas-based systems as fuel storage is also considered. Another factor that increases the score is operational emissions of the solid and liquid fuels, where applying a measure of spread impacted the results of these fuel systems.

Gaseous fuel systems (Mains gas, LPG, blue hydrogen, and grey hydrogen) all found an increase of rank, due to high boiler efficiency and the relatively lower capital cost with the use of existing condensing boilers that are hydrogen ready and LPG compatible. One assumption made is to include a £250 conversion cost to convert hydrogen ready boilers to hydrogen boilers. A trend among the gaseous and solid fuel systems is that the direction of change of rank (that is going up a rank or down a rank) is consistent across all building types/levels of insulation. This is not the case with the electricity-based systems (Heat pump, electric boiler, electric tank, and storage heater). Where there has been a variance in the direction of the change of rank if any change at all across the different building/insulation types. Notably heat pump systems either retain rank or drop, this is due to the high capital costs of a heat pump, which can somewhat outweigh the high efficiency, low emissions.

Storage heating is the highest scoring (therefore poorest performing) electricity-based technology, due to a low system efficiency and a high capital cost, due to requiring multiple storage heaters to ensure that heat demand is met. Electric boilers perform will, like gaseous boilers with an improved rank.

5.6.4 Renewable energy models comparison

The renewable energy models seen in table 5.10 are smaller in scope with only 8 iterations compared and the extended analysis produces fewer changes of rank different from the original results. The extended scoring of the renewable energy model includes the metric of the proportion of self-sufficiency (i.e. the proportion of energy that is consumed which is renewably generated) which is not included in the extended analysis of the extended fuels model.

The trend of change in rank is consistent across all three building/insulation types other than one model iteration, electric tank, where in the new build building/insulation category there is an increase of rank rather than remaining the same. As mentioned, there are a few model iterations that do not change rank, particularly the green hydrogen systems where there is high/poor scores across all categories in the extended analysis. Model iterations that dropped rank were biomass and mains gas. Primarily due to lower efficiencies and lower proportions of self-sufficiency (with biomass the assumption is that all wood consumed is bought and none foraged) than heat pump based systems which ranked well in both these attributes. Results that increased in rank are the heat pump based results (Heat pump, hybrid hp bottled h2 and hybrid hp gh2 boiler) increased in rank due to the higher levels of self-sufficiency and system efficiency which contribute to a higher rank.

This comparison between the two methods of analysis finds that there is some change in rank, particularly positive for low cost, high efficiency, high self-sufficiency systems. With the top three results across all types of buildings being heat pump, hybrid heat pump bottled h2 and biomass. These three model iterations have varying other attributes not considered in this analysis that may make one system more suitable than in other in varying contexts, however this top 3 ranking provides a guide in what heat and power system should be considered for an off-grid property that can provide a level of energy self-sufficiency.

Heat pump only systems are the simplest system with a relatively low number of system components, that have a high technological maturity that lends to a lower capital and operational cost at zero emissions. Heat pump, bottled hydrogen boiler systems provides greater resilience with a robust secondary hydrogen heating system, and is more viable for properties that heat pump only installation is overly costly or subject to greater extremes of weather. Biomass (wood) systems offers a more traditional albeit more bespoke method heating where other technologies may not be cost effective in installation of particularly older properties or higher, irregular demand at low (not zero) carbon.

Table 5.9: The results of each model iteration of the existing fuels model, comparing the rank results from the original analysis to the rank results in the extended analysis.

Existing fuels model						
Original analysis					**Extended analysis**	
Old and uninsulated						
Wood	1	↓	change	↑	Mains Gas	1
Heat Pump	2	=	match	=	Heat Pump	2
Mains Gas	3	↓	change	↓	Blue hydrogen	3
Blue hydrogen	4	↓	change	↑	LPG Bottle	4
Oil	5	↓	change	↑	Electric boiler	5
Electric boiler	6.5	↑	change	↓	Wood	6
LPG Bottle	6.5	↑	change	↓	Oil	7
Coal	8.5	↓	change	↑	Storage heater	8
Storage heater	8.5	↑	change	↓	Elec Tank	9
Elec Tank	10	↑	change	↓	Grey Hydrogen	10
Grey Hydrogen	11	↑	change	↓	Coal	11
Old and insulated						
Heat Pump	1	=	match	=	Heat Pump	1
Wood	2	↓	change	↑	Mains Gas	2
Mains Gas	3	↑	change	↑	Blue hydrogen	3
Blue hydrogen	4	↑	change	↑	Electric boiler	4
Oil	5	↓	change	↑	LPG Bottle	5
Electric boiler	6.5	↑	change	↑	Grey Hydrogen	6
LPG Bottle	6.5	↑	change	↑	Elec Tank	7
Storage heater	8	↓	change	↓	Oil	8
Coal	9.5	↓	change	↓	Wood	9

Elec Tank	9.5	↑	change	↓	Storage heater	10
Grey Hydrogen	11	↑	change	↓	Coal	11
New build						
Heat Pump	1	↓	change	↑	Mains Gas	1
Wood	2	↓	change	↑	Blue hydrogen	2
Mains Gas	3	↑	change	↑	Electric boiler	3
Blue hydrogen	4	↑	change	↑	LPG Bottle	4
Oil	5	↑	change	↓	Heat Pump	5
LPG Bottle	6	↓	change	↑	Grey Hydrogen	6
Electric boiler	8	↑	change	↑	Elec Tank	7
Elec Tank	8	↑	change	↓	Oil	8
Storage heater	8	=	match	=	Storage heater	9
Coal	10	↓	change	↓	Wood	10
Grey Hydrogen	11	↑	change	↓	Coal	11

5.6.5 Implementing hydrogen technologies in UK homes

To implement truly “green” hydrogen, that is using electricity solely from renewable sources would become cost prohibitive given the required renewable and electrolysis capacity required to achieve a truly off electric grid system. An opportunity could be to look at minimising the use of grid electricity to locally electrolyse hydrogen for individual domestic use. Currently electrolysing hydrogen for one household is not practical. This method of locally generating hydrogen for domestic use is unfeasible due to the high cost and electricity required at larger scales this would be more feasible as Mendoza et al. explored (Parra Mendoza 2014). Where there is opportunity for single home off gas grid hydrogen use is in delivered hydrogen stored on site combined with hybrid heat pump systems. Particularly in climates where low winter temperatures can make heat pump systems less effective. More

Table 5.10: The results of each model iteration of the renewable energy model, comparing the rank results from the original analysis to the rank results in the extended analysis. Renewable energy model.

Renewable energy model						
Original analysis					**Extended analysis**	
Old and uninsulated						
Biomass	1	↓	change	↑	Heat Pump	1
Heat Pump	2	↑	change	↑	Hybrid HP Bottled H2	2
Hybrid HP Bottled H2	3	↑	change	↓	Biomass	3
Mains Gas	4.5	↓	change	↑	Hybrid HP GH2 Boiler	4
Hybrid HP GH2 Boiler	4.5	↑	change	↓	Mains Gas	5
Elec Tank	6	=	match	=	Elec Tank	6
Green H2 Boiler	7	=	match	=	Green H2 Boiler	7
Green H2 FC	8	=	match	=	Green H2 FC	8
Old and insulated						
Biomass	1	↓	change	↑	Heat Pump	1
Heat Pump	2	↑	change	↑	Hybrid HP Bottled H2	2
Hybrid HP Bottled H2	4	↑	change	↑	Hybrid HP GH2 Boiler	3
Mains Gas	4	↓	change	↓	Biomass	4
Hybrid HP GH2 Boiler	4	↑	change	↓	Mains Gas	5
Elec Tank	6	=	match	=	Elec Tank	6
Green H2 Boiler	7	=	match	=	Green H2 Boiler	7
Green H2 FC	8	=	match	=	Green H2 FC	8
New build						
Biomass	1	↓	change	↑	Heat Pump	1
Heat Pump	2	↑	change	↑	Hybrid HP Bottled H2	2
Hybrid HP Bottled H2	4	↑	change	↓	Biomass	3
Mains Gas	4	↓	change	↑	Hybrid HP GH2 Boiler	4
Hybrid HP GH2 Boiler	4	↑	change	↑	Elec Tank	5
Elec Tank	6	↑	change	↓	Mains Gas	6
Green H2 Boiler	7	=	match	=	Green H2 Boiler	7
Green H2 FC	8	=	match	=	Green H2 FC	8

work on this would be beneficial.

In the UK Government policy has been indecisive in pushing towards sector wide decarbonisation of heat, through insulation, heat pump electrification, hydrogen, district heat networks or otherwise. This reluctance of the UK government to commit to any measure or technology with real meaning has led to a stagnation of progress towards low carbon heating. Examples of this include a woefully underfunded and underutilised boiler upgrade scheme and it's predecessor the domestic renewable heat incentive. Which sought to partially subsidise the installation of low carbon energy efficient heating systems such as heat pumps. However these schemes are not sufficient or just, beside the yet still high capital cost when the grant is included. Which is only available to homeowners and not renters creates a social divide as rented homes typically have a lower energy efficiency and poorer heating systems than owner occupied homes (Miu and Hawkes 2020).

Proposals for trials of hydrogen heated villages and communities across the UK have been cancelled or delayed due in part by community opposition, questions of cost, safety and security of supply of energy from the energy companies proposing these trials. The lack of government support in implementing a community hydrogen heating trial signals a great lack of uncertainty and indecision by the government towards exploring different avenues towards net zero heating.

More broadly energy infrastructure concerns the lack of investment into hydrogen electrolysis and electrolyser manufacturing. A real bottleneck in any utilisation of clean and green hydrogen by any sector, residential, industrial or transport. Wide scale electrification similarly is of concern with the lack of investment into upgrading the national and local transmission networks taking the ever increasing demands from electrified heat and electrified vehicles today, let alone in the future with greater electrification. In this context, greater utilisation of alternative low/zero carbon fuels such as hydrogen have a greater appeal.

It is this context which this piece of work sits within. Where in rural and remote settings an assumption is made that the current energy infrastructure is insufficient and with that reality how could such a domestic setting reduce their domestic emissions? The public mood and technological challenges of hydrogen technologies for heating will probably find that hydrogen for heating will not be adopted at wide, national scale however there is some opportunity in hard to decarbonise settings as explored here.

5.7 Conclusion

This work here demonstrates the variance in the best scoring technology dependent on factors considered when analysing the best performing energy system. Showing that a balanced approach is needed when looking at technical aspects of a system such as capital cost, efficiency, emissions and other factors that have not been considered in this work, such as the health impact of different energy systems. This work highlights having a an informed and multi factor approach when selecting the optimal energy system, or decision making in general.

Rural buildings are not all isolated single buildings, the results here model a single dwelling microgrid. Finding biomass and heat pump technologies producing the lowest (and best) scores across three different dwelling types. Research into modelling small communities of hamlets and villages forming systems such as micro district heat or hydrogen gas networks could be explored, to see what small scale network benefits on energy efficiency and cost of production and distribution could be investigated.

Understanding at what scale of rural settlement would suit well to alternative low carbon energy networks. Looking at mixed use utilisation of low carbon energy systems where commercial, industrial, or agricultural buildings adjacent to domestic homes (where people often live next to their work) can find more beneficial uses for technologies not widely explored for rural domestic usage such as hydrogen and biofuels.
An example that could be investigated is crop farm where local production of hydrogen, with on-site renewables supplementing grid electricity could be used for domestic heat for the farmhouse and power and fuelling hydrogen powered vehicles and machinery.

This chapter explores through energy modelling the costs and emissions of fuels predominately used currently for off gas grid heating and the future low carbon technologies that are options to replace them. From an operations cost and emissions basis biomass (wood) was found to be a lowest emissions and lowest cost system. When other factors are considered in selecting the optimal technology for rural heating such as capital cost and system efficiency, heat pump based systems scored the best.

There is further scope to economise low carbon technologies through local area energy networks or synergies with local agriculture and industry.

Chapter 6

Modelling with smart meter data

6.1 Introduction

The previous chapter explored developing a series of microgrid energy system models of a rural home off the national gas grid. Evaluating and comparing presently available fuels and technologies and looking at a renewable energy scenario with low emissions fuels and technologies.

All these models were evaluated across three different heating user profiles generated by using the technical properties of a building (such as the building dimensions, floor space, number of windows, etc.) and the heating degree days for a given location. These attributes are typically used by engineers across the energy industry to estimate energy consumption across many uses, including determining energy performance certificates (EPCs), energy bills and in energy research. The use of estimated energy demand profiles has been due to no other reasonable method of estimating energy consumption effectively. As such it has become commonplace in industry as the method of determining energy consumption of buildings and communities.

Now in the UK the use of smart meters, which can log energy consumption at a half hourly (or even smaller) intervals. Using such data, real data is of great value and has been used by domestic energy supply companies to provide accurate and realistic energy bills. In other sectors of the energy industry, including research, the uptake of using data from smart meters is slow and sometimes challenging due to the difficulty of accessing smart meter data. Energy companies operate and maintain the fleets of smart meters of their customers, and have direct access to the meter data and lower the bills of their customers.
This chapter explores using and applying smart meter data to the microgrid developed in the previous chapter. To investigate what differences there may be in the results of an energy system model by using metered energy consumption data

compared to estimated energy consumption profiles.

6.1.1 Finding smart meter data to use

Energy researchers commonly do not have readily available access to such data (or at such quantities) due to academic institutions not typically owning or maintaining residential homes let alone smart meters. Accessing smart meter data held by other groups is challenging, there is reluctance to work with researchers from data owning groups due to commercial interests and data protection laws such as GDPR, which would apply to smart meter data from people's homes.

Historic household level smart meter data from previous projects have been found from the Republic of Ireland (Commission for Energy Regulation (CER) 2012a), (Commission for Energy Regulation (CER) 2012b) and New Zealand (Anderson et al. 2018). The limitations of using such datasets include that there is limited information regarding the surrounding metadata of the datasets, such as demographics, geography and building characteristics. As these are historic datasets, there will be little to no contacts that may have more information regarding the projects.

In the UK now there is a research project collecting smart meter data from households across the country for research purposes. The Smart Energy Research Lab (SERL) (Smart Energy Research Lab and University College London n.d.) at University College London holds this collection of smart meter data that has been active and updating since 2017. Accessing the SERL dataset is via the UK Data Service (UKDS) at the University of Essex. Accessing this data for this project took over a year and a half of communications, training and forms between SERL, UKDS, University of Nottingham and myself.

Aside from challenges of accessing the SERL data, the data itself is rich, high resolution and high quality. There are half hourly gas and electricity readings for approximately 13,000 different participant homes across Great Britain in the project. Each participant has filled out a survey containing demographic and technical information about the participant home, such as how many rooms in the property, what heating fuels are used for heating, hot water, etc. Also attached in the dataset are any available EPC certificates for the property if applicable, 41% of SERL participants have no recorded EPC rating.

Access to SERL data is managed by the UK Data Service, due to the raw data containing personal identifiable information of participants and their homes. Access to the data is via the SecureLab computer system where users login to a controlled environment to transform the data. To export the SERL data for use in energyPro, the data needs to be transformed to be non disclosing, the method is explained below.

6.2 Smart meter data methodology

The data from SERL is filtered within the Secure Lab environment using python to 21 different energy demand profiles based on different characteristics of the home: GB EPC ratings (A, B, C, D, E, F, G, no EPC), Rural GB EPC ratings (A, B, C, D, E, F, G, no EPC), user profiles developed in chapter 4 Rural Energy Study, P01, P02, P03, P04, P05.

The resulting energy demand profiles from the filter is then averaged to produce a single set of energy demand time series. The Great Britain (GB) EPC energy demand profiles were developed by filtering the SERL dataset according to reported EPC (or lack of EPC).

The GB rural EPC energy demand profiles are filtered first by Lower layer Su-

Table 6.1: Filters applied to the SERL dataset to produce the 5 archetypal rural energy user groups defined in chapter 4 Rural Energy Study.

Energy demand profile	Filters applied				Number of SERL particpants
P01	Rural GB	Semi Detatched /Detached home	Main heating fuel is Gas	EPC rating of C	68
P02	Rural GB	Semi Detatched /Detached home	Main heating fuel is Oil	EPC rating of C	47
P03	Rural GB	Semi Detatched /Detached home	Main heating fuel is Oil	EPC rating of D	67
P04	Rural GB	Detached home	Main heating fuel is Electricity	EPC rating of A, B or C	39
P05	Rural GB	Detached home	Main heating fuel is Gas or Electricity	EPC rating of D, E, F or G	237

per Output Areas (LSOAs) that are considered rural at the 2011 census and then by EPC rating (or not). *2011 census results are used as the 2021 census results were not published at the time of the research being carried out.*

The rural urban classification varies between England, Wales and Scotland. England and Wales defines a rural area as a settlement area with a population of less than 10,000 (Bibby 2013). In Scotland an area and community is considered rural if there is a population less than 3,000 (Scottish Government 2022b).
The rural energy study responses energy demand profiles P01, P02, P03, P04 and P05 are produced based on the characteristics of each profile as defined in chapter 4 Rural Energy Study. Key attributes of each profile are used in each filtering the SERL dataset for each output.

The produced energy demand profiles are processed for export and checked by the UK Data Service to ensure no possible disclosures of personal information is possible before sending the exported data over email. The files are a half hourly time series in .CSV format. The data collected encompasses a 12 month period from September 2021 to August 2022. This time period was selected rather than one calendar year of 12 months as at the time of accessing the data this was the most complete and recent dataset available.

Table 6.2: Filters applied to the SERL dataset to produce GB and rural GB EPC energy demand profiles.

Energy demand profile	Filters applied		Number of SERL particpants
Rural EPC A	Rural GB	EPC A	<10
Rural EPC B	Rural GB	EPC B	74
Rural EPC C	Rural GB	EPC C	385
Rural EPC D	Rural GB	EPC D	571
Rural EPC E	Rural GB	EPC E	257
Rural EPC F	Rural GB	EPC F	71
Rural EPC G	Rural GB	EPC G	19
Rural EPC N/A	Rural GB	EPC N/A	1017
Energy demand profile	**Filters applied**		**Number of SERL particpants**
GB EPC A	EPC A		<10
GB EPC B	EPC B		474
GB EPC C	EPC C		2488
GB EPC D	EPC D		3388
GB EPC E	EPC E		1191
GB EPC F	EPC F		187
GB EPC G	EPC G		47
GB EPC N/A	EPC N/A		5510

The majority of energy demand profiles extracted from the SERL dataset are complete, only a handful (GB EPC G, Rural EPC A, P02 and P03) are incomplete wither eiter a missing or unfinished gas or electricity energy demand profile. The reasons to this incomplete datasets is unclear. This may be due to the datasets used being incomplete or an error with the code filtering and compiling the average energy demand profiles produced. All energy demand produced profiles are included in the appendix.

The figures below of the SERL data of both Great Britain and rural Great Britain energy demand profiles of EPC C and EPC D. They are the two most numerous energy performance ratings in the SERL dataset and the most prevalent EPC ratings in the UK (*Energy Performance of Buildings Certificates Statistical Release: January to March 2024 England and Wales - GOV.UK* 2024). The EPC C results for gas (assumed to be primarily heating) consumption figure 6.1 has quite a variance between the GB and rural datasets. Particularly in the winter months of consistently 1000 Wh (1 kWh) and in the spring and summer months a consistent variance of approximately 500 Wh throughout. When comparing to the EPC D datasets in figure 6.2 for gas the variance is much smaller in closer agreement with each other. Finding nationally and rurally EPC D homes are much similar in their energy consumption whereas EPC C homes are quite varied heating energy consumption.

Electricity consumption patterns varies between rural and GB homes, however the magnitude of electricity consumption is much smaller and the variance between rural and GB homes is much smaller and consistent.

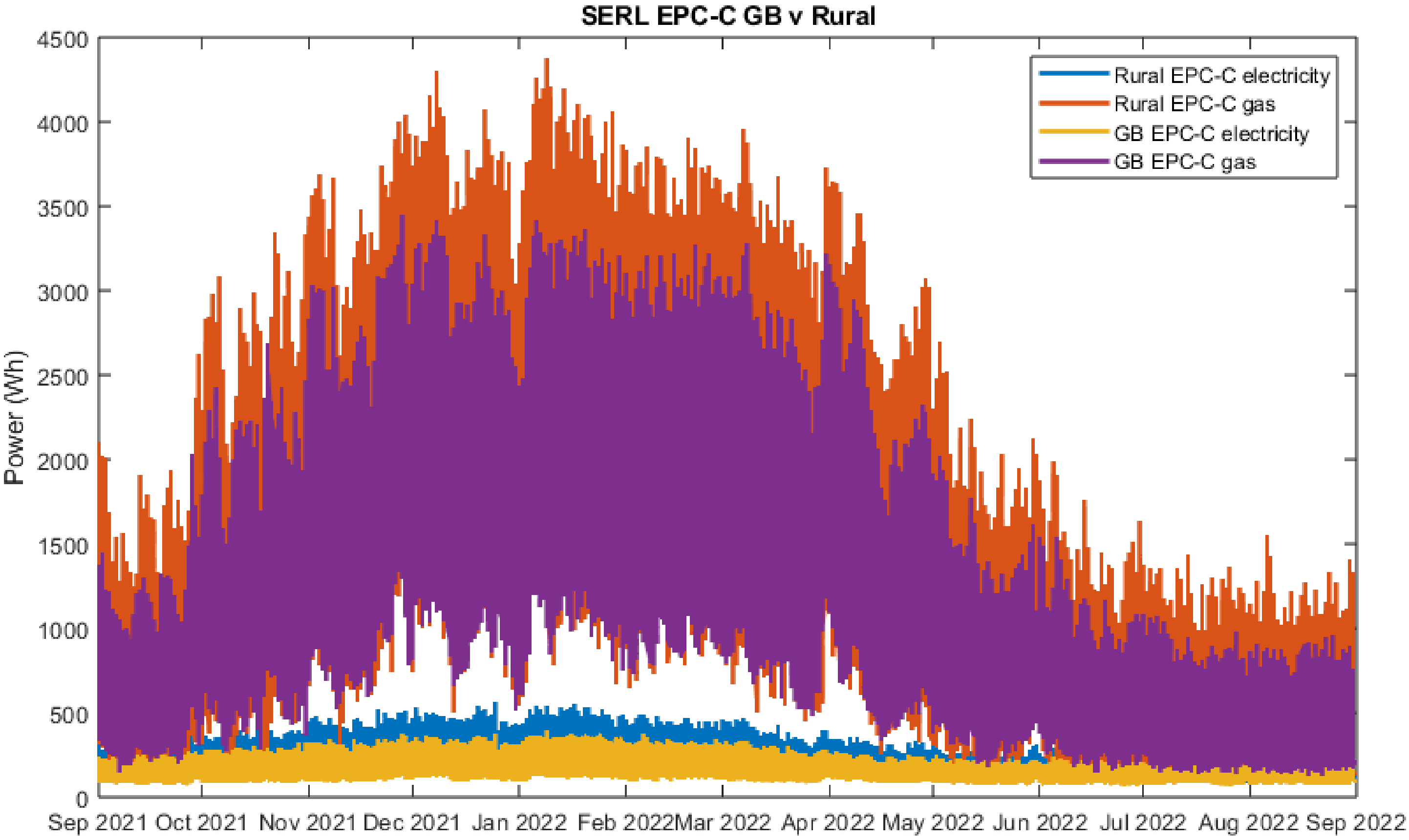


Figure 6.1: Extracted average electricity and gas energy demand profiles from SERL of homes with an EPC rating of C in GB and rural GB

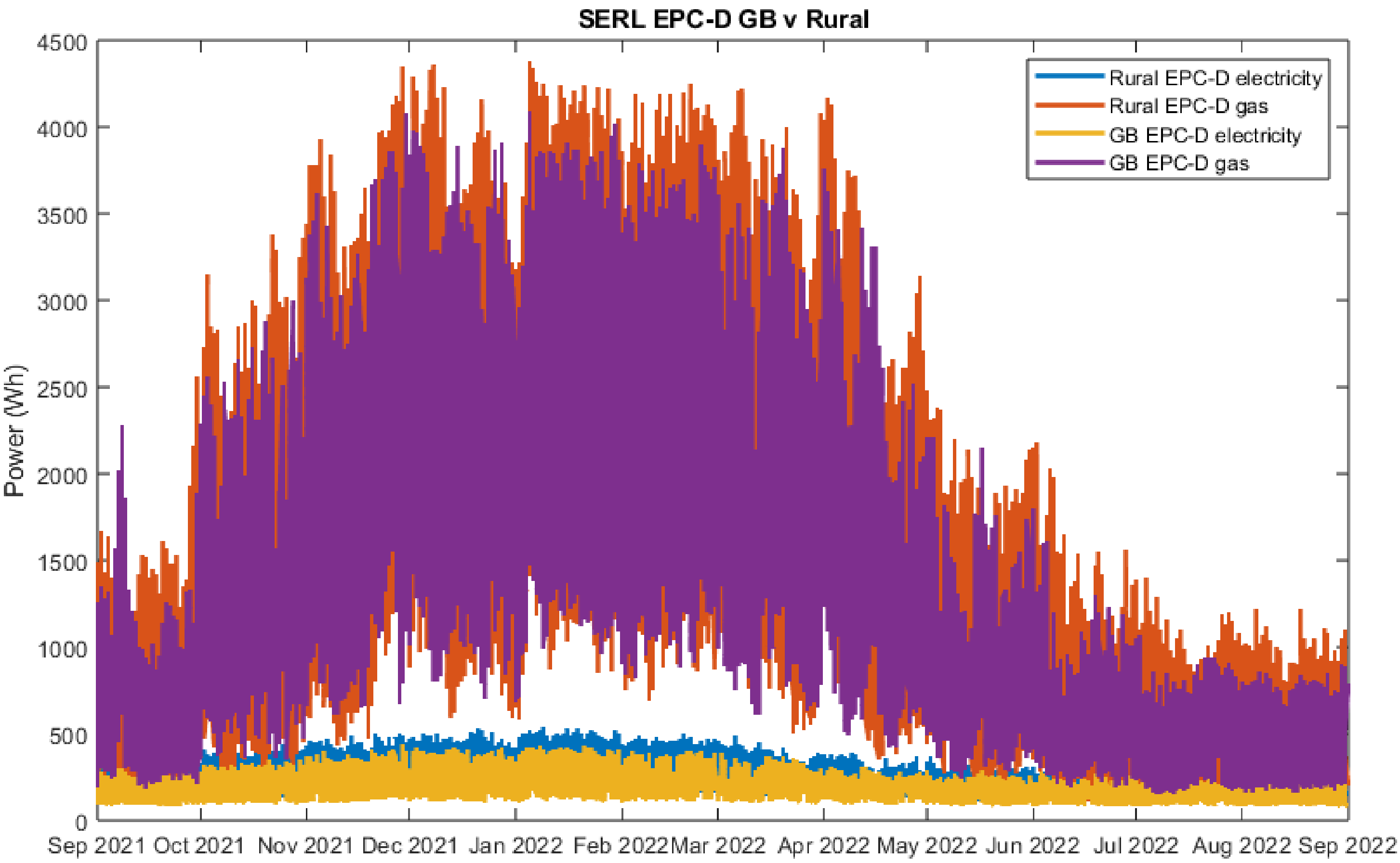


Figure 6.2: Extracted average electricity and gas energy demand profiles from SERL of homes with an EPC rating of D in GB and rural GB

Using the derived archetypal user groups

Due to time constraints, only three of the average energy demand profiles will be used in the micro grid models in energyPro, P01, P04 and P05. These energy demand profiles are used as they are based off the user profiles developed in chapter 4 rural energy study. When observing these energy demand profiles the typical peak instantaneous energy consumption is 6000 Wh when excluding outlier results.

Table 6.3 summarises the total electricity and heat demands for each demand profile. The differences between the different energy demand profiles finds that P01 has the lowest total energy demand and P04 with the highest total energy demand.

Table 6.3: Total energy consumption across the three energy user profiles P01, P04 and P05

Building heat profile type	Total heat demand (kWh)	Total electricty demand (kWh)
P01	15446	1804
P04	13925	4277
P05	14744	2916

Finding that there are similar magnitudes of gas (heat) consumption with an absolute difference of 1521kWh (10%), whereas the electricity demands observed for P04 is over double P01 and just under double of P05 with an absolute difference of 2473kWh (58%).

This is unexpected as P04 is "Modern Rural" archetypal group with high energy efficiency ratings of EPC A, B and C. Where one hypothesis when processing and analysing this data is that such users would have lower energy consumption due to better insulated homes. The different than expected result suggests an issue with the sample size (n = 39) of the P04 dataset. Alternatively there could be a psychological impact of having a high energy efficiency home makes the occupants less concerned about domestic energy consumption, and therefore consumes more energy than other groups. However total heat consumption is an order of magnitude greater than the total electricity as seen in table 6.3. The difference between the highest energy consuming user profile (P04) and the lowest energy consuming user profile (P01) is 5%.

Figure 6.3: Gas (assumed to be heat) and electricity consumption profiles of P01, P04 and P05 energy profiles

6.2.1 Updating the microgrid models

The smart meter energy demand profiles that have been derived for user groups P01, P04 and P05 are applied to the microgird model used in chapter 5. Some of the models used are revised since used in the previous chapter to ensure that the successfully compute and in the correct method. This includes that models including energy storage correctly uses the energy stores implemented. Another set of revisions includes revising some of the green hydrogen models, reducing the quantity of electrolysers from a conservative over estimate to a smaller capacity.

This revision is made possible as there is a smaller magnitude of energy demand in the SERL data from the previously used energy demand profiles. Partially due to the SERL data recording energy consumption in half hourly intervals whereas the originally used estimated energy consumption profiles are hourly. The gas consumption profiles for P01, P04, and P05 are produced in figure 6.3.

6.3 Results

The data computed in the energyPro model is processed, scored and ranked using the same methodology as found in section **??**. Which creates a score based on the operational cost, capital cost, operational emissions, system effectiveness and the proportion of renewably generated energy consumed. Full detailed results figures are found in appendix B.

6.3.1 Existing fuels model

Across all three archetypes the lowest scoring technologies are interchangeably heat pump and mains gas systems as seen in in figure 6.4. Reflecting the high efficiency and low running cost of these systems. Factors that equalise the score between heat pump and mains gas is the high capital cost of a Heat pump and the relatively high operational emissions of a natural gas heated system. Archetype P01 has a large difference in score between the heat pump and mains gas systems, similar in magnitude of difference only by grey hydrogen and coal systems at the higher end of the ranking.

Subsequent scoring technologies in ascending order of score (therefore worse) are the typically middling emissions fuels of blue hydrogen, LPG, wood and electric boilers. The remaining fuels analysed score highly with key influences on the score being system efficiency and emissions.
These trends are reflected across all three archetypal user profiles with P01 scoring the best and P04 scoring the worst as previously discussed.

6.3.2 Renewable model

The renewable model includes a 6kW wind turbine, a 3 kW solar photovoltaic array, a solar thermal array and a hot water cylinder in every iteration of the model. The top two lowest scoring systems (and hence best scoring) as seen in in figure 6.5 are the heat pump and hybrid heat pump bottled hydrogen systems. The similar results are due to the similar capital capital costs for these systems and the varying operational and emissions costs found from a heat pump and hybrid heat pump method of operation.

Unlike in the existing fuels model, the mains gas simulation in the renewable model has a middling score alongside the wood pellet biomass system and the electric tank (heated with immersion heater only). This result can be attributed to the renewable energy systems present in every model in this group of simulations. Where there is little synergy and increased effectiveness between the mains gas or wood biomass systems with the wind or solar generated electricity.

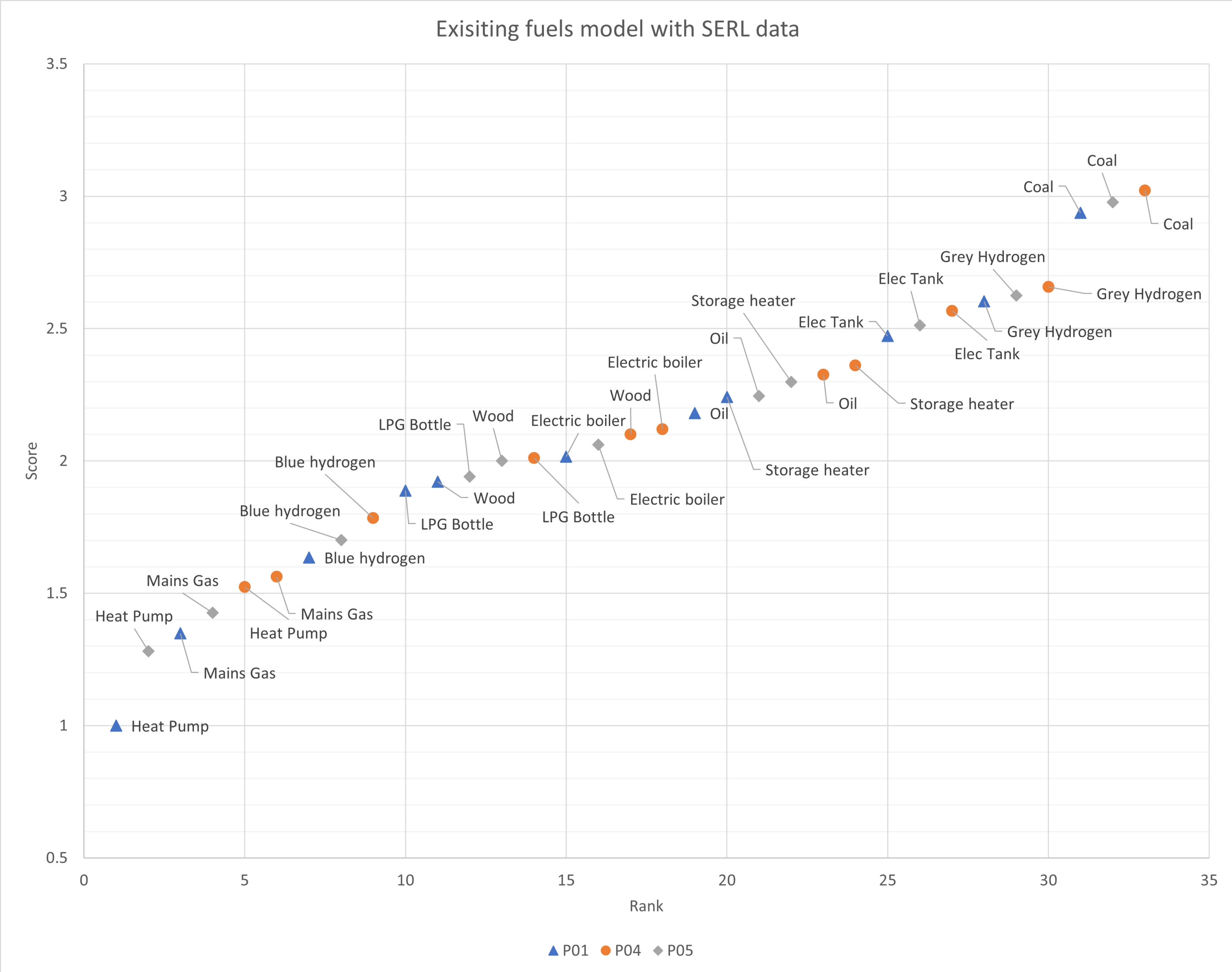


Figure 6.4: Scored and ranked results of archetypal energy user profiles P01, P04, P05 for the existing fuels model

The systems with electrolysers included in the simulations where hydrogen is the primary heating fuel all score highly, due to the high grid electricity consumption due to a low round trip efficiency of electrolysing hydrogen and converting the hydrogen into heat. Particularly fuel cells where heat is a byproduct of generating electricity, causing increased emissions from using grid electricity. In turn this results in a poor score for the "proportion of renewable energy used" metric.

For the renewable energy model some of the models were revised from the simulations completed in chapter 5, these revisions were made to hydrogen system models due to the initial renewable energy models having over sized components at extremely high capital cost (£500,000-£1.6 million). After resizing the hydrogen system components a much reduced system cost is calculated, however remaining the highest cost systems in the group of renewable energy models as seen in table 6.4. Hydrogen energy technologies remain the highest energy technologies and remain the least accessible to find public cost data of household scale components.

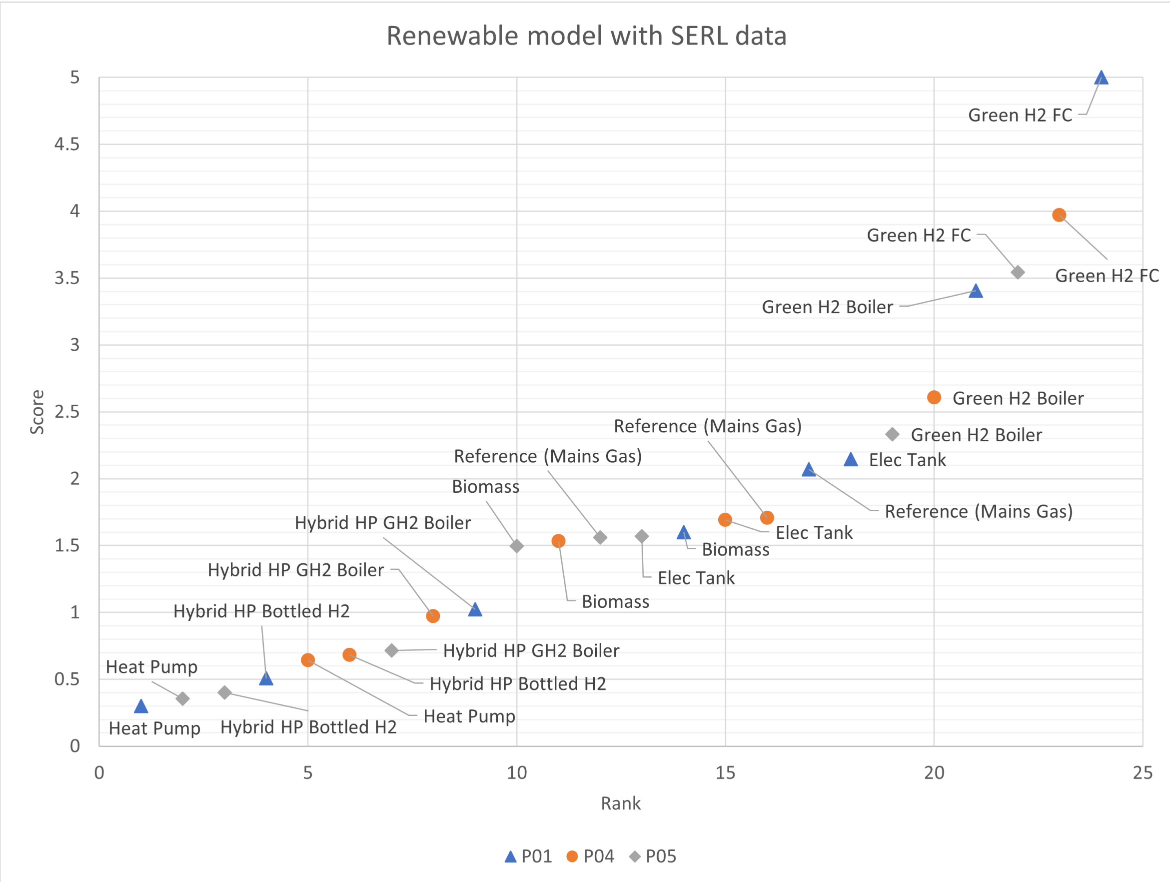


Figure 6.5: Scored and ranked results of archetypal energy user profiles P01, P04, P05 for the renewable model

6.4 Discussion

Both sets of simulations across the 19 unique models using three different energy demand profiles using smart meter data result in 57 unique results evaluating the operating cost, capital cost, operating emissions, system effectiveness and the proportion of energy used that is renewably generated (for the renewable energy mod-

Table 6.4: Updated capital costs and number of system components for the renewable energy model systems simulated using the SERL data.

Renewable energy model		
Model iteration	**Number of Components**	**Capital cost**
Mains Gas	5	£ 39,312.50
Biomass	10	£ 48,865.31
Green H2 Boiler	7	£ 72,136.67
Electric Tank	11	£ 38,910.63
Green H2 FC	8	£ 169,099.17
Heat Pump	9	£ 46,571.42
Hybrid HP GH2 Boiler	8	£ 53,029.11
Hybrid HP Bottled H2	7	£ 48,084.11

els).

The results presented show based on the above mentioned factors what domestic micro grid technologies score relative to all the other technologies and fuels analysed. Simulating each model against different user profiles derived from smart meter data representative of different user groups as developed in chapter 4.

The findings show that heat pump based systems score the best in both the existing fuels group of models and the renewable energy group of models. This low (and best scoring) result is due to high system efficiency, low running costs and relatively low emissions.

The highest (and worst) scoring results are the systems that include hydrogen electrolysis on site from primarily grid electricity. This is due to the installed renewable energy generators not covering the sufficient energy demanded by the electrolyser. Due to using grid electricity and the low efficiency of a green hydrogen system from electron to hydrogen molecule and back to an electron. The total system efficiencies of the green hydrogen systems modelled were found to be between 29% and 55% as seen in appendix B table B.2.

6.4.1 Limitations of the modelling software

In the same set of results the hybrid heat pump and green hydrogen boiler system score a high system efficiency. This is due to a very low utilisation of the hydrogen generation components of the simulation. This result is in part due to utilising the built in solver algorithm of the simulation software energyPro, which uses a Mixed Integer Linear Programming (MILP) solver.

Other similar simulations and modelling in literature develop their own algorithms to ensure that the desired components are utilised at desired scenarios through model optimisation. The models used in the energyPro microgrid software can be further optimised to ensure the desired operation strategy is achieved at an improved level than currently achieved.

The optimisation of the model can include tuning the sizing and capacities of certain system components, as well as enabling different settings that can influence the outcomes of the simulation. This is an iterative process of tuning the models, and with 19 different models to tune there was unfortunately not enough time successfully achieve this completely. Particularly with the more complex and interesting models such as the hybrid heat pump hydrogen models. Warranting further investigation of hybrid heat pump systems for remote settings and extreme weather locations.

6.4.2 Variance between energy user groups

This set of simulations are carried out across three different smart meter derived energy user profiles, P01 (Rural village with gas connection), P04 (Modern rural, EPC A, B or C) and P05 (Old Rural, EPC D, E, F or G).
As analysed in section 6.2 there is relatively little difference of the total energy demanded between the highest using energy profile (P04) and the lowest (P04) of 5%. There is very little total variance of energy consumption between these user

groups. The results seen in figures 6.4 and 6.5 reflect this where similar trends in results are found across all three user groups. Such as P01 typically scoring the best followed by P05 then P04. Some variance was found when looking at the renewable model results where simulations for the user group P01 scored cumulatively both the best and the worst.

There would be no need to simulate all three user groups when sufficiently similar results are produced. simulating with more varied user groups would provide greater detail in the results. As mentioned previously due to time and technical challenges other derived user group data was not of sufficient quality to be used in the simulations.

6.4.3 Comparing between smart meter consumption data and estimated energy consumption data

In this section models of 19 different rural domestic microgrids are computed with three different energy demand profiles derived from smart meter data of rural homes. The previous chapter computed the same models using energy demand profiles that are estimated and derived from weather data and building characteristics.

One aim of doing this is to compare the outcomes and results of the estimated and smart meter datasets, to understand briefly what benefits can be from using real energy consumption data in energy modelling.

There are no exact comparable datasets between the estimated and smart meter data which reflect the exact same type of building or characteristics. An approximate comparison can be made between the estimated and smart meter datasets. Observing the trends between the similar pairs of estimated and smart meter datasets provides some comparison of the data.

When comparing the characteristics of the three estimated and three smart meter datasets some are similar to each other to enable a basic comparison. The datasets selected that have a similar agreement are "Old and Uninsulated" estimated dataset and "P05 - Old Rural" smart meter dataset. These two datasets both represent detached homes with low to little levels of insulation. The rankings of the fuels/technology modelled can be compared. However the differences between the two datasets is primarily due to the total energy consumption. The "Old and Uninsulated" estimated dataset has a total energy demand of 45267kWh and "P05 - Old Rural" smart meter dataset has a total energy demand of 17660 kWh, a difference of 61%.

The large difference in total energy consumption suggests that any direct statistical analysis of key characteristics unrepresentative. The two comparable energy demand profiles analysed ("Old and Uninsulated" and "P05 - Old Rural") although are quite varied in magnitude. The large magnitude of difference suggests that there is a discrepancy between an estimated energy demand profiles and actual energy consumption trends of a similar Representative property.
A similar conclusion has been found by comparing EPC predicted use and smart meter consumption data from the same source used in the simulations presented here *(Few et al. 2023).* Finding a greater and growing discrepancy between estimated and metered data EPC ratings of C and below (D, E, F and G).

Table 6.5: Comparing the ranking and scores of similar estimated and smart metered energy demand profiles

Existing fuels model								
		Estimated data				**Smart meter data**		
Score	**Rank**	**Iteration**	**User profile**		**User profile**	**Iteration**	**Rank**	**Score**
1.517	1	Mains Gas	Old and uninsulated	change	P05	Heat Pump	1	1.281
1.591	2	Heat Pump	Old and uninsulated	change	P05	Mains Gas	2	1.427
1.651	3	Blue hydrogen	Old and uninsulated	match	P05	Blue hydrogen	3	1.701
2.007	4	LPG Bottle	Old and uninsulated	match	P05	LPG Bottle	4	1.941
2.058	5	Electric boiler	Old and uninsulated	change	P05	Wood	5	2.001
2.119	6	Wood	Old and uninsulated	change	P05	Electric boiler	6	2.061
2.350	7	Oil	Old and uninsulated	match	P05	Oil	7	2.245
2.536	8	Storage heater	Old and uninsulated	match	P05	Storage heater	8	2.299
2.543	9	Elec Tank	Old and uninsulated	match	P05	Elec Tank	9	2.513
2.578	10	Grey Hydrogen	Old and uninsulated	match	P05	Grey Hydrogen	10	2.625
3.078	11	Coal	Old and uninsulated	match	P05	Coal	11	2.977
Renewable energy model								
		Estimated data				**Smart meter data**		
Score	**Rank**	**Iteration**	**User profile**		**User profile**	**Iteration**	**Rank**	**Score**
1.075	1	Heat Pump	Old and uninsulated	match	P05	Heat Pump	1	0.354
1.349	2	Hybrid HP Bottled H2	Old and uninsulated	match	P05	Hybrid HP Bottled H2	2	0.402
1.451	3	Biomass	Old and uninsulated	change	P05	Hybrid HP GH2 Boiler	3	0.715
2.037	4	Hybrid HP GH2 Boiler	Old and uninsulated	change	P05	Biomass	4	1.497
2.250	5	Reference (Mains Gas)	Old and uninsulated	change	P05	Elec Tank	5	1.561
2.322	6	Elec Tank	Old and uninsulated	change	P05	Reference (Mains Gas)	6	1.569
4.155	7	Green H2 Boiler	Old and uninsulated	match	P05	Green H2 Boiler	7	2.333
4.978	8	Green H2 FC	Old and uninsulated	match	P05	Green H2 FC	8	3.543

Comparing the rankings of iterations between the two energy demand profiles as seen in table 6.5. Finding that there is a 58% of iterations that match and have the same ranking for both the estimated and smart metered demand profiles.

Results that changed rank all consisted of moving up or down one rank paired with another result. Such as in the existing fuels model in which Mains gas swapped ranking with Heat Pump from first to second and vice versa. There are four pairs of rank swaps across all 19 model iterations, 42% of the ranks change. Therefore although there is a large difference in total energy of each demand profile there is a broad similar trend between the estimated results and the smart metered results. From this using estimated energy demand profiles when comparing and evaluating different fuels and technologies for a given scenario can provide an approximate trend of results, compared to metered data.

However the use of estimated data in this analysis is not similar enough to smart metered data to forego the use of smart metered data. Which should be used when at any early opportunity in energy research to provide better responses.

6.5 Conclusion

Chapter 6 utilised both the archetypal rural energy user groups and microgrid modelling methodologies to develop and use smart metered energy demand profiles to compute the 19 earlier outlined models.
The results found that heat pump and hybrid heat pump technologies scored best when considering capital cost, operational running cost, operational emissions and system efficiency. Whereas electrolysed hydrogen systems scored the worst.

A more detailed statistical method of evaluating and scoring the 19 systems highlighted can provide greater analysis and result. Another result is evaluating and comparing results from estimated data and metered data, to see how much agreement between the two sets of results. An agreement of 58% was found. Which is determined to be insufficient to forego using metered data and use only estimated data when evaluating energy technologies. Future development could include using more related and similar in characteristic estimated and metered datasets to better evaluate the effectiveness of estimated datasets compared to real energy demand data.

Further work on developing and improving the quality of the smart metered datasets used in this research. To be tuned for more specific characteristics of each archetype as initially defined in chapter 4 than currently exists.

Chapter 7

Experimental work

Constructing and operating a medium scale solid state hydrogen storage system

7.1 Introduction

The aim of the work in this chapter is to develop a working solid state hydrogen energy storage system that is sized to act as a domestic energy store, developing this system with a hydrogen electrolyser and fuel cell and to compare to other energy systems with a digital twin.

7.1.1 Why use hydrogen energy in a home?

This thesis explores analysing low emissions energy systems (particularly heat) for rural and remote rural homes. i.e. homes where there is little to no energy infrastructure to a home, where there could be no connection to the national gas grid and/or a limited connection the national electric grid supplementing local renewable sources of electricity as the primary source of energy. The scale of renewables required to make a completely or mainly energy independent home using hydrogen energy storage is not determined in this work. The work carried out here is vital for future research that can evaluate this.
By harnessing localised generation of electricity from renewable energy sources this work explores storing the energy by converting into hydrogen gas to be later utilised. The round trip efficiency of converting electricity into hydrogen and back to electricity is low. Depending on the type of electrolysers and fuel cells used to convert the electricity into hydrogen and back again, the energy efficiency from electron to hydrogen and then back to electron is typically between 35% to 65%.

Hydrogen system efficiency this is not competitive to a battery electric energy storage system, more in terms of efficiency comparable to diesel or petrol electric generators which achieve an efficiency in the range of 25% to 40%. There are other considerations to having a hydrogen energy storage system: The duration of energy storage, the amount of energy storage, the renewable energy potential of the site, the energy demands of the property. These are the primary considerations that may be needed in selecting the energy system for a remote property.

7.2 Methodology

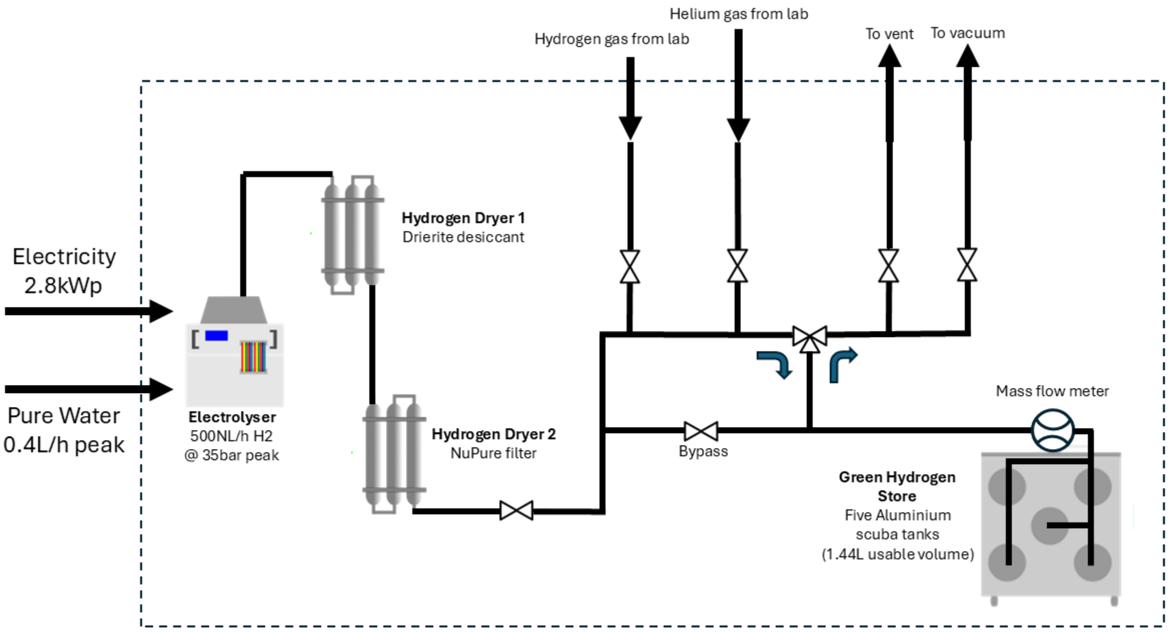
7.2.1 System description

The experimental system developed consists of an alkaline electrolyser producing hydrogen at 500 nL/h, hydrogen drying unit and central manifold. Where gas inputs and outputs to the Green Hydrogen metal hydride Store (GHS) are managed. The final component is the Green Hydrogen Store, where hydrogen gas was stored in an array of 5 1.44 L aluminum scuba tanks each containing 9072 g of AB2 alloy with thermocouples inserted that are charged and discharged by passing gas through a mass flow meter. All major system components for this demonstration system (other than the central manifold) are repurposed from previous projects in the University of Nottingham hydrogen research group. However during the course of the project the fuel cells in operation lost technical support and were no longer operational when technical support was needed to keep them operating.

Figure 7.1 illustrates the input and output flows from the system boundary. With electricity and water entering the system to supply the electrolyser. Hydrogen gas can also enter the system to operate the system without the electrolyser. The helium gas input is for leak testing the system whenever a major change to the system is had, such as removing one of the aluminium tanks. The external flows from the system are venting the hydrogen gas released from the GHS or venting via a vacuum pump.

There are various sensors placed around the system that enable recording of data for later results and analysis. Each of the five aluminium Luxfer scuba tanks have

Figure 7.1: Diagram of the Green Hydrogen Store demonstration system



a thermocouple inserted within the vessel, with one vessel with a thermocouple attached to the exterior of the tank. The mass flow meter data is digitally captured and there are two pressure transducers in the system, one located of the left hand side of the three way valve, recording the pressure when charging the GHS. Similarly a second pressure transducer on the right hand side of the three way valve, enabling recording of pressure when discharging the GHS.

7.2.2 Metal hydride selection and characterisation

An important part of the system is the metal alloy material that will be used to store the hydrogen gas. Storing hydrogen gas in a metal alloy (also known as a metal hydride) occurs through the process of hydriding (charging the store) and dehydriding (discharging the store). For this hydriding and dehydriding process to occur the metal hydride alloy needs to be subject to hydrogen gas at certain temperatures and hydrogen gas pressures. The exact temperature and pressure varies according to the metal hydride used, for this demonstration system the hydride selected should be something that could be situated in a home. This means it should work at ambient temperatures and relatively low pressures (10-60 bar).

A hydride that works and adsorbs hydrogen at ambient temperatures (approximately 20-30C) would be ideal as there would be no energy requirement in preheating the solid state store to charge the store, there is still a thermal transfer required but ambient conditions can be sufficient to supply this. Hence not reducing the energy efficiency of the charging process by adding another parasitic energy demand. A hydride that works relatively low pressures of 35 bar or less, which would be ideal a the electrolyser has a peak operating pressure of 35 bar. In many hydrogen gas systems the compressor is a large contributing factor to lower energy, due to the high energy requirement needed to compress the gas, with the potential up to 20% energy loss (Costamagna et al. 2022). And the loud noises it produces while in operation, added continued maintenance and high initial CAPEX of would make a hydrogen compressor undesirable in a domestic setting.

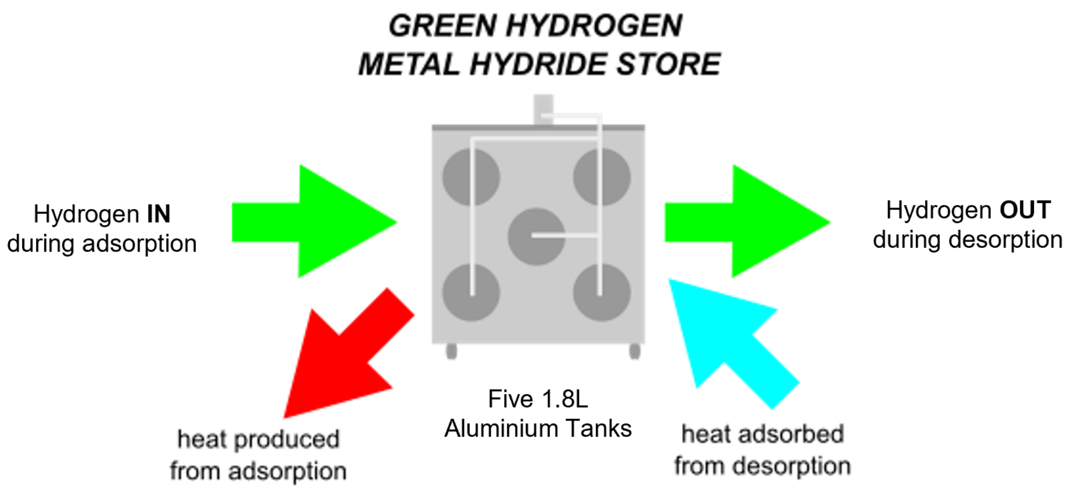


Figure 7.2: Diagram of the energy flows in and out of the Green Hydrogen Store during hydriding (adsorption) and dehydriding (desorption)

The metal hydride alloy Hydralloy C5 ($Ti_{0.95}$ $Zr_{0.05}$ $Mn_{1.46}$ $V_{0.45}$ $Fe_{0.09}$), which is an AB_2 alloy. Produced by GfE, this is a commercially available (there are few hydrides that are commercially available) and well known metal hydride material in hydrogen energy research and in broader industry. Hydralloy C5 (HC5) is known as a room temperature alloy, with the capacity to adsorb hydrogen at temperatures below 100C.

The theoretical capacity of HC5 is 1.8 wt% H_2 (Capurso et al. 2016). weight % is the convention of defining the capacity of a solid material to store hydrogen related to the proportion of the unit mass of the storage material. For HC5 the mass of hydrogen stored in the alloy is 1.8% the mass of the alloy. The University of Nottingham (UoN) has a sufficient quantity of HC5 to load up kilograms of HC5 into the GHS demonstration system.

To validate the performance of the University of Nottingham's batch of HC5 a pressure composition isotherm (PCI) is taken of a 1g sample of HC5 on a sieverts apparatus as seen in figure 7.3. A sample with a mass of 1g is used as this is a typical capacity of sieverts apparatus used. The sieverts apparatus is a system used to test the properties of metal alloy hydrides for chemically storing energy such as hydrogen and ammonia. A PCI tests the capacity of a material to store hydrogen at various temperatures and pressures. The results of a PCI plot is used to generate a Van't Hoff Plot, a single line (and hence equation which can characterise the performance of a material at various temperatures and pressures. A Van't Hoff plot is produced by taking the natural log of the pressure at the midpoint of the plateau point at each PCI, against temperature in Kelvin and coefficients of the material's enthalpy and entropy with the ideal gas constant.

$$Ln(P) = \frac{-\Delta H}{RT} + \frac{\Delta S}{R} \tag{7.1}$$

A PCI on the UoN batch was performed only in adsorption Therefore the comparison of data from the literature (Capurso et al. 2016) has both hydrogenation and dehydrogenation data whereas there is only experimental data for hydrogenation. Literature which have performed PCIs and calculated Van't Hoff plots for both adsorption (ADS) and desorption (DES).
Comparing PCIs to find that the experimental PCIs carried out at 10 and 20 degrees Celsius are similar to PCIs carried out by Capurso (ibid.) in literature. Looking at the PCIs at 50C all three adsorption PCIs achieve an overlap of the plateau pressure in the 25 to 30 bar range. However there is a variance in the final capacity across the three adsorption runs (2 experimental and 1 literature) from 1.7wt% to 1.3wt%.

The capacity of the experimental sample dropped in capacity from 1.4wt% to 1.3wt%, this difference in the change of capacity is observed by the 28C experimental runs. However those results straddled either side of the results from literature. The 50C results are noticeably lower than the literature results, as this similar trend has not been found in the other experimental results, there is uncertainty as to why this is the case.

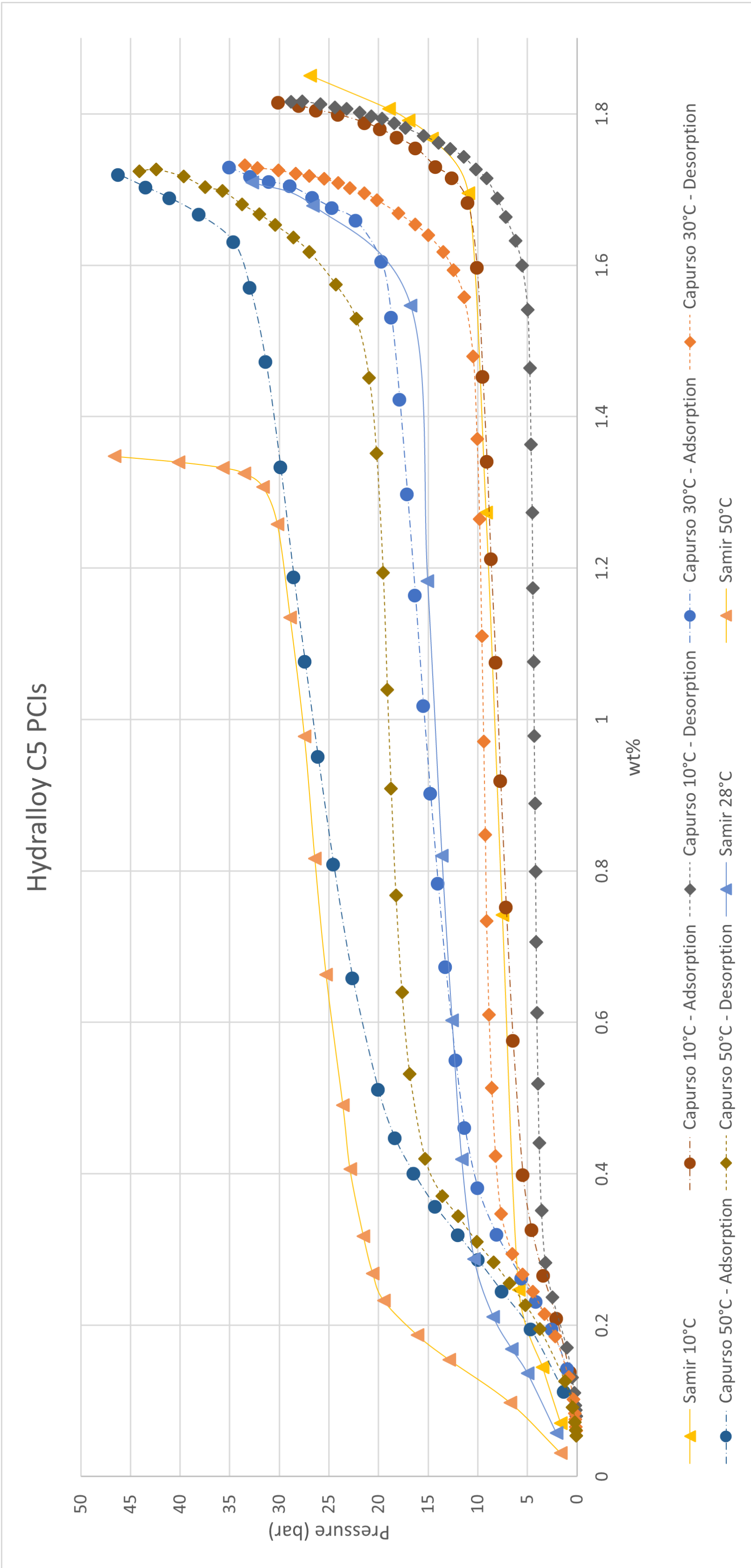


Figure 7.3: PCIs of HC5 comparing the results of the UoN batch to literature (ads = adsorption, des = desorption) (Capurso et al. 2016)

The Van't hoff plots of adsorption (figure 7.4) show the relationship of the temperature and pressure required for hydrogen to be adsorbed or desorbed from the hydride after the capacity has been determined by PCIs, in this case 1.8 wt%. The Van't hoff plots of adsorption are sufficiently similar between the experimental and literature results to use the data from literature to calculate the material properties of the batch of Hydralloy C5 used for adsorption and desorption. Both Van't hoff plots were manually calculated in Excel, the literature results use data from the literature PCIs.

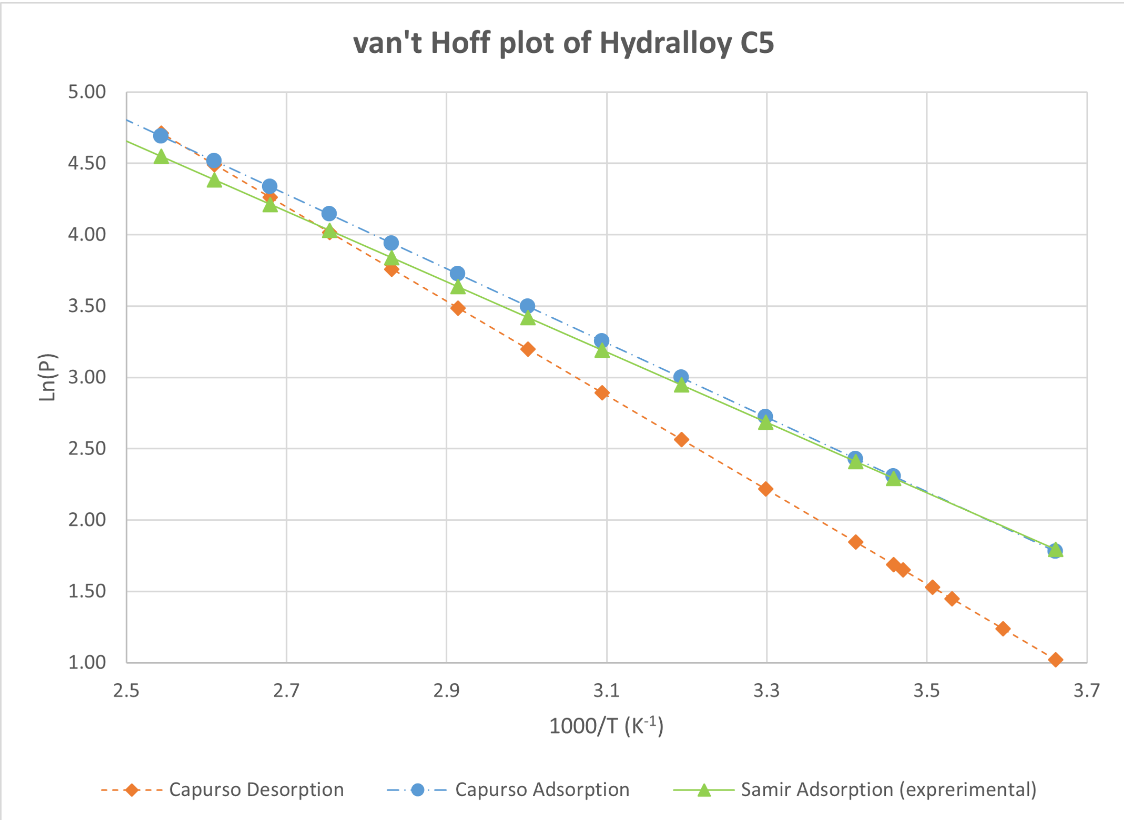


Figure 7.4: Van't Hoff plots of HC5 comparing the results of the UoN batch to literature (Capurso et al. 2016)

7.2.3 Construction of the GHS system

This demonstration system is comprised primarily of existing equipment present at the University of Nottingham hydrogen systems lab. Using a Pure Energy H-500 alkaline electrolyser from a previous project, re purposing a series of three buffer tanks as a large desiccant drying column (only two of the three tanks have Drierite desiccant within). An unused hydrogen purifier by NuPure follows the desiccant dryer down the line and next is a central manifold panel controlling the flows of hydrogen from the electolyser, the building and helium from the building into the store. There is facility to bypass the store to operate the electrolyser separately. Figure 7.1 illustrates the system.
The hydrogen store itself was built initially for another research project which ended before being able to use the store built. Therefore work was carried out to ensure this equipment was safe to be repurposed for this project.

Loading and activating the metal hydride material

The metal hydride material is crushed from the 10 mm flake size as supplied to a 1-2 mm in diameter particle size. Before being loaded into the aluminium tank. The tank has a measured 1.8 L volume and only 1.44 L of Hydralloy C5 is filled into the tank. This leaves the tank to be 80% filled. A 20% headroom is left in the vessel as a safety measure for any expansion and thermal effect for the hydride, which can cause expansion and rupture of the storage vessel (Charlas et al. 2012). Hydralloy C5 can be crushed and processed in air if carried out quickly, which is what happened in this case.

To activate the hydride tank it is placed on another system in the hydrogen system lab as seen in figure 7.5. This panel operates by controlling the flow rate of hydrogen gas to and from the attached vessel. The activation process involves repeatedly charging and discharging the hydride tank with hydrogen gas at a 35 bar of pressure

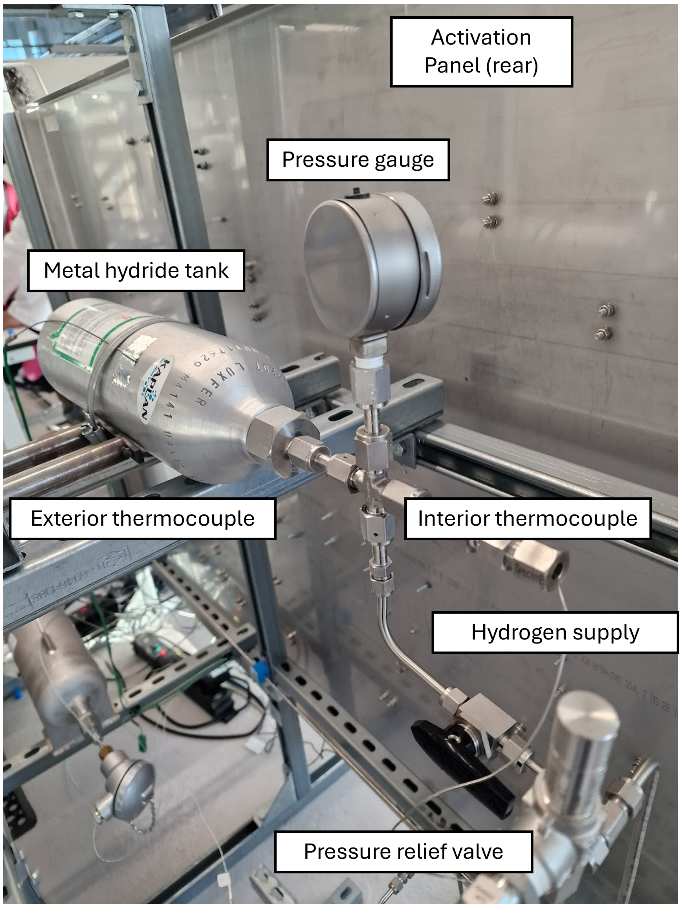


Figure 7.5: One of the GH2 Store's vessels filled with Hydralloy C5 in place on a different panel for activation.

at a flowrate of 14 L/min at ambient temperatures. Activation is achieved when there is a temperature increase is the vessel during charging and a temperature decrease during discharging, which is captured by thermocouples withing the storage vessel and on the exterior. This activation cycle is repeated 10 times to ensure that a stable hydrogen capacity is reached.

7.3 Results

7.3.1 Experimental results

Five complete cycles of hydrogenation and dehydrogenation of the GH2 system were completed. A further four cycles of hydrogen adsorption and desorption are completed but only the desorption profiles are recorded. This is due to some uncertainty of the quantity of hydrogen adsorbed. This is discussed in the next section.

Three different strategies of filling the tank with hydrogen gas on the GHS system was used throughout the experimental process.

1. The first adsorption run utilised hydrogen supplied from the lab building (RAD) at 35 bar, to simulate hydrogen being supplied from the electrolyser at the maximum output pressure of the electrolyser of 35 bar.
2. The second and third adsorption runs involved using the electrolyser to charge the tank from ambient pressure.
3. The fourth and fifth adsorption runs first generated hydrogen from the electrolyser to 35 bar within the system before opening valve to the tank.

Hydrogen capacity issues

During the activation process of this tank of Hydralloy C5, the quantity of hydrogen adsorbed into the metal hydride material was found to be less than the expected quantity of hydrogen. The observed experimental capacity of hydrogen in Hydralloy C5 on the GH2 store finds a capacity of 0.4 to 0.45wt%, wheras the expected capacity of Hydralloy C5 derived from literature (Capurso et al. 2016) and earlier characterisation in section 7.2.2 was 1.4 to 1.8wt%.

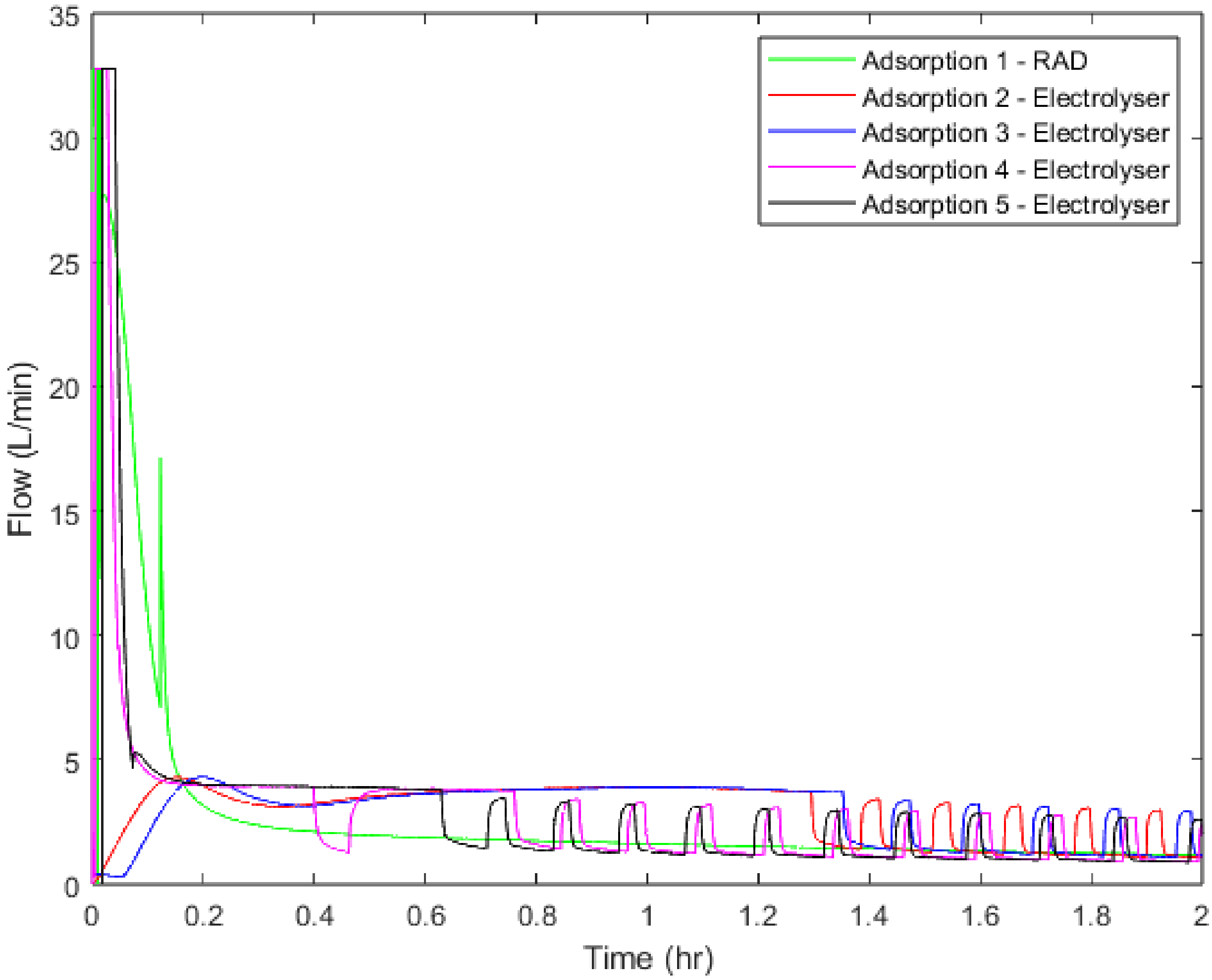


Figure 7.6: All experimental results of hydrogen adsorption into Hydralloy C5 on the GHS system. Showing hydrogen gas flow (L/min) and time elapsed (hr)

Experimental results discussion

Investigating the low uptake of hydrogen

A lower than expected hydrogen storage capacity was found 3.4 to 4.5 times smaller in capacity. This result was first seen during the activation process on the ERA panel. An investigation of this unusual result was made.

Inital discussion as to why this occurred was that the metal hydride material was not completely activated. The tank was removed from the ERA panel and gently rolled on the workbench to mix up the material. One hypothesis for the low capacity

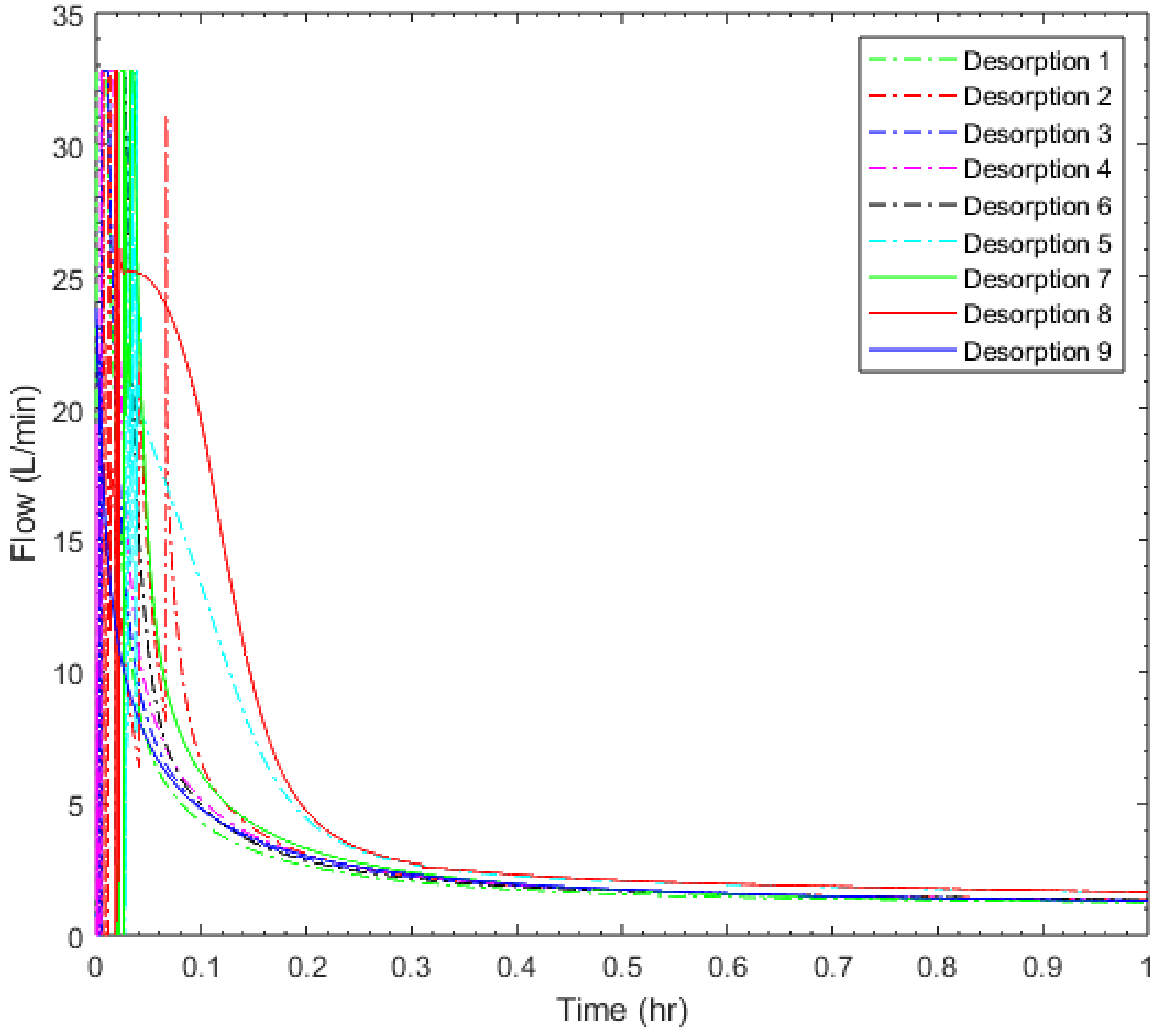


Figure 7.7: All experimental results of hydrogen desorption into Hydralloy C5 on the GHS system. Showing hydrogen gas flow (L/min) and time elapsed (hr)

is that not all the Hydralloy C5 was activated and that there may be pockets of unactivated material, rolling the tank may mix the activated and unactivated hydride. After rolling the tank and re connecting the tank to run another test, this did not result in any change in recorded capacity during subsequent cycles.

The next investigation was to remove a sample of the metal hydride material and test 1g of the material in a sieverts apparatus. This involved removing the tank and moving it to a large glove box where the hydride can be decanted and a sample collected as in figure . This operation needs to take place within a glove box as once

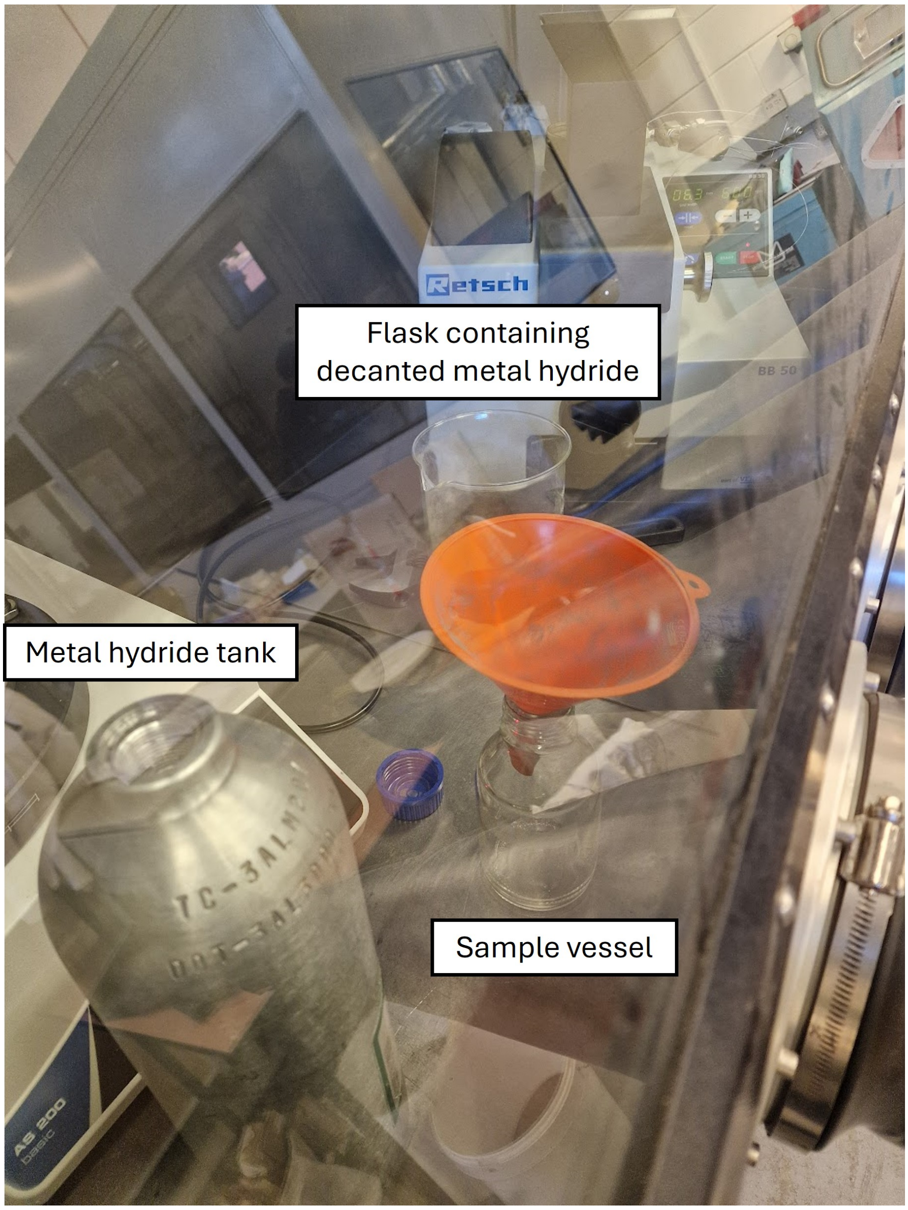


Figure 7.8: Images from the process of decanting Hydralloy C5 from the tank to extract a sample

a metal hydride is activated (exposed to hydrogen) it becomes air sensitive and will combust when exposed to oxygen.

When the sample was tested in the sieverts apparatus with a 1g sample the working capacity of Hydralloy C5 was found to be 1.6wt%, within the range of capacity determined from characterisation in section 7.2.2. The metal hydride tank was fitted to the green hydrogen store (GHS) system where the four cycles of hydrogenation and dehydrogenation as seen in the results were completed. Later after the initial experimental cycles were carried out further discussion regarding the lower than expected hydrogen capacity was carried out concluding in further experimental cycles of adsorption and desorption to confirm the capacity.

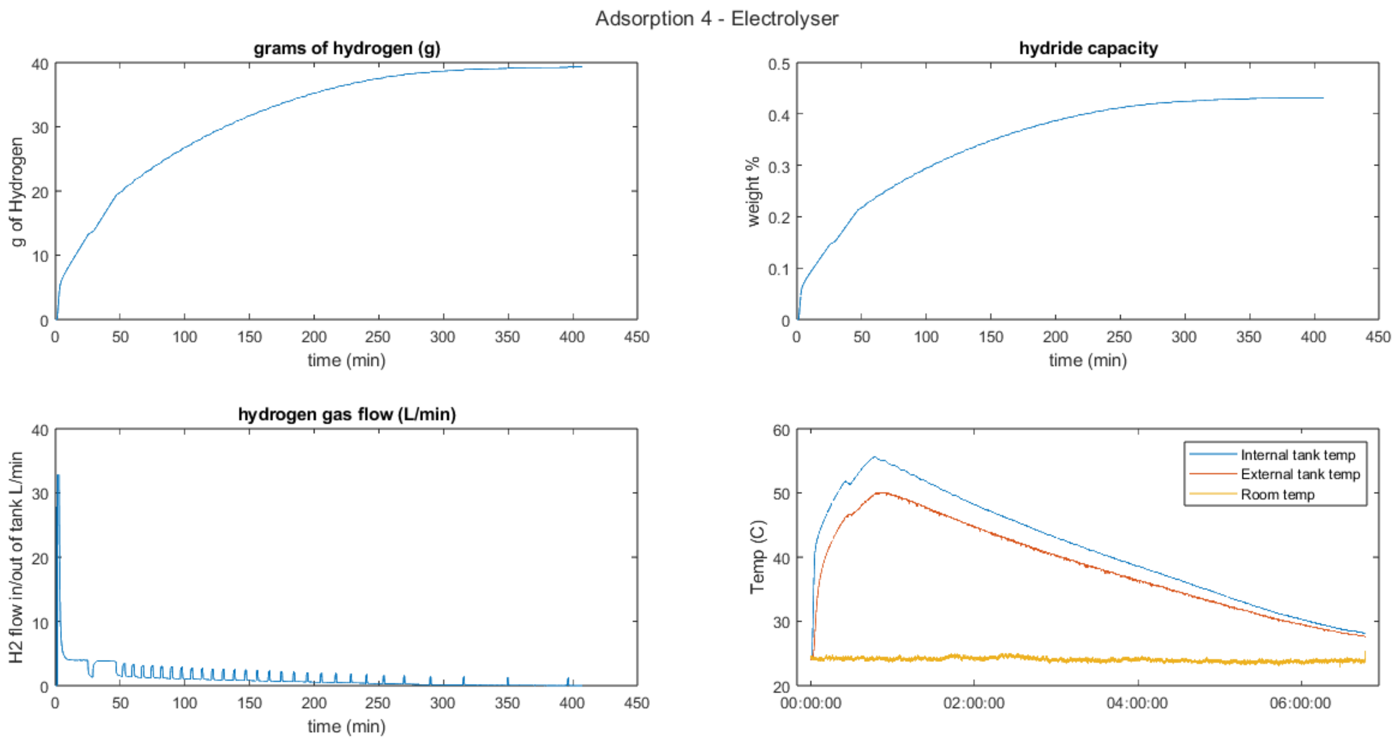


Figure 7.9: Figures of the mass of hydrogen stored, hydride capacity for storing hydrogen, the flow of hydrogen gas and the temperatures during the adsorption 4 experiment.

In figures 7.9 and 7.10 temperature profiles of the interior and exterior of the tank containing the metal hydride Hydralloy C5 for the few hours of the adsorption experiments with a peak of 56 C within the first hour of each experiment. Heat is generated due to the chemical reaction between the hydrogen gas and the metal alloy Hydralloy C5 stored within. The chemical reaction forms a metal hydride and releases heat as a byproduct which is observed. The quantity of heat is directly related to the rate flow of hydrogen gas into the tank. This is observed by comparing the hydrogen gas flow and temperature plots in both figures, where the initial filling of the tank with hydrogen gas peaks at a rate of 32L/min. In this period the

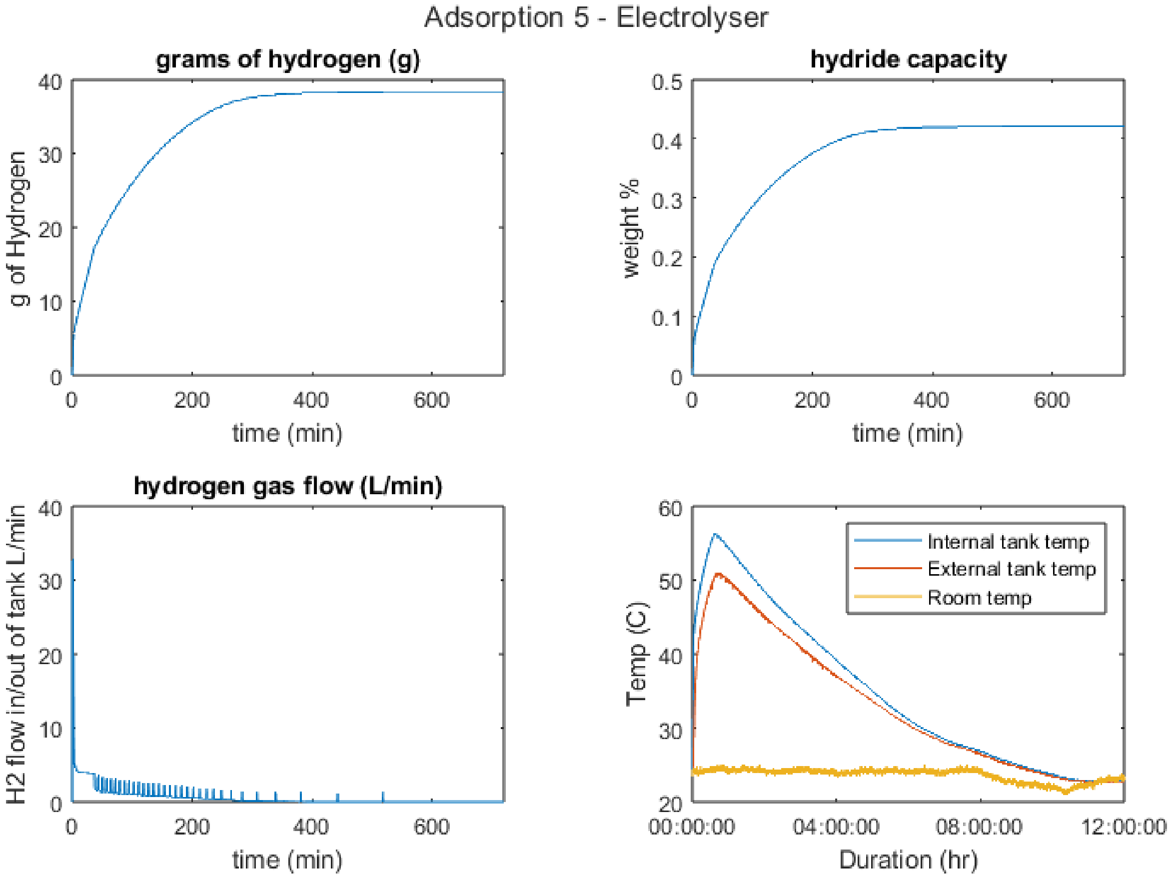


Figure 7.10: The mass of hydrogen stored, hydride capacity for storing hydrogen, the flow of hydrogen gas and the temperatures during the adsorption 5 experiment for 12 hours (720 minutes).

hydrogen gas is both reacting with Hydralloy C5 and filling the tank with hydrogen gas. This high hydrogen gas flow rate period enables high penetration of hydrogen into the Hydralloy C5 bed and therefore high reaction rate and heat released. Once the tank is filled with hydrogen gas the flow rate drops to less than 10L/min with the remaining flow only attributable to hydrogen reacting with Hydralloy C5.

Intermittent use of electrolyser.

Looking at the hydrogen flow profiles for adsorptions 2, 3, 4 and 5 in figure 7.6. After a period initially of rapidly filling the tank with hydrogen gas as the electrolyser ramps up to its operational output flow rate of 500NL/min. The mass flow rate drops as the pressure within the tank builds until 35 bar. At this pressure the electrolyser shuts down until the pressure drops to 30 bar at which point the electrolyser restarts producing hydrogen. The cycle of the electrolyser turning off and on again repeats until the hydride stops adsorbing hydrogen and the pressure is approximately between 35 and 30 bar.

Rate of charge

The rate of charge of a solid state hydrogen storage tank is nonlinear. Initially quickly charging before slowing down and plateauing at higher states of charge in an exponential manner. This is illustrated in figure 7.10. This phenomenon is also found in capacitors, where the state of charge and the time to charge are related by an exponential relationship between the state of chare (voltage) and the time constant of a capacitor (time constant = resistance x capacitance). Where the first 80% can be similar in time frame to charging the final 20% as seen in figure 7.11. This phenomenon occurs when charging a hydride tank as a hydride tank charging is a chemical reaction with similar reaction mechanisms to charging a lithium ion chemical battery with electrons. The "internal resistance" of Hydralloy C5 increases as more of the metal hydride is formed, increasing the time required for the hydrogen atoms to infiltrate the Hydralloy C5 material to find and react with unhydrided material.

Table 7.1 illustrates the difference in the time required to fill the hydride tank with hydrogen gas to an 80% state of charge (approximately 0.37wt%) and a 100% stage of charge (approximately 0.47wt%). Over double the charge time to 80% state of charge (SOC) is required to reach 100%. This finding illustrates that in future deployment of such a metal hydride hydrogen storage system the optimal charging cycle time to charge a majority of the tank in a reasonably quick time frame would be 168 minutes (2.8hrs). In use cases where a short charging time is required this is beneficial and informs future system design and modelling.

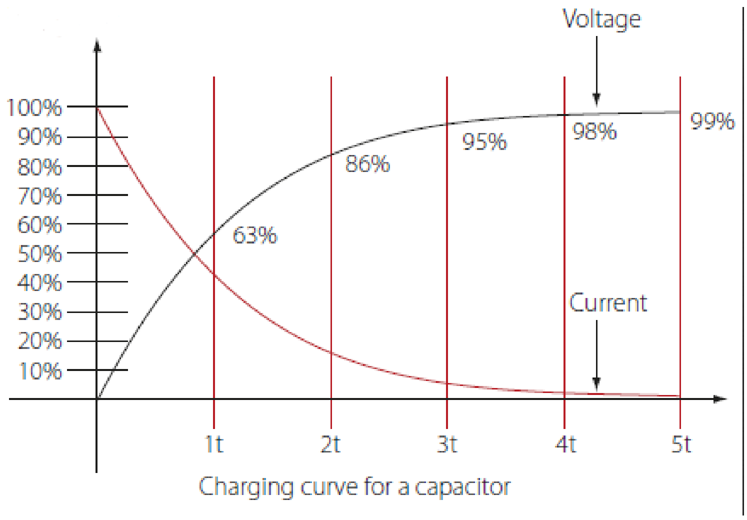


Figure 7.11: The state of charge (V) on the x-axis and time constant of a capacitor on the y-axis. Where 2 time constants (2t) required to achieve 86% charge and 4t required for 98% charge (Utmel Electronic 2025).

Table 7.1: Time to reach 80% and 100% state of charge of GH2 store tank

Median Adsorption	
Time to 80% state of charge (min)	168
Time to 100% state of charge (min)	424

7.3.2 Virtually modelling the GH2 store

A virtual computer model of the of the green hydrogen store demonstration system has also been produced in the microgrid software energyPro as seen in figure 7.3.2. This model is used to simulate the GH2 store demonstration system in a simulated rural home energy system. The digital twin places the electrolyser and metal hydride store with all five tanks filled with Hydralloy C5 in a rural home, alongside all the other models discussed in chapter 5 and chapter 6. This enables comparing the operational performance, cost and emissions impact of solid state hydrogen storage to the other fuels and technologies analysed. This is key as utilising the heating and cooling produced when the store is adsorbing and desorbing hydrogen could produce different system dynamics.

Digital twin methodology

The GH2 system digital twin adapts the ”Green H2 Boiler” energyPro model from the renewable energy group of models. This model is adapted by incorporating the heat release during hydrogenation when the store is charging and the heat/cooling demand of the store during dehydrogenation when the store is discharging.

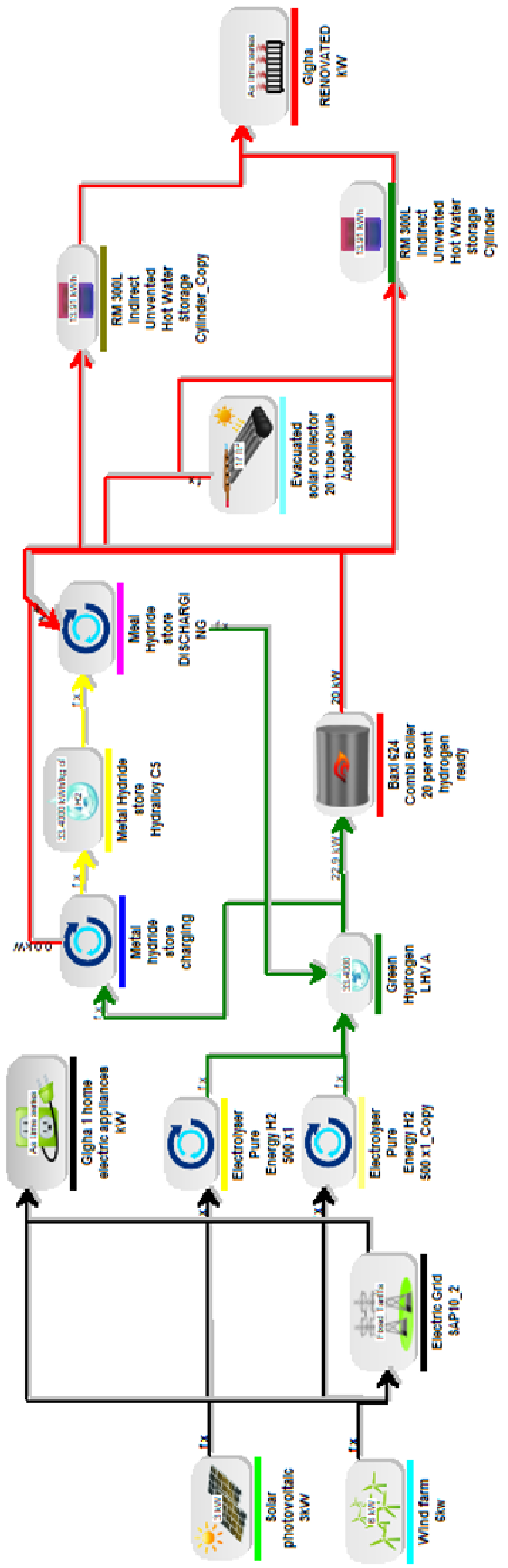


Figure 7.12: Diagram of the GH2 metal hydride store in the simulation software

To simulate the heating and cooling effects during charging and discharging of the store, the enthalpies of hydrogenation and dehydrogenation are taken and multipled with the hydrogen flowrate for charging and discharging of the store (both are 100NL/hr (1.6L/min) combining two 500NL/hr mass flow rate electrolysers). The enthalpies used are 31kJ/mol for adsorption and 27.8kJ/mol for desorption calculations (Kölbig, Bürger, and Linder 2021). The two equations (7.2 and) are used to calculate the power (W) input and output from the metal hydride store in the energyPro simulations. Using the hydrogen flow rate (mol/m^3s), volume of material (m^3) and enthalpies for adsorption (hydrogenation) and desorption (dehydrogenation) (kJ/mol) respectively.

$$Q_{charging} = \Delta H_{hydrogenation} \times flow_{h_2} \times v \tag{7.2}$$

$$Q_{discharging} = \Delta H_{dehydrogenation} \times flow_{h_2} \times v \tag{7.3}$$

Differences the experimental systems and digital twin

The digital twin uses two electrolysers unlike one in the lab, This is due to desiring a higher heat produced during charging and cooling during discharging. As heat is directly proportional to the flow rate, having two electrolysers produces double the flow and double the energy. This model looks at the scenario where all five of the vessels in the physical system are filled with the same quantity of Hydralloy C5. The experimental system was not able reach this stage with only one tank filled.

Digital twin results and discussion

This digital version of the green hydrogen metal hydride storage system is the 20th model produced in this complete set of 120 unique results. It is valuable as this model demonstrates some of the more novel hydrogen energy storage technologies and their potential use and comparison with other heating technologies. As a digital model there are opportunities to explore synergies of utilising waste heat from the hydrogenation process and to feed heat during dehydrogenation to produce a more effective system. This is advantageous as greater system efficiency reduces the overall unit cost of energy consumed and solid state hydrogen storage can be safer than compressed gas storage. However currently with such a novel technology costs are impossible to reasonably estimate in a comparable way to other technologies, even other hydrogen technologies.

Capital costs associated to the demonstration system is difficult to acquire, particularly due to much of the equipment being reused from previous projects and there financial history is limited if any at all. An approximate cost for the metal hydride Hydralloy C5 was used of 125 Euros per kg of material, for a mass of 36.29kg of Hydralloy C5. With an approximate cost of the metal hydride material derived a total system capital cost was calculated to be £55,399.06. This capital cost is used alongside the emissions, operational cost and performance of the model as seen earlier in chapter 5 and 6. Finding that the meta; hydride models score better than other green hydrogen models. This is due in part to a more realistic sizing of the electrolysers included in the model which greatly reduces the capital cost and hence score.

The digital twin was computed again with new energy demand profiles from the Smart energy Research Lab (Smart Energy Research Lab and University College London n.d.) using smart meter data as seen in chapter 6. Similar results in the total rank of the metal hydride models are found compared to the simulations carried out with the estimated energy demand profiles. As discussed in section 6.4.3 there is a poor 58% agreement between the estimated and smart metered energy demand profiles. This low correlation between the two groups of energy demand profiles impacts the quality of result achieved using only estimated datasets to real metered datasets. Suggesting that the use of metered data is much more reliable.

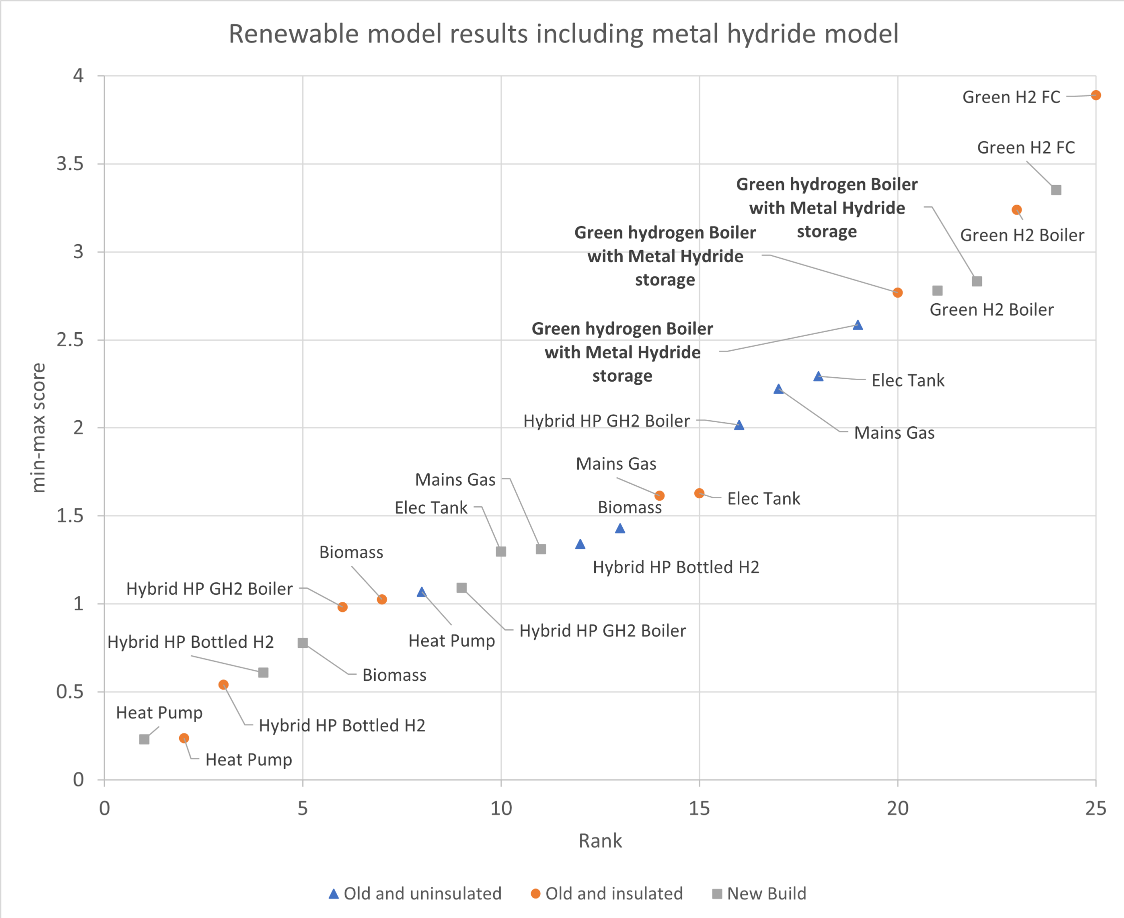


Figure 7.13: An updated figure 5.3 of analysed and ranked renewable model results including the metal hydride system digital twin

One investigation in comparing metal hydride systems to other green hydrogen storage systems is looking at improved system efficiency by recovering the heat produced in hydrogen adsorption and the using the stored heat during hydrogen desorption. Understanding if the reversible thermochemical process can provide any advantages over other energy storage processes.

Table 7.2 presents the calculated total system efficiency as defined in equation 5.3 finding that the "green hydrogen boiler with metal hydride storage" model has an approximately 20% reduced efficiency as modelled than the "green hydrogen boiler" model which used compressed hydrogen cylinders. However a the "green hydrogen boiler" model does not include in the simulations a compressor, which is required to store hydrogen at small volumes at high pressures. And is often the source re-

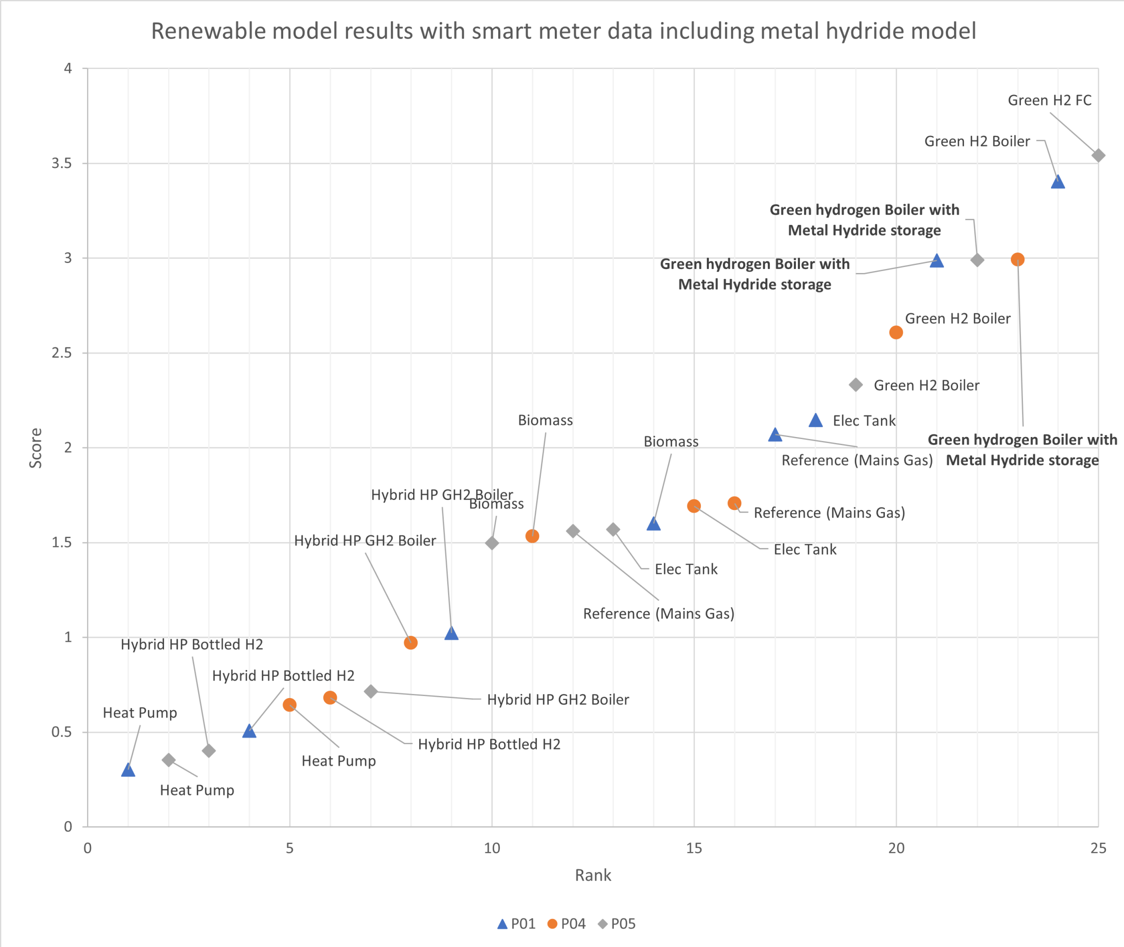


Figure 7.14: An updated figure 6.5 of analysed and ranked renewable model results including the metal hydride system digital twin

duced system efficiency of hydrogen energy systems. The "green hydrogen fuel cell" model has a comparable system efficiency of the metal hydride system as simulated. This reflects the low efficiency of the fuel cell modelled, where 50% of the energy consumed produces electricity, the remaining 50% as heat recovered and utilised in this simulation.

Further improvements to modelling the metal hydride storage system can include modelling different operation strategy algorithms that are found, modeling with a hydrogen fuel cell where the waste heat from the fuel cell can be utilised in the dehydriding process of the store.

A challenge with optimising a metal hydride hydrogen system in the context of this work is due to the primary focus of delivering heat to the end user. The demand for heat is an order of magnitude greater than the electricity demand in all the energy demand profiles explored estimated or from smart meters, optimising heat recovery improves system efficiency. The scale of improvement perhaps is not sufficient to justify added cost and complexity. This question could be explored in future work.

Table 7.2: Total system efficiencies (total energy demanded/total energy consumed) of the three green hydrogen model iterations. (See equation 5.3 for further detail)

Total system efficiency			
	P01	**P04**	**P05**
Green H2 Boiler with Metal Hydride storage	34%	34%	34%
Green H2 Boiler	53%	57%	55%
Green H2 FC	29%	32%	30%

7.4 Summary

By developing both a digital model of this system, which enables experimentation with scale up and operation design of the technology. And developing a practical demonstration system showcasing solid state hydrogen storage technology in action. The experimental system demonstrates the solid state hydrogen storage technology in action at scale. With components and design considerations that allow for a future completion and demonstration of the experimental system in a home fuelling a hydrogen fuel cell or boiler.

The constraints and challenges in the period of this project did not enable a complete construction of the demonstration system with all five tanks of the GH2 system filled with metal hydride material. And also including a working fuel cell to the system.

The digital twin of the experimental system allows modelling of what the complete experimental would have operated if totally completed in a demonstration home. The digital twin also allows comparison with the 19 other microgrid models developed, discussed and presented in the previous chapters.

Finding a green hydrogen energy system delivering heat to the end user with metal hydride storage scores poorer than green hydrogen systems with non metal hydride storage. There is opportunity to iterate and tune the models used in further detailing and exploring the potential effectiveness and use cases for metal hydride hydrogen storage in domestic settings. This work is a starting point for future modelling and analysis with different scenarios, devices and metal hydride materials.

Chapter 8

Conclusions

This thesis explores and researches the decarbonisation of rural and remote rural domestic heating in general.

8.1 Defining archetypal rural energy user groups

Chapter 4 explores ***who*** lives in rural UK and ***what*** kind of home they live in. Key elements in defining a series of five domestic rural energy user groups representing a spread of rural home compositions and their occupants. The five archetypal user defined groups are;

- P01 - On gas grid in a village
- P02 - Off gas grid in a village
- P03 - Off gas grid outside of a village
- P04 - Modern rural
- P05 - Old rural

These five user groups produced reveal other information that may be of interest in other research, such as a typical age of residents aged 54 and over and the majority of households having only two occupants. One major key insight is regarding a large proportion (45%) of respondents not knowing the energy performance certificate (EPC) rating of their home. This is troubling as this suggests that almost half of rural residents are not aware of the current level of energy efficiency of their building. Presenting a challenge in furthering public engagement and ownership of energy matters in their own life.

8.2 Modelling microgrids of rural remote homes

The five rural user groups developed are used to inform subsequent energy modelling demand profiles using smart meter data in chapter 6. Using a modelling and analysis methodology defined in chapter 5. Finding in all sets of results the best scoring technologies to be heat pump based systems due to the high system efficiencies, relatively low emissions and relatively low running costs. Other low emissions fuels and technologies found to be of interest are hybrid heat pump hydrogen systems, biomass wood systems and hydrogen fuel delivered to a domestic hydrogen storage tank. Discussed is the merit in further investigating the various secondary scoring low emissions heating fuels and systems to what other local conditions that are not quantified in the analysis methodology of this work. Developing a detailed and reusable analysis methodology. An element to the feasibility of rural usage low carbon fuels such as hydrogen in the proximity to industrial hydrogen hubs, where a large hydrogen electrolysis plant may primarily supply hydrogen to anchor industries such as steelworks, agriculture or quarrying. That may find heat pump based heating less feasible and necessitate alternate heat and power technologies.

8.2.1 Using using metered data

Chapter 6 computed the same models developed in chapter 5 with different energy demand profiles from smart meters across Great Britain. An outcome of this is to evaluate the variance in the simulation results between using smart meter energy consumption profiles and estimated energy consumption profiles. There is a 42% difference between the result ranks of the estimated data simulation and the smart meter data simulations. Therefore a large variance between the results from the two different groups of energy demand profile suggest that there is benefit from using metered data in simulations to provide more representative results, besides any of the increased labour required to acquire smart metered data.

8.3 Experimental work with metal hydride hydrogen storage

In chapter 7 metal hydrides to store hydrogen in a solid state are explored. Characterising Hydralloy C5 material used and developing a domestic scale hydrogen electrolyser and metal hydride storage demonstration system at the University of Nottingham.

This demonstration system has the opportunity to be further developed introducing more and various hydride materials with a synergistic operation strategy. Utilising the different temperatures and pressures that different metal hides may operate at with a heat management system surrounding the storage tanks and integrating exhaust heat from electrolysers and fuel cells.

8.3.1 Digital twin

In section 7.3.2 a digital twin of the demonstration system is developed. To enable simulation and comparison of the metal hydride hydrogen storage system alongside the other 19 simulations carried out in chapters 5 and 6. With the digital twin of the metal hydride demonstration system there are 20 different models simulated across 6 different energy demand profiles (3 estimated profiles and 3 smart meter data profiles). Totalling 120 individual simulation results each with figures for operational cost, operational emissions, system efficiency and capital cost. Finding that a metal hydride storage system in the modelling completed scores poorer than the equivalent green hydrogen system model using non hydride hydrogen storage. Further work on the metal hydride system digital twin modelling could include further detailed updating of the model and applying different operations or user group scenarios.

8.4 Final conclusion - Linking all the research together

The challenges of decarbonising rural domestic energy with a comparison of current and future heating technologies including hydrogen are many and varied.
There are three main strands of research that encompass this thesis are all linked and combine together. By investigating the decarbonisation of rural remote homes and exploring the place of up and coming energy storage technologies such as hydrogen and solid state metal hydride hydrogen storage in rural settings. Achieving these three challenges involved a multi-disciplinary, multi-skill approach of first social science in developing and researching the results of the rural energy study in chapter 4.

Second, the results of the social research used later on are the 5 archetypal rural user groups used in chapter 6 to derive energy demand profiles from smart meter data. This data is then applied to energy system micro grid models of 20 different heating fuels and technologies that have been and could feasibly be used in a rural remote off gas grid home first developed and demonstrated in chapter 5. The simulation development and processing of the smart meter data involves extensive computational engineering skills in acquiring, collating, coding and processing data inputted and outputted from the microgrid simulation software energyPro. Finding a difference between the two sets of energy demand data (estimated and smart metered) finds that estimated energy demand profiles used 42% more energy than the comparable smart meter dataset.

Third is the experimental work described in chapter 7 is key to provide a physical experimental pillar of this research project, demonstrating in practice one of the technologies described in the simulations. Having a demonstration system that can be provides a tangible output of this research that is mirrored with a digital twin, enabling some comparison between experimental and digital systems. Finding the metal hydride hydrogen storage technology with heat a management system and hydrogen boiler (removing heat during store charging to the central heating circuit and supplying heat during store discharging) scoring better and more effective than the green hydrogen fuel cell energy system modelled.

Each element of this research has brought novel results to science and contributed towards furthering net zero, particularly decarbonising domestic rural and remote heating. Some key conclusions are made, such as the best technology to apply to a rural off gas grid home are heat pumps, closely followed by hybrid heat pump, bottled hydrogen systems. Green hydrogen energy systems, where hydrogen is generated on site performed the worst. However green hydrogen metal hydride systems (and hydrogen boiler) systems scored better than green hydrogen fuel cell systems. This research highlights the importance of a better evaluation of the current heating technologies of rural UK homes to inform future policy of decarbonising rural home heating. It is the intention that this thesis, or works derived from the same research can be disseminated to other relevant stakeholders, policymakers or researchers to furthering of science and engineering.

8.5 Future work

This multidisciplinary body of research has numerous opportunities of future work. An enhanced rural energy survey distributed truly nationwide to thousands of parish or equivalent councils could be the basis of a ”rural energy census” that can provide valuable data to researchers and policy makers in understanding clearly the national state of rural energy access. From this enhanced survey more detailed energy user profiles can be produced and also other analysis regarding attitudes and occupant's interactions with their home and the energy they use.

Key future work to improve the experimental work carried out includes to fill the remaining four tanks of the metal hydride storage tank with metal hydride material, of Hydralloy C5 or another material. Doing this will enable experiments of the charging and heating dynamics of an array of storage tank or charging from one tank to another.

This work focused on a single rural home, there will be network benefits with all the technologies evaluated that can impact the scoring and ranking of the technologies/fuels. Technologies such as hydrogen where the generation of the fuel on the premises is an example of where individual distributed generation of hydrogen is not effective. A more effective used case for using hydrogen for rural domestic use is as part of a local community/regional energy system. Where hydrogen generated primarily for industrial or agricultural uses could have off takes for local domestic use. An example of this would be any of the ”Bottled H2/blue hydrogen/grey hydrogen” iterations modelled which represent this scenario. More detailed micro grid modelling such as adding compressors can change the dynamics and cost benefits of such technologies simulated. Improving the financial modelling off all the simulations to enhance the techno-economic analysis with potential subsidies, inflation and other financial aspects could be improved. Other technologies or permutations of current technologies and systems could be modelled. Including further hydrogen fuel cells, electric batteries, metal hydride hydrogen storage and adsorption heat pumps could all be explored and evaluated in future.
Some of the rural energy challenges identified yet not included in this research which

could be integrated into a broader techno-economic analysis include local planning restrictions (such as in national parks), the cost of retrofit insulation (often required for technologies such as heat pumps), local weather considerations, heath impacts and network effects of sharing community/district energy systems.

Another result is evaluating and comparing results from estimated data and metered data, To see how much agreement between the two sets of results. An agreement of 58% was found. Which is determined to be insufficient to forego using metered data and use only estimated data when evaluating energy technologies. Future development could include using more related and similar in characteristic estimated and metered datasets to better evaluate the effectiveness of estimated datasets compared to real energy demand data. Further work on developing and improving the quality of the smart metered datasets used in this research. To be tuned for more specific characteristics of each archetype as initially defined in chapter 4 than currently exists.

This research has been extremely challenging and dynamic, requiring the ability to do may different tasks and research in numerous scientific disciplines. Requiring a resilience and optimism to continue through challenging periods of work to create this final body of research in this thesis.

A PhD thesis is a story, a narrative detailing the key triumphs and questions arising from a concentrated period of research. That is what we PhD students are told throughout our research. It may not seem like it at the start of the PhD as an eager and ambitious researcher, however at the end it all comes together. Through the trials and tribulations, from the stressful and long nights working to days when there is so little to do you can plan cooking a Christmas dinner minute by minute. These are all some of the experiences of a PhD researcher all in the name of science and to write their own thesis, their own story. *(To the best of their writing ability...)*

It has been an honour to have the rare opportunity to pursue a PhD and contribute a small part, a small verse to the literary epic of science and engineering.

The end.

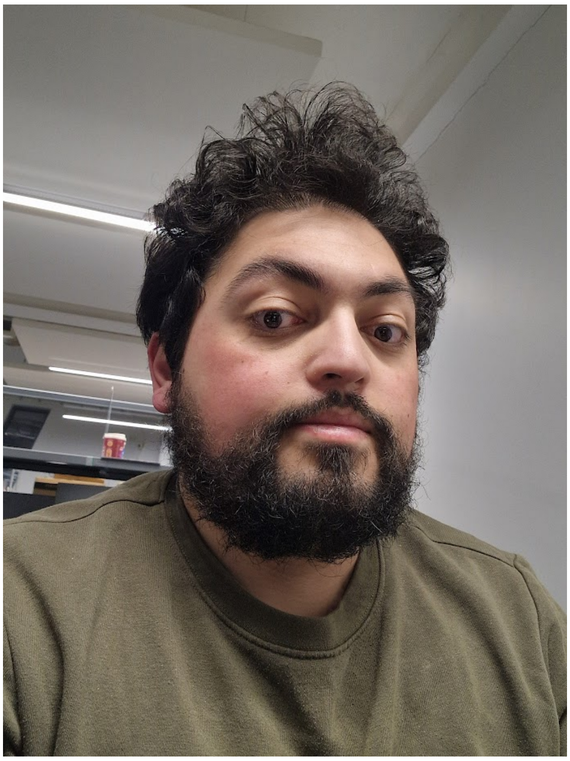


Figure 8.1: Me at the end of writing the corrections of this thesis

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Appendices

Appendix A

Rural Energy Study data

Complete compiled data results from chapter 4.

Comprising of results for all quantitative questions in the survey distributed to the public. Where the results of this survey produced the five archetypal user groups (P01 - P05).

A.1 Survey questions

Energy Fuel Survey – Part A

This survey is to look at the different fuels used at home for heating, power and transport.

It forms part of a PhD project at the University of Nottingham looking at rural energy usage and the feasibility of converting current rural heat and energy systems to low or zero carbon hydrogen electric systems.

All data collected through this survey (and any follow up communications) will be kept securely in line with University of Nottingham data protection policies and anonymised in further work and any potential publications.

Please complete this survey to the best of your ability, any questions or queries regarding this study contact Samir.soares@nottingham.ac.uk

Part 1 – Information about you and your home

1. Name

2. Email

3. What is the first half of your postcode (or equivalent)?

4. What is your gender?

Please select one

o Male

o Female

o Other

o Rather not say

5. How many occupants live in your home?

Please select one

o 1

o 2

o 3

o 4

o 5

o 6+

6. What is the age range of the occupants?

Please select all that apply

o Under 18

o 18-24

o 25-34

o 35-44

o 45-54

o 55-64

o 65-74

o 75+

7. Where do you consider yourself to live in?

Please select one

o City

o Town

o Suburb

o Village

o Hamlet

o Single dwelling (e.g. single rural cottage)

o Farm

o Other [please specify]

8. What kind of home/building do you reside in?

Please select one

o Flat, purpose built

o Flat, converted

o Bungalow

o Terrace

o Semi detached

o Detached

o Farmhouse

o Other [please specify]

9. What is the EPC rating of your home/building?

Please select one

o I don't know

o A

o B

o C

o D

o E

o F

o G

10. What is your employment status?

Please select one

o Employed

o Self employed

o Student

o Retired

o Part Time

o Not employed

11. Do you work from home?

Please select one

o 0% of the time - I do not work from home

o 25% of the time - Sometimes

o 50% of the time

o 75% of the time - Often

o 100% of the time – I always work from home

Part 2 – Your thoughts on the environment and sustainability

12. Do you consider yourself environmentally conscious?

Please select one

o Extremely

o Very

o Moderately

o Slightly

o Not at all

13. Are you interested in sustainability?

Please select one

o Extremely

o Very

o Moderately

o Slightly

o Not at all

14. Are you interested in installing your own sustainable technologies? (such as fuel cells, heat pumps, wind and solar power)

Please select one

o Definitely

o Probably

o Possibly

o Probably not

o Definitely not

15. Do you think about the cost of energy?

Please select one

o No concern. I have no concern regarding energy costs

o Occasionally concerned.

o Sometimes concerned.

o Regularly concerned. It is often difficult to afford to pay my energy bills

o Yes, always concerned. I cannot afford to pay for my energy.

16. Do you actively take measures to reduce your energy consumption?

Please select one

o No. I do not care how much energy I use

o Sometimes. When I am able to

o Yes. I actively take measures to reduce energy consumption

Part 3 – How do you consume energy at home?

17. Does your building include any of the following features?

Please select all that apply

o Double glazing Y/N

o Insulation Y/N

o EV charging point Y/N

o Heat pump Y/N

o Smart Meter Y/N

o Energy efficient lighting (eg. LED bulbs) Y/N

18. a. What rough temperature do you usually set your thermostat or equivalent throughout the year?

Please select all that apply

	Less than 10 degrees	10 – 15 degrees	16 – 20 degrees	21 – 25 degrees	26 – 30 degrees	I do not have temperature control
Winter						
Spring						
Summer						
Autumn						

b. What temperature do you usually set your thermostat or equivalent when in use?

Any other details on temperature control in your home? – e.g. variation from room to room.

[Insert answer here]

c. Is that in Celsius or Fahrenheit?

Celsius/Fahrenheit

19. What energy fuels do you use (for power, heating, transport)

Please select all that apply

Electricity	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Natural Gas	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Oil	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Coal	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Smokeless Coal	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Diesel	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Red Diesel	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Biodiesel	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Petrol	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Peat/Turf	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Wood	Heating	[]	Power	[]	Transport	[]	Cooking	[]
Other (please specify)	[Insert answer here]							

20. Heat/hot water supply: How do you get your heat/hot water?

Please select all that apply

o Gas boiler

o Oil boiler

o Biomass boiler

o Electric boiler (eg. immersion heater)

o Electric heater

o Heat pump

o Hot water tank

o (District) Heat network

o Solar thermal

o Other [Insert answer here]

21. How is your building typically heated?

Please select one

o Central heating

o Electric space heater

o Fireplace

o (what fuel is used?) [Insert answer here]

o Other [Insert answer here]

22. Storage: Do you store energy onsite?

Please select all that apply

o No, I do not store energy

o Electric Battery (eg. Tesla Powerwall)

o Hot water cylinder

o Heating oil tank

o Gas tank

o Gas bottles

o Wood pile

o Coal store

o Other (please specify) [Insert answer here]

23. How do you get your energy to your building?

Please select all that apply

Electricity

o Grid [ ]

o Onsite generator [ ]

§ *If generator what fuel does the generator use?* [Insert answer here]

o Onsite wind turbine [ ]

o Onsite solar panel [ ]

o Other [Insert answer here] [ ]

Natural Gas

o Grid [ ]

o Bottle [ ]

o Other [Insert answer here] [ ]

Heating Oil

o Bottle delivered [ ]

o Oil delivered by tanker [ ]

o Other [Insert answer here] [ ]

Coal

o Delivered [ ]

o Brought in by yourself [ ]

o Other [ ]

Other fuels, how do you get them to your building? [ ]

24. This survey forms the first stage of a study into rural energy use. Are you happy to be contacted for your input into future stages (e.g. further surveys, follow-up conversations, analysis of your energy usage data)?

Y/N

Thank you for participating in this survey!

Any questions or queries contact Samir.soares@nottingham.ac.uk

A.2 Survey results

Rural energy survey archetypes	Over-all	P01	P02	P03	P04	P05

4. What is your gender?	Male	**54%**	54%	47%	45%	59%	37%
	Female	**45%**	46%	53%	51%	38%	63%
	Prefer not to say	**1%**	0%	0%	4%	3%	0%
	Other	**0%**	0%	0%	0%	0%	0%
5. how many occupants live in your home?	1	**13%**	12%	16%	5%	8%	7%
	2	**56%**	63%	59%	58%	69%	58%
	3	**14%**	13%	14%	13%	10%	12%
	4	**11%**	9%	6%	18%	10%	19%
	5+	**4%**	3%	4%	6%	3%	5%
6. What is the age range of the occupants [Tick all that apply]	Under 18	**9%**	6%	6%	9%	9%	9%
	18-24	**10%**	12%	3%	12%	3%	8%
	25-34	**12%**	9%	9%	7%	16%	11%
	35-44	**9%**	10%	6%	9%	10%	13%
	45-54	**12%**	8%	18%	11%	10%	19%
	55-64	**18%**	21%	18%	22%	17%	15%
	65-74	**20%**	23%	29%	21%	22%	18%
	75+	**9%**	12%	10%	11%	12%	9%

7. Where do you consider yourself primarily to live?	City	**5%**	0%	0%	0%	0%	0%
	Town	**12%**	0%	0%	0%	0%	0%
	Suburb	**5%**	0%	0%	0%	0%	0%
	Village	**51%**	100%	100%	0%	90%	60%
	Hamlet	**12%**	0%	0%	42%	8%	16%
	Single Dwelling	**8%**	0%	0%	29%	0%	16%
	Farm	**5%**	0%	0%	22%	3%	2%
	Other	**2%**	0%	0%	7%	0%	5%
8. What kind of home-/building do you reside in?	Flat, purpose built	**3%**	0%	2%	0%	3%	0%
	Flat, converted	**2%**	0%	2%	0%	0%	0%
	Bungalow	**7%**	4%	10%	13%	10%	12%
	Terrace	**13%**	7%	8%	2%	5%	2%
	Semi detached	**20%**	19%	24%	16%	15%	30%
	Detached	**44%**	62%	49%	36%	62%	47%
	Farmhouse	**7%**	3%	0%	24%	0%	5%
	Other	**5%**	4%	4%	9%	5%	5%

9. What is the EPC rating of your home/building?	A	**3%**	0%	4%	2%	8%	0%
	B	**6%**	7%	2%	5%	18%	0%
	C	**17%**	25%	20%	7%	74%	0%
	D	**17%**	15%	16%	18%	0%	47%
	E	**9%**	9%	10%	11%	0%	40%
	F	**3%**	1%	6%	5%	0%	12%
	G	**0%**	0%	2%	0%	0%	2%
	I do not know	**45%**	43%	39%	51%	0%	0%
10. What is your employment status?	Employed	**34%**	32%	24%	36%	33%	40%
	Self Employed	**9%**	7%	12%	15%	15%	9%
	Not Employed	**1%**	1%	0%	2%	3%	0%
	Student	**14%**	6%	2%	11%	0%	5%
	Retired	**32%**	43%	45%	31%	46%	26%
	Part time	**8%**	9%	16%	4%	0%	21%
	Prefer not to say	**1%**	1%	0%	2%	3%	0%

11. Do you work from home?	0% of the time - I do not work from home	**38%**	41%	35%	40%	33%	33%
	25% of the time - Sometimes	**23%**	29%	16%	13%	33%	21%
	50% of the time	**7%**	3%	10%	7%	10%	7%
	75% of the time - Often	**15%**	12%	12%	25%	5%	23%
	100% of the time - I always work from home	**17%**	15%	27%	15%	18%	16%
12. To what extent do you consider yourself aware of environmental issues?	Extremely	**27%**	22%	22%	38%	36%	14%
	Very	**46%**	56%	47%	44%	44%	63%
	Moderately	**25%**	22%	27%	16%	21%	21%
	Slightly	**2%**	0%	4%	2%	0%	2%
	Not at all	**0%**	0%	0%	0%	0%	0%
13. How interested are you in sustainability?	Extremely	**31%**	28%	24%	42%	38%	26%
	Very	**50%**	51%	57%	44%	41%	58%
	Moderately	**17%**	18%	16%	15%	18%	16%
	Slightly	**1%**	1%	2%	0%	3%	0%
	Not at all	**0%**	1%	0%	0%	0%	0%

14. Are you interested in installing your own sustainable low emissions technologies at home?	Definitley	**39%**	35%	45%	42%	54%	30%
	Probably	**28%**	32%	20%	29%	21%	37%
	Possibly	**24%**	25%	27%	22%	23%	28%
	Probably not	**7%**	6%	6%	7%	3%	2%
	Definitley not	**3%**	1%	2%	0%	0%	2%
15. How concerned are you about your cost of energy?	No concern. I have no concern regarding affording energy	**8%**	12%	6%	11%	13%	12%
	Occasionally concerned	**17%**	21%	27%	13%	18%	26%
	Sometimes concerned	**53%**	50%	51%	53%	51%	49%
	Regularly concerned. It is often difficult to afford to pay my energy bills	**18%**	18%	16%	15%	15%	12%
	Yes, always concerned. I cannot afford to pay for my energy	**3%**	0%	0%	9%	3%	2%

16. Do you actively take measures to reduce your energy consumption?	No. I do not take active measures	**2%**	3%	0%	4%	0%	2%
	Sometimes. When I am able	**25%**	24%	27%	20%	21%	16%
	Yes. I actively take measures to reduce energy consumption	**72%**	74%	73%	76%	79%	81%
17. Does your building include any of the following features?	Double/triple Glazing	**86%**	85%	88%	91%	100%	86%
	Insulation	**87%**	91%	96%	87%	100%	93%
	electric vehicle charging point	**8%**	7%	12%	7%	10%	0%
	Heat pump	**9%**	3%	16%	16%	21%	0%
	Smart meter	**44%**	56%	45%	22%	69%	42%
	Energy efficient lighting	**89%**	90%	98%	89%	97%	91%
18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [Less than 10 degrees]	Winter	**1%**	0%	0%	0%	0%	0%
	Spring	**9%**	7%	6%	16%	13%	12%
	Summer	**30%**	29%	33%	42%	38%	35%
	Autumn	**5%**	6%	2%	9%	8%	5%

18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [10 - 15 degrees]	Winter	**3%**	3%	4%	4%	0%	5%
	Spring	**15%**	15%	20%	15%	21%	16%
	Summer	**10%**	13%	14%	7%	13%	9%
	Autumn	**9%**	9%	10%	13%	8%	14%
18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [16 - 20 degrees]	Winter	**44%**	46%	53%	51%	64%	56%
	Spring	**34%**	40%	41%	33%	49%	42%
	Summer	**19%**	16%	29%	16%	28%	23%
	Autumn	**37%**	46%	43%	36%	46%	44%
18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [21- 25 degrees]	Winter	**19%**	24%	20%	16%	23%	14%
	Spring	**6%**	9%	6%	5%	10%	2%
	Summer	**3%**	4%	2%	2%	5%	0%
	Autumn	**7%**	12%	6%	5%	18%	2%
18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [26 - 30 degrees]	Winter	**0%**	1%	0%	0%	3%	0%
	Spring	**0%**	0%	0%	0%	0%	0%
	Summer	**0%**	1%	0%	0%	3%	0%
	Autumn	**0%**	0%	0%	0%	0%	0%

18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [30+ degrees]	Winter	**0%**	0%	0%	0%	0%	0%
	Spring	**0%**	0%	0%	0%	0%	0%
	Summer	**0%**	0%	0%	0%	0%	0%
	Autumn	**0%**	0%	0%	0%	0%	0%
18.a. What rough temperature do you usually set your thermostat or equivalent throughout the year? [I do not have temperature control]	Winter	**11%**	9%	18%	9%	3%	9%
	Spring	**11%**	38%	53%	47%	67%	60%
	Summer	**12%**	41%	57%	51%	72%	65%
	Autumn	**10%**	35%	49%	44%	62%	56%
18.c. Is that in Celsius or Fahrenheit?	Celsius	**84%**	85%	84%	82%	90%	88%
	Farenheit	**1%**	3%	2%	0%	3%	0%
19. What energy fuels do you use? [Electricity]	Heating	**32%**	31%	43%	33%	49%	26%
	Power	**93%**	96%	90%	89%	97%	93%
	Cooking	**79%**	84%	90%	78%	82%	88%
	Transport	**7%**	7%	10%	4%	10%	0%
	I do not use	**0%**	0%	0%	2%	0%	0%

19. What energy fuels do you use? [Mains Gas]	Heating	**47%**	90%	2%	0%	49%	37%
	Power	**1%**	3%	0%	0%	3%	0%
	Cooking	**26%**	44%	2%	0%	26%	16%
	Transport	**0%**	0%	0%	0%	0%	0%
	I do not use	**51%**	6%	98%	100%	46%	63%
19. What energy fuels do you use? [Bottled Gas]	Heating	**6%**	3%	6%	13%	3%	7%
	Power	**0%**	0%	0%	0%	0%	0%
	Cooking	**15%**	1%	27%	31%	10%	19%
	Transport	**0%**	0%	0%	0%	0%	0%
	I do not use	**82%**	97%	69%	60%	90%	77%
19. What energy fuels do you use? [Oil]	Heating	**27%**	0%	53%	62%	21%	35%
	Power	**0%**	0%	0%	0%	0%	0%
	Cooking	**4%**	0%	0%	15%	0%	2%
	Transport	**1%**	3%	0%	0%	3%	2%
	I do not use	**71%**	97%	47%	35%	77%	63%

19. What energy fuels do you use? [Coal]	Heating	**25%**	22%	43%	29%	26%	35%
	Power	**0%**	0%	0%	0%	0%	0%
	Cooking	**0%**	0%	2%	0%	0%	0%
	Transport	**1%**	0%	2%	2%	0%	0%
	I do not use	**73%**	78%	53%	69%	74%	65%
19. What energy fuels do you use? [Diesel]	Heating	**1%**	1%	0%	2%	3%	2%
	Power	**1%**	0%	2%	2%	0%	0%
	Cooking	**0%**	0%	0%	0%	0%	0%
	Transport	**61%**	54%	57%	95%	59%	81%
	I do not use	**37%**	44%	41%	2%	38%	16%
19. What energy fuels do you use? [Petrol]	Heating	**0%**	0%	0%	2%	0%	2%
	Power	**0%**	0%	0%	2%	0%	0%
	Cooking	**0%**	0%	0%	0%	0%	0%
	Transport	**60%**	69%	61%	55%	62%	56%
	I do not use	**39%**	31%	39%	44%	38%	42%
19. What energy fuels do you use? [Peat/turf]	Heating	**2%**	0%	2%	5%	0%	7%
	Power	**0%**	0%	0%	0%	0%	0%
	Cooking	**0%**	0%	0%	0%	0%	0%
	Transport	**1%**	0%	2%	2%	0%	0%
	I do not use	**97%**	100%	96%	95%	100%	93%

19. What energy fuels do you use? [Wood]	Heating	**56%**	53%	80%	84%	67%	74%
	Power	**0%**	0%	0%	0%	0%	0%
	Cooking	**3%**	4%	4%	4%	0%	7%
	Transport	**0%**	0%	0%	0%	0%	0%
	I do not use	**44%**	49%	18%	16%	33%	26%
20. Heat/hot water supply. How do you get your heat/hot water?	Gas boiler	**52%**	93%	8%	11%	51%	47%
	Oil boiler	**26%**	0%	53%	58%	21%	35%
	Electric boiler	**7%**	4%	8%	7%	5%	0%
	Biomass boiler	**2%**	0%	6%	2%	3%	5%
	Heat pump	**7%**	3%	12%	15%	21%	0%
	Electric heater	**15%**	10%	20%	20%	13%	16%
	(District) Heat network	**0%**	0%	0%	0%	0%	0%
	Solar thermal	**7%**	7%	14%	7%	10%	7%
	Other	**12%**	9%	16%	20%	10%	16%
21. How is your building typically heated?	Central heating	**71%**	84%	53%	56%	74%	60%
	Electric	**3%**	0%	8%	0%	3%	2%
	Fireplace	**17%**	13%	24%	27%	15%	26%
	Other	**8%**	3%	14%	16%	8%	12%

22. Storage. Do you store energy on site? [Please select all that apply]	Electric battery	**5%**	6%	6%	7%	10%	2%
	Hot water cylinder	**41%**	35%	53%	55%	46%	40%
	Heating oil tank	**21%**	0%	37%	53%	18%	33%
	Gas tank	**4%**	0%	4%	9%	0%	5%
	Gas bottles	**10%**	1%	20%	18%	13%	9%
	Wood pile	**46%**	46%	61%	69%	56%	60%
	Coal store	**14%**	12%	27%	16%	15%	21%
	Other	**3%**	1%	4%	5%	3%	5%
	No	**35%**	41%	14%	11%	28%	21%
23. How do you get electricity to your building? [Please select all that apply]	National grid	**100%**	100%	100%	98%	100%	100%
	On site generator	**3%**	1%	0%	7%	5%	0%
	On site wind turbine	**0%**	0%	0%	0%	0%	0%
	On site solar panel	**20%**	18%	24%	33%	36%	19%
	Other	**0%**	0%	2%	0%	0%	2%
	I do not use	**0%**	0%	0%	0%	0%	0%

24. How do you get natural gas to your building? [Please select all that apply]	The gas grid	**51%**	100%	0%	0%	56%	35%
	Bottled gas brought in yourself	**4%**	0%	6%	9%	5%	5%
	Bottled gas delivered	**7%**	0%	12%	18%	0%	12%
	Delivered by tanker	**4%**	0%	4%	11%	0%	7%
	Other	**0%**	0%	0%	0%	0%	0%
	I do not use	**34%**	0%	78%	62%	38%	44%
25. How do you get heating fuel oil to your building? [Please select all that apply]	Bottle (brought in yourself)	**0%**	0%	0%	0%	0%	0%
	Bottle (delivered)	**0%**	0%	0%	0%	0%	0%
	Delivered by tanker	**28%**	0%	55%	67%	21%	35%
	Other	**0%**	0%	0%	0%	0%	0%
	I do not use	**72%**	100%	45%	33%	79%	65%
26. How do you get Coal to your building? [Please select all that apply]	Delivered	**10%**	10%	20%	5%	8%	9%
	Brought in by yourself	**11%**	7%	20%	16%	13%	19%
	Other	**0%**	1%	0%	0%	3%	0%
	I do not use	**80%**	82%	61%	78%	79%	72%

A.3 Survey distribution email to parish councils

Rural energy study Parish council email

Subject:

Research on rural energy consumption - RS

Dear Clerk,

I am a PhD researcher from the University of Nottingham looking at rural energy use and I have developed a survey looking to understand the way energy is consumed rurally. Particularly in recent times with the cost of living crisis, sustainability and decarbonising energy this is a key topic to gather information on. Linked below is a survey I have developed on the topic of energy usage.

Please could you distribute and discuss this within your council, local magazines (or equivalent), your wider community and specifically those who may be interested in this topic. It is a short survey that should take no longer than 5-10 minutes to complete, asking about what energy fuels are used at home and how. Attached is a document with some information on myself and the survey.

If you do not consider yourself or your community to live in a rural area, please still consider this survey as it is important to have non-rural respondents in this survey for a complete comparative analysis.

Rural energy survey [hyperlink to the survey]

An outcome of this survey would be to have follow up research questions on energy bills and actual energy consumption from respondents who have expressed an interest in further engagement. This survey will be open for responses for the first few months of 2023 and I will communicate the results of this survey to you in the future.

Please do not hesitate to contact me for any further information, questions and feedback regarding this research.

Kind regards,

Samir

Appendix B

SERL Smart meter derived data

B.1 SERL smart meter energy consumption profiles

Energy demand profiles of gas and electricity consumption from SERL (Smart Energy Research Lab and University College London n.d.) divided into:

- Great Britain EPC A to G and No EPC
- Rural Great Britain EPC A to G and No EPC
- User profiles P01-P05 as defined in chapter 4

Data processed and compiled by Samir Soares, University of Nottingham, 2024.
Reference for SERL data:
Soares, S., Elam, S., Webborn, E., Few, J., McKenna, E., Pullinger, M., Oreszczyn, T., Anderson, B., University of Nottingham (2024), Ministry of Housing, Communities and Local Government, European Centre for Medium-Range Weather Forecasts, Royal Mail Group Limited. (2022). Smart Energy Research Lab Observatory Data, 2019-2022: Secure Access. [data collection]. 6th Edition. UK Data Service. SN: 8666, DOI: 10.5255/UKDA-SN-8666-6

B.1.1 GB and Rural EPC average profiles

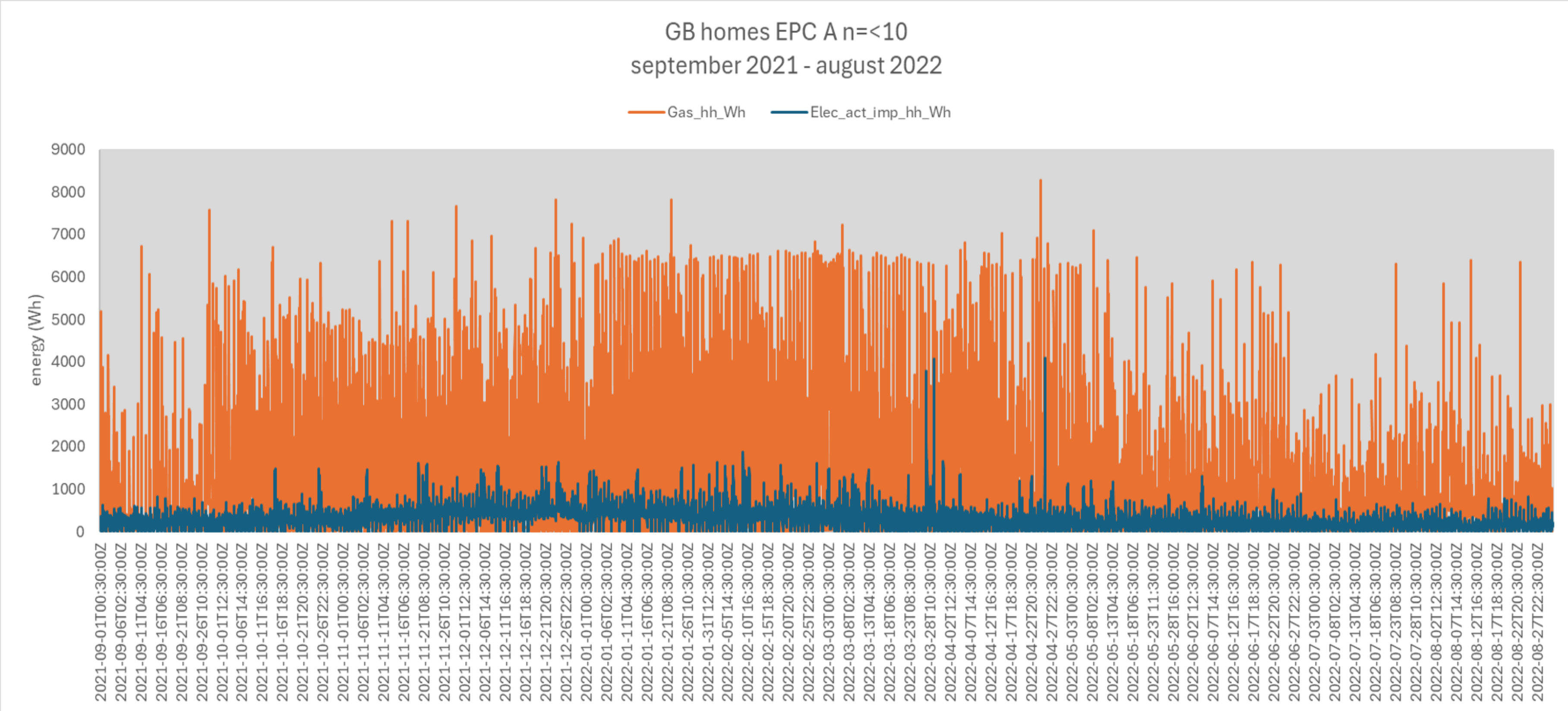


Figure B.1: Average energy demand profile of GB EPC A homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

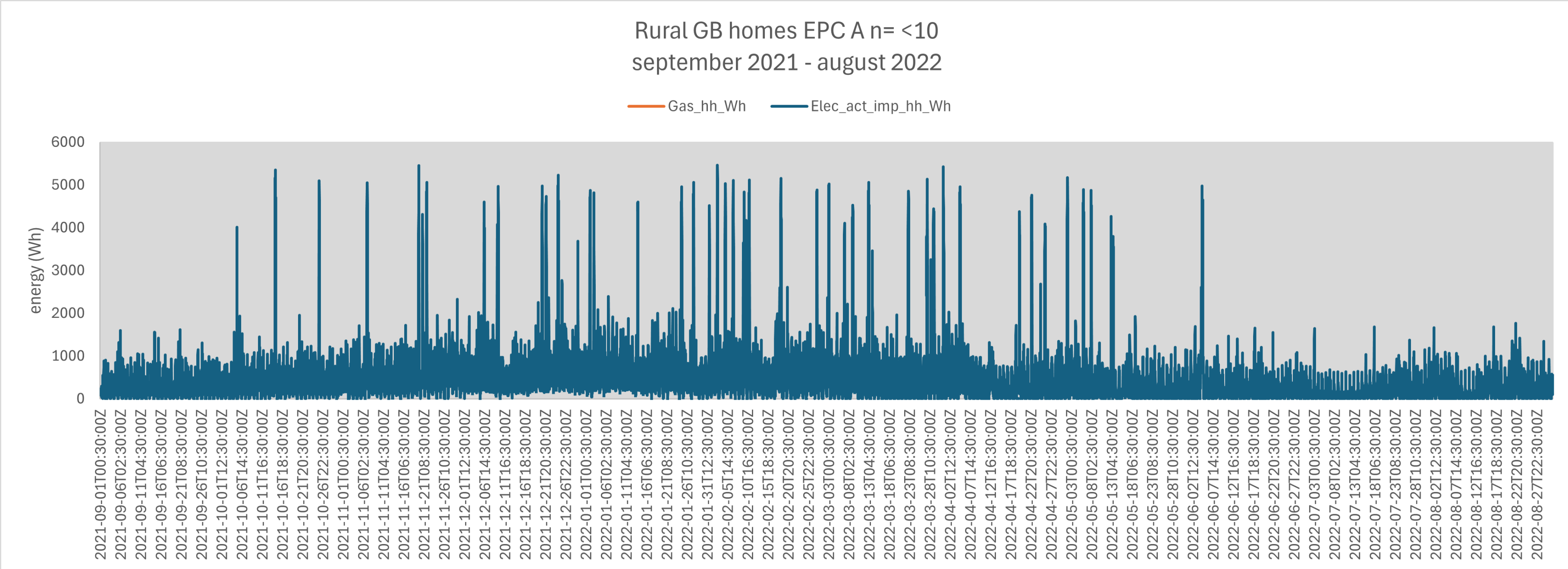


Figure B.2: Average energy demand profile of rural GB EPC A homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

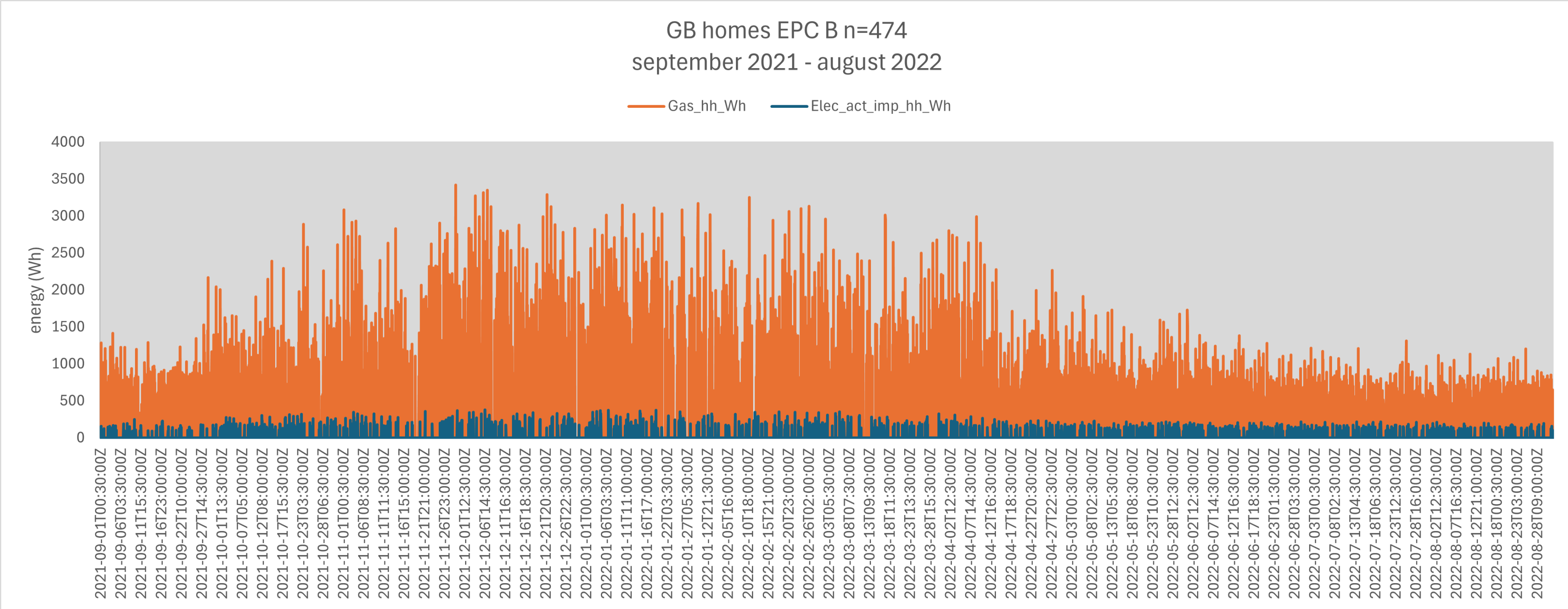


Figure B.3: Average energy demand profile of GB EPC B homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

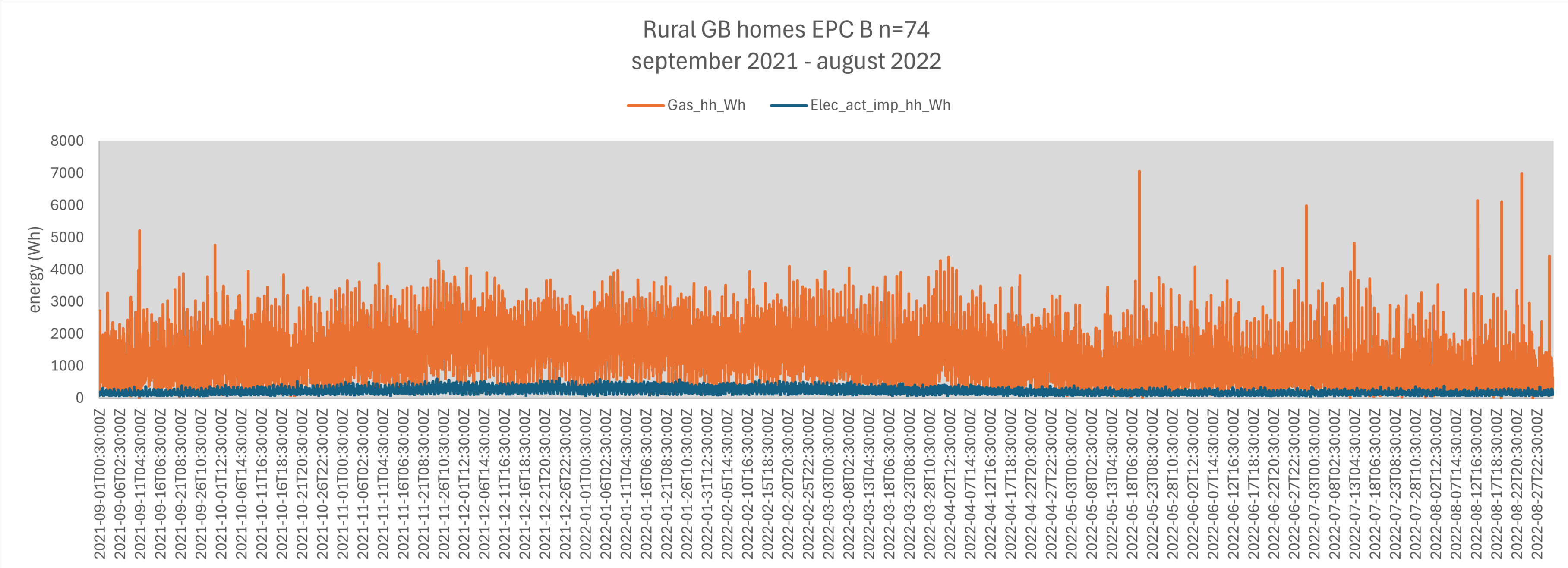


Figure B.4: Average energy demand profile of rural GB EPC B homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

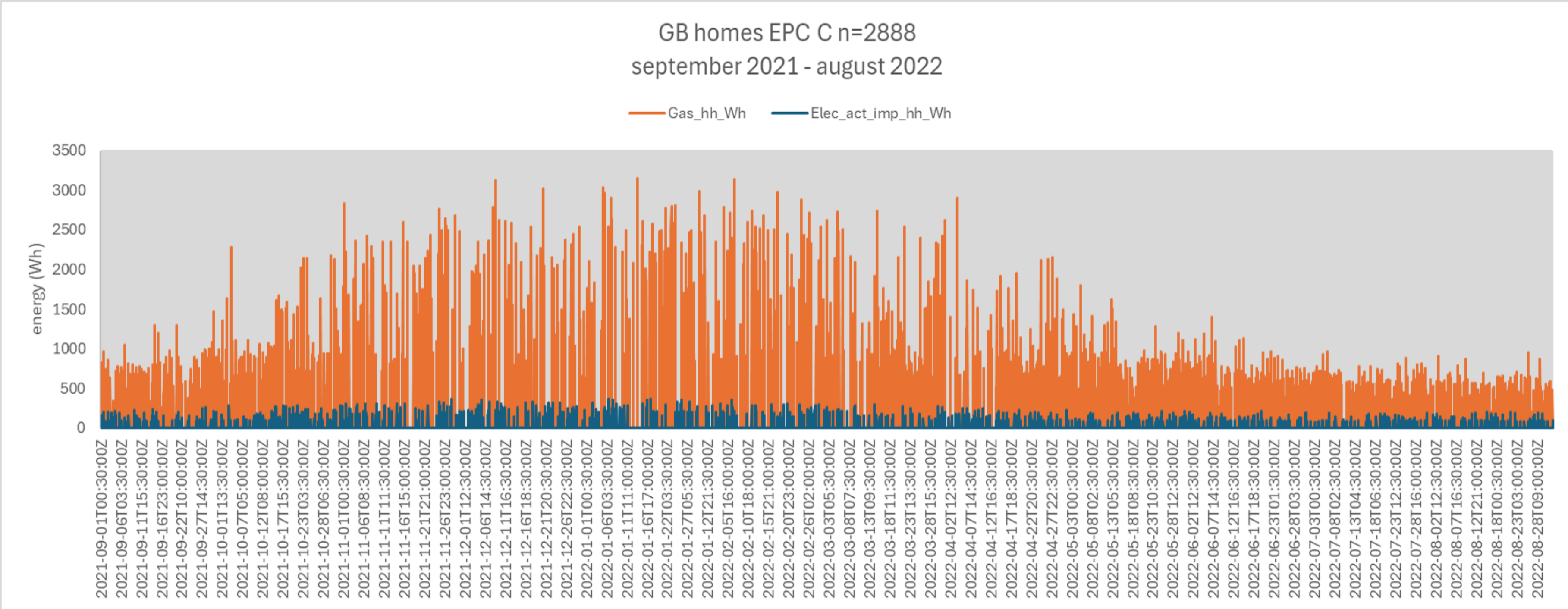


Figure B.5: Average energy demand profile of GB EPC C homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

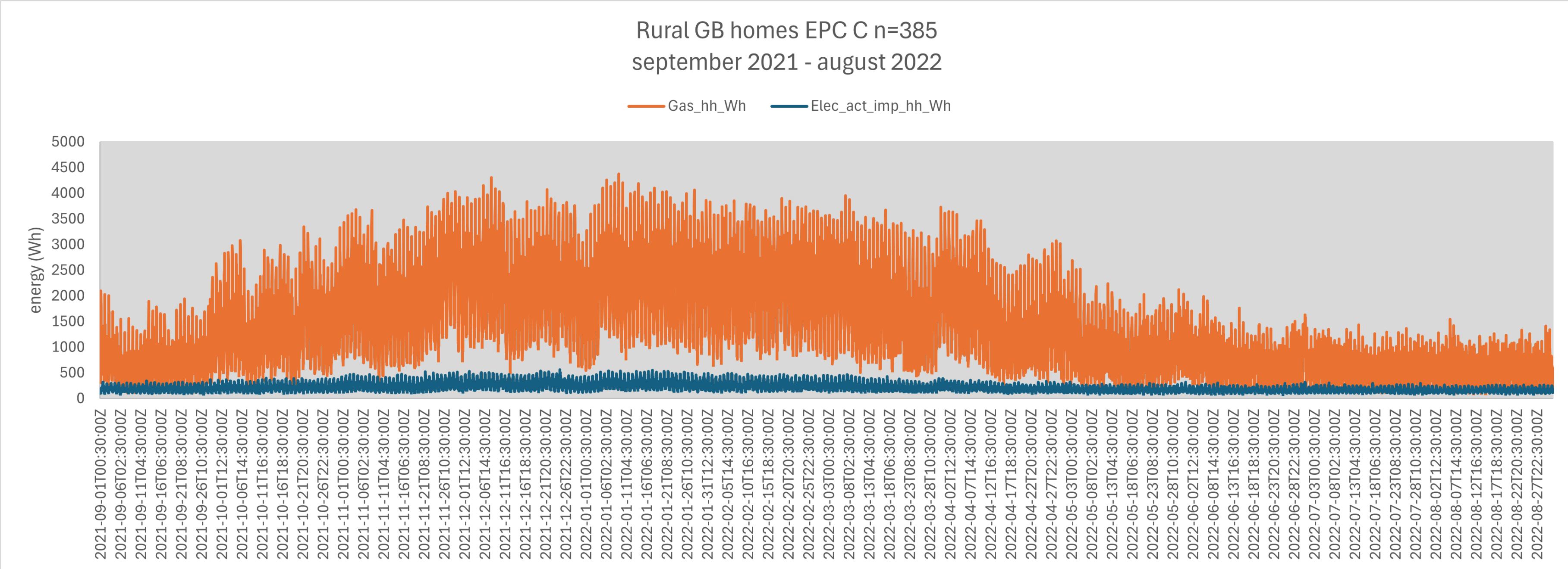


Figure B.6: Average energy demand profile of rural GB EPC C homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

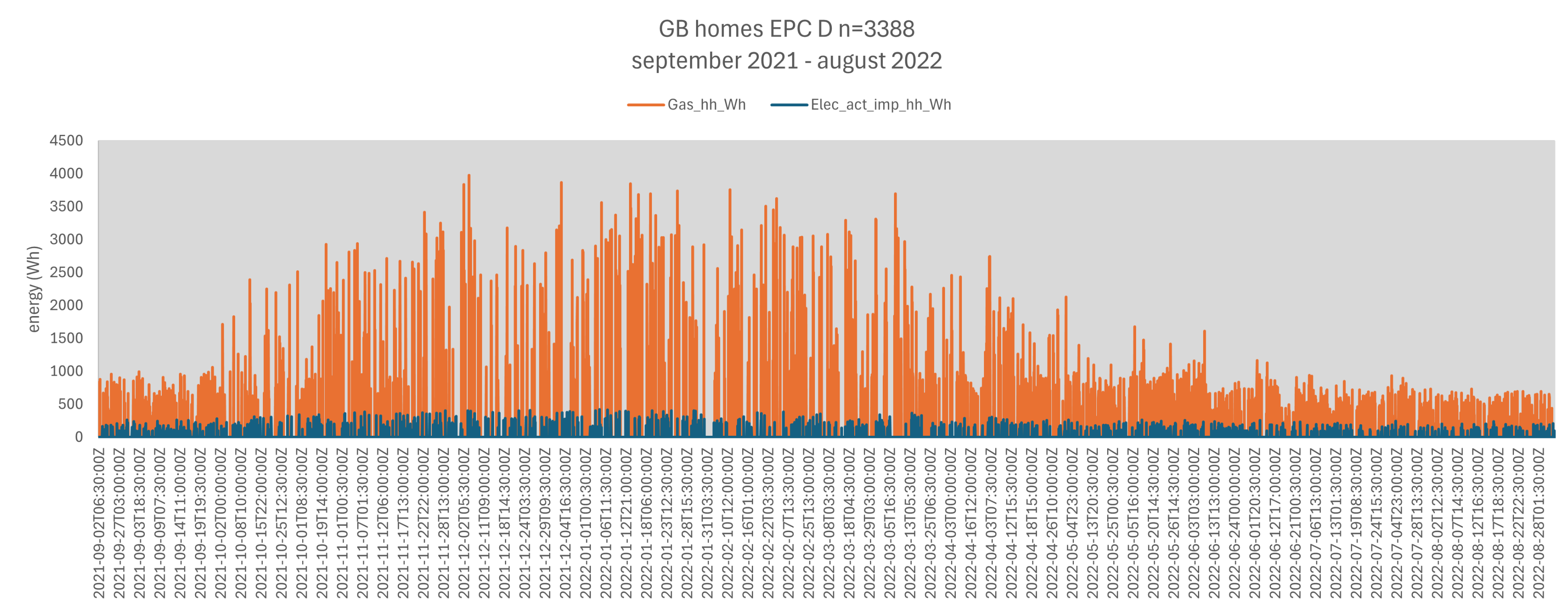


Figure B.7: Average energy demand profile of GB EPC D homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

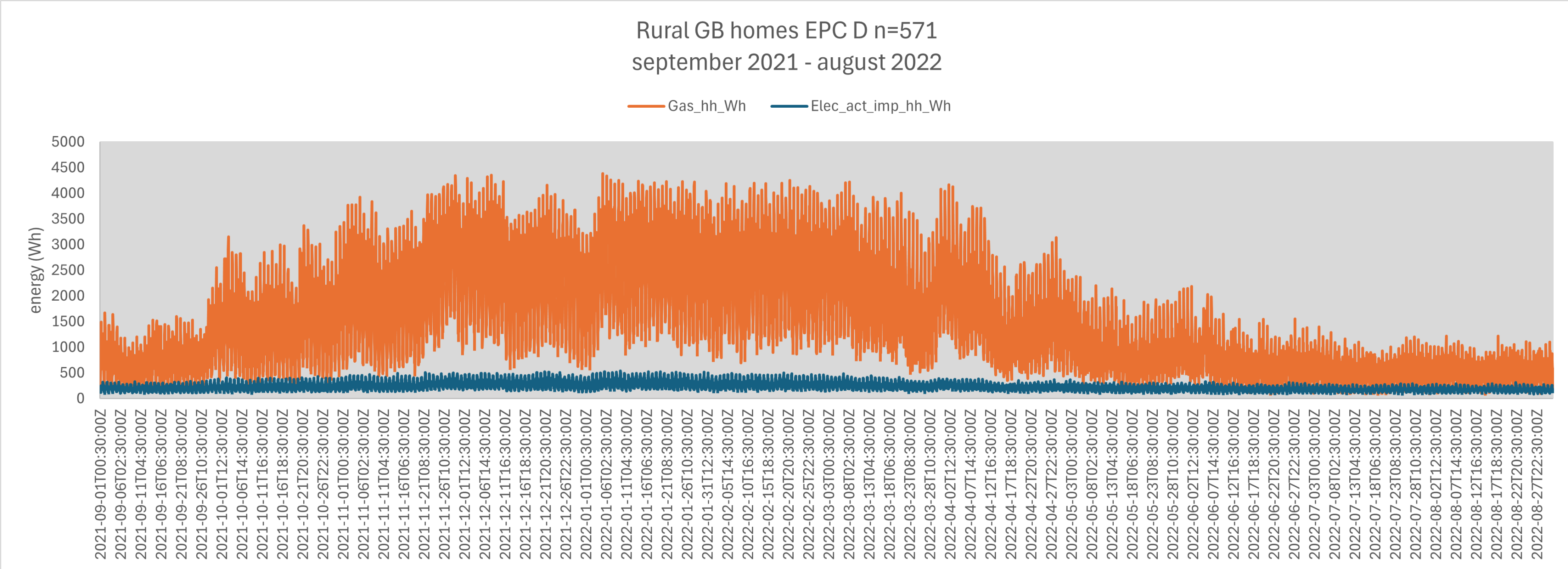


Figure B.8: Average energy demand profile of rural GB EPC D homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

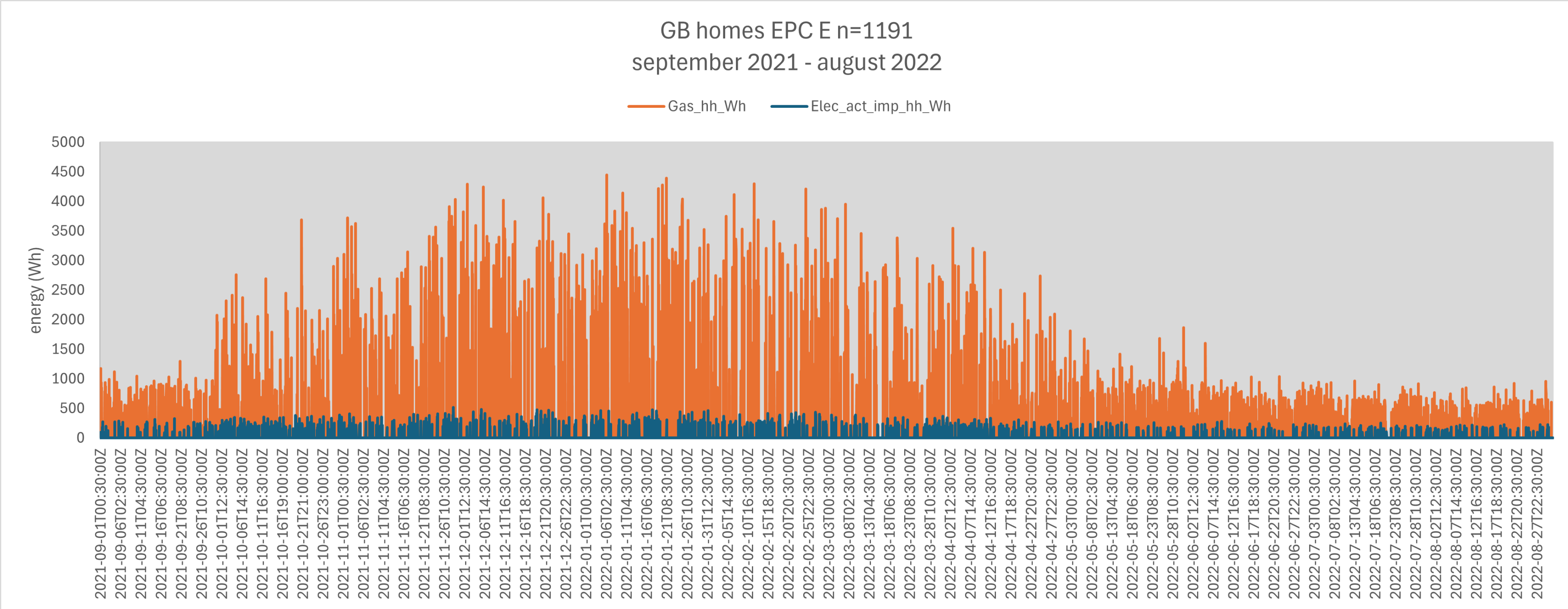


Figure B.9: Average energy demand profile of GB EPC E homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

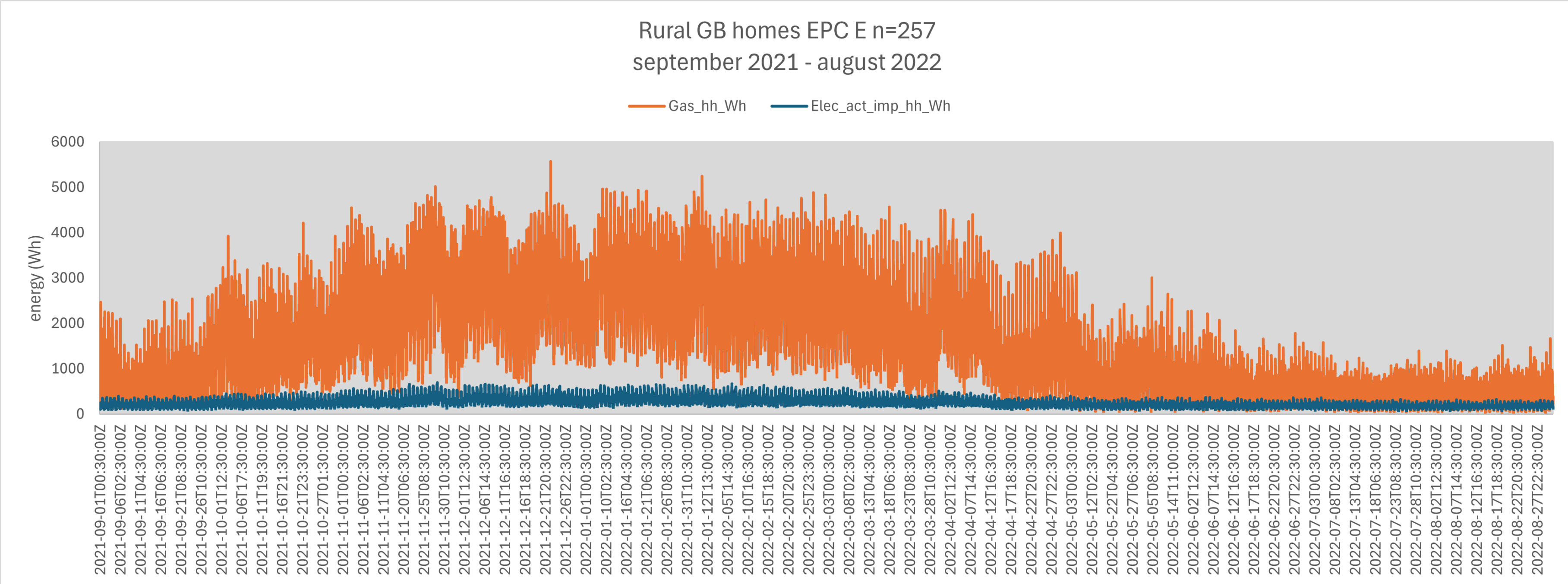


Figure B.10: Average energy demand profile of rural GB EPC E homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

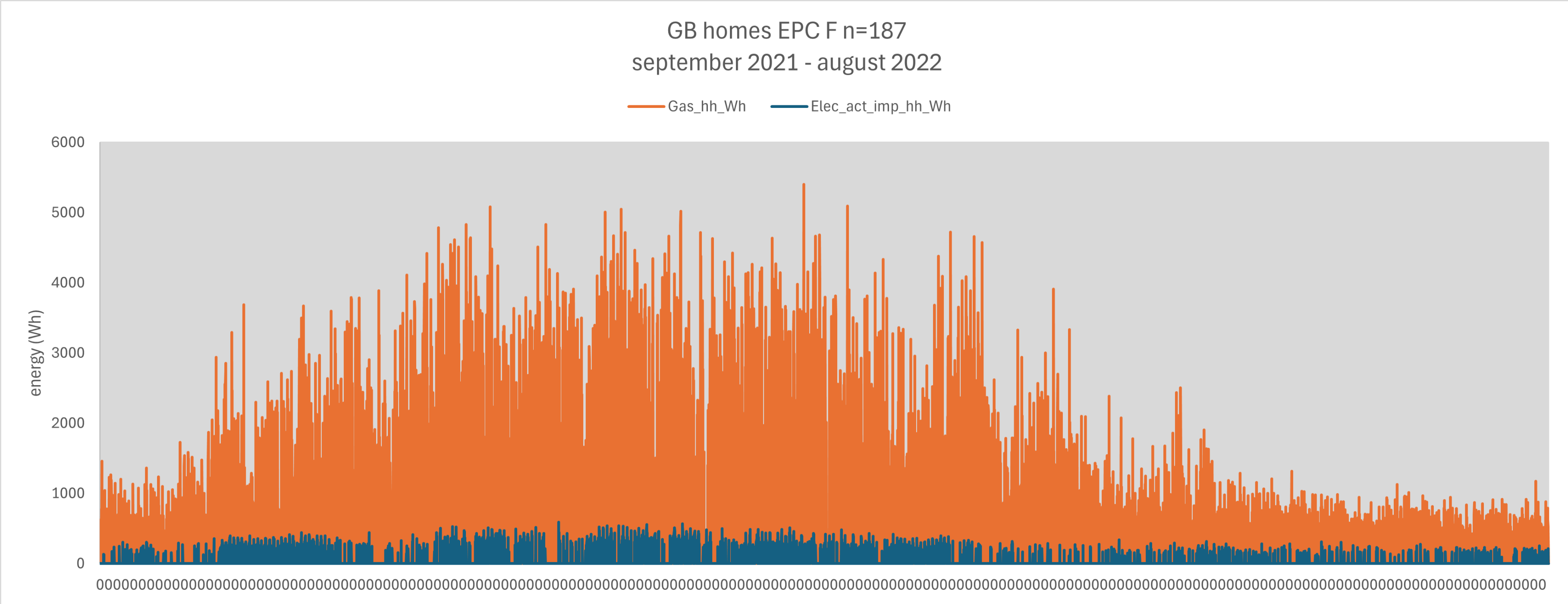


Figure B.11: Average energy demand profile of GB EPC F homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

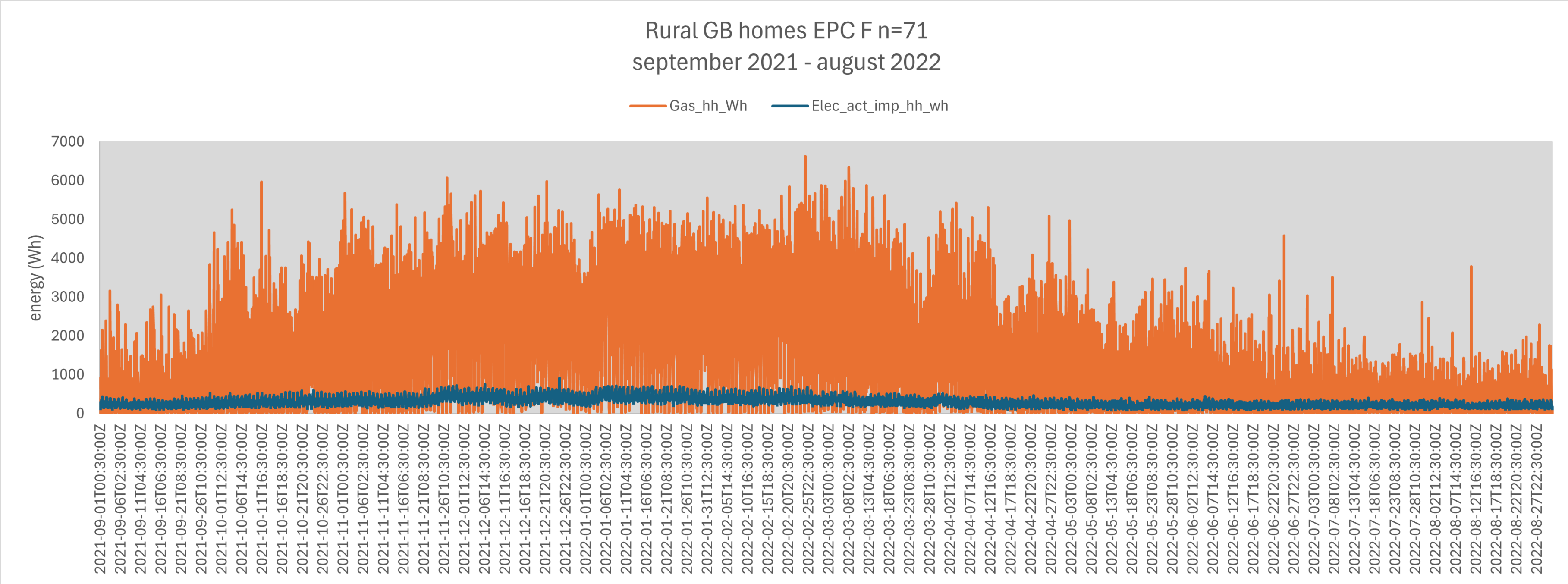


Figure B.12: Average energy demand profile of rural GB EPC F homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

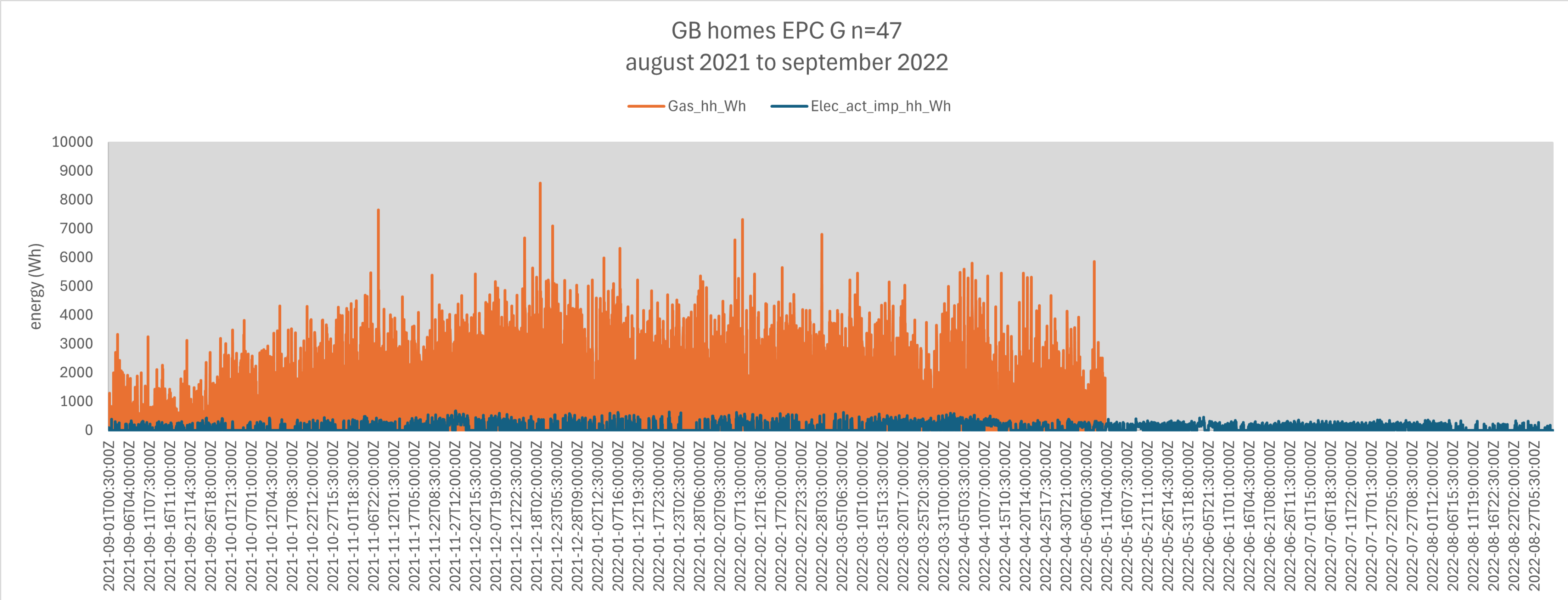


Figure B.13: Average energy demand profile of GB EPC G homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

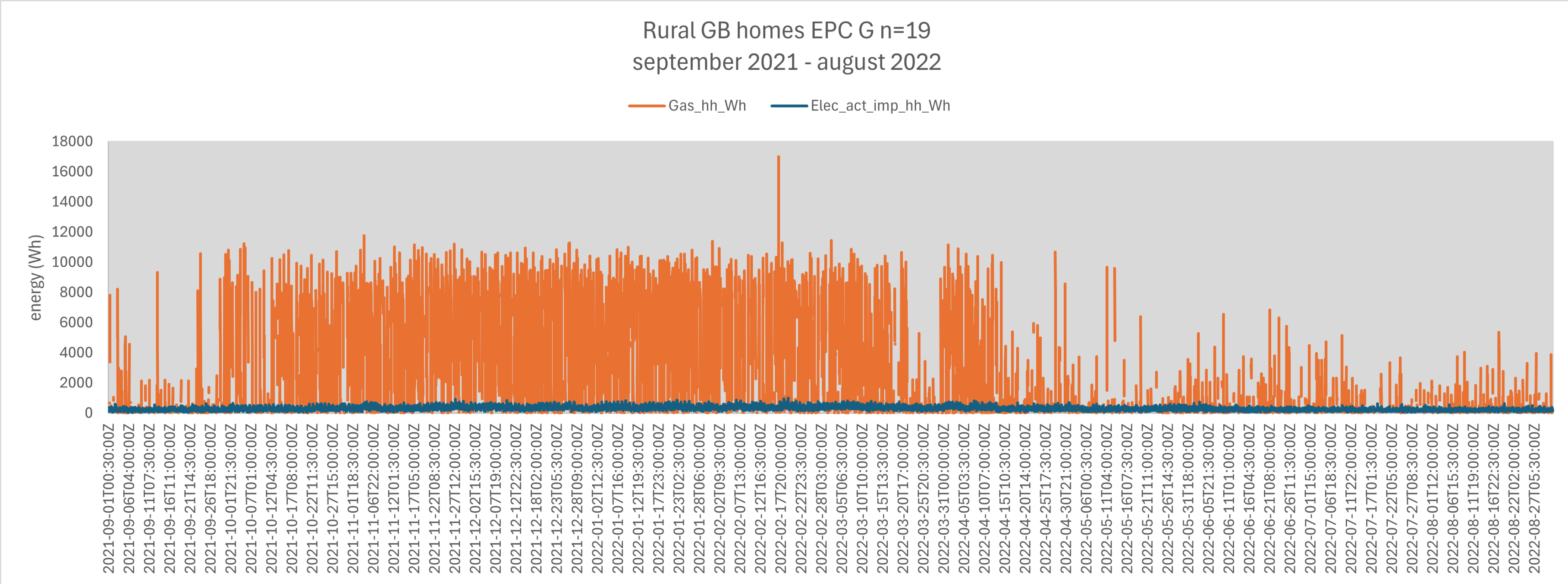


Figure B.14: Average energy demand profile of rural GB EPC G homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset

B.1.2 Rural energy user profiles P01 - P05 as defined in chapter 4

These figures are averaged from the SERL dataset according to some of the characteristics as defined in chapter 4.

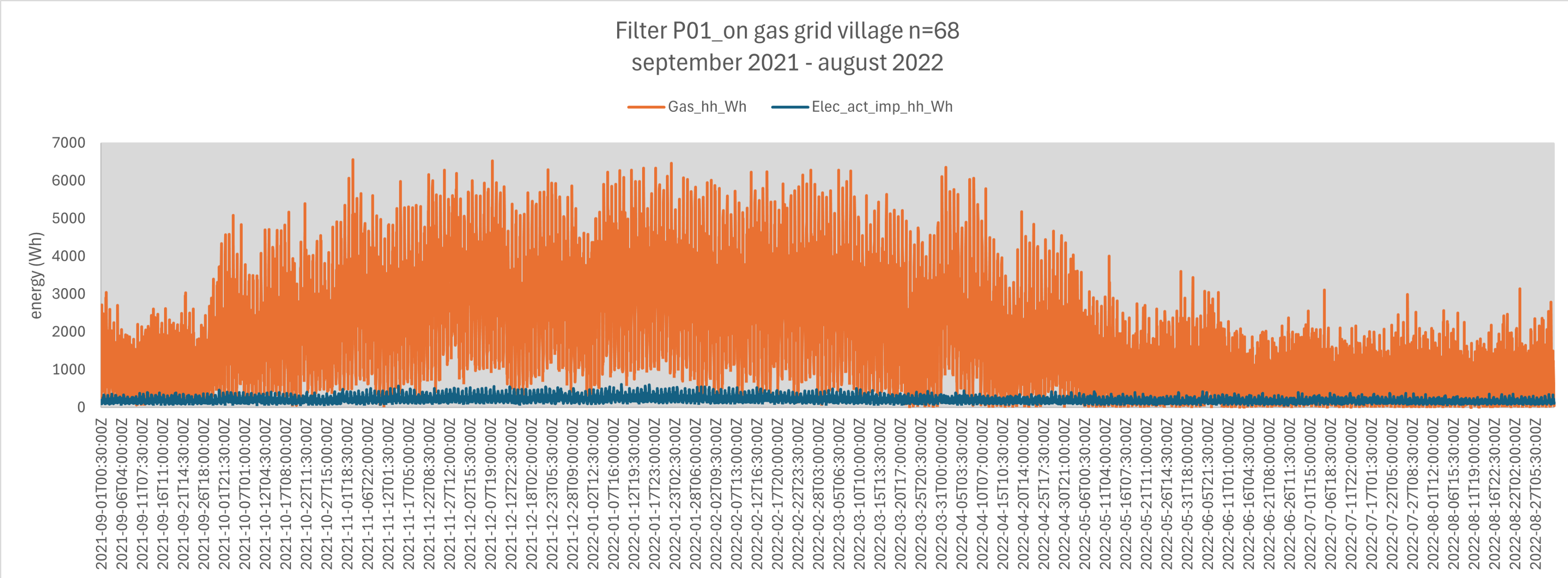


Figure B.15: Average energy demand profile of homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset and filtered according to the energy user profile P01 as defined in chapter 4

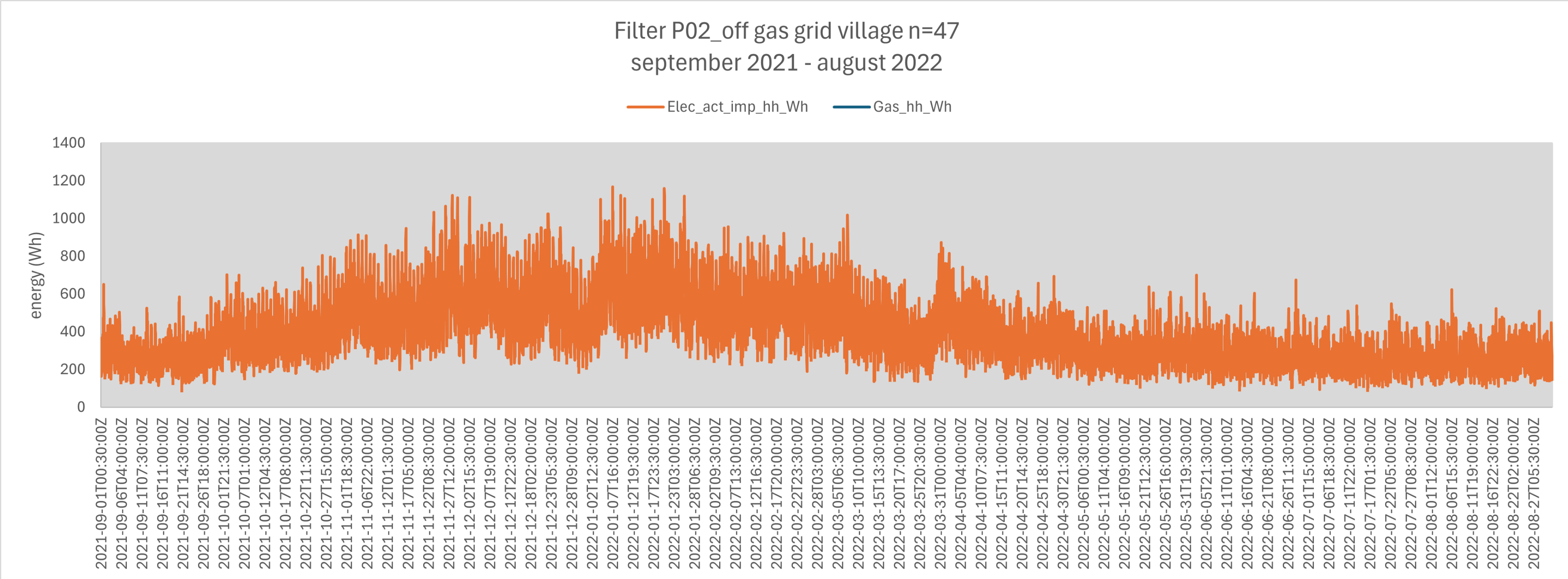


Figure B.16: Average energy demand profile of homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset and filtered according to the energy user profile P02 as defined in chapter 4

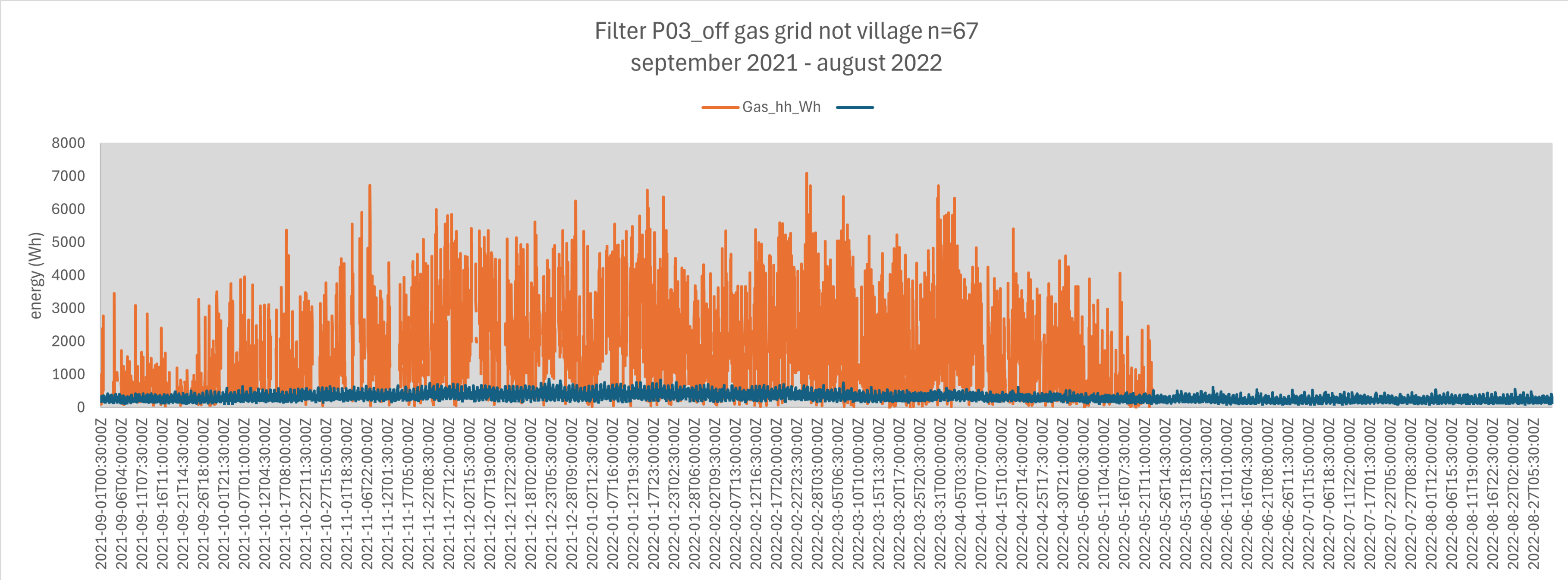


Figure B.17: Average energy demand profile of homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset and filtered according to the energy user profile P03 as defined in chapter 4

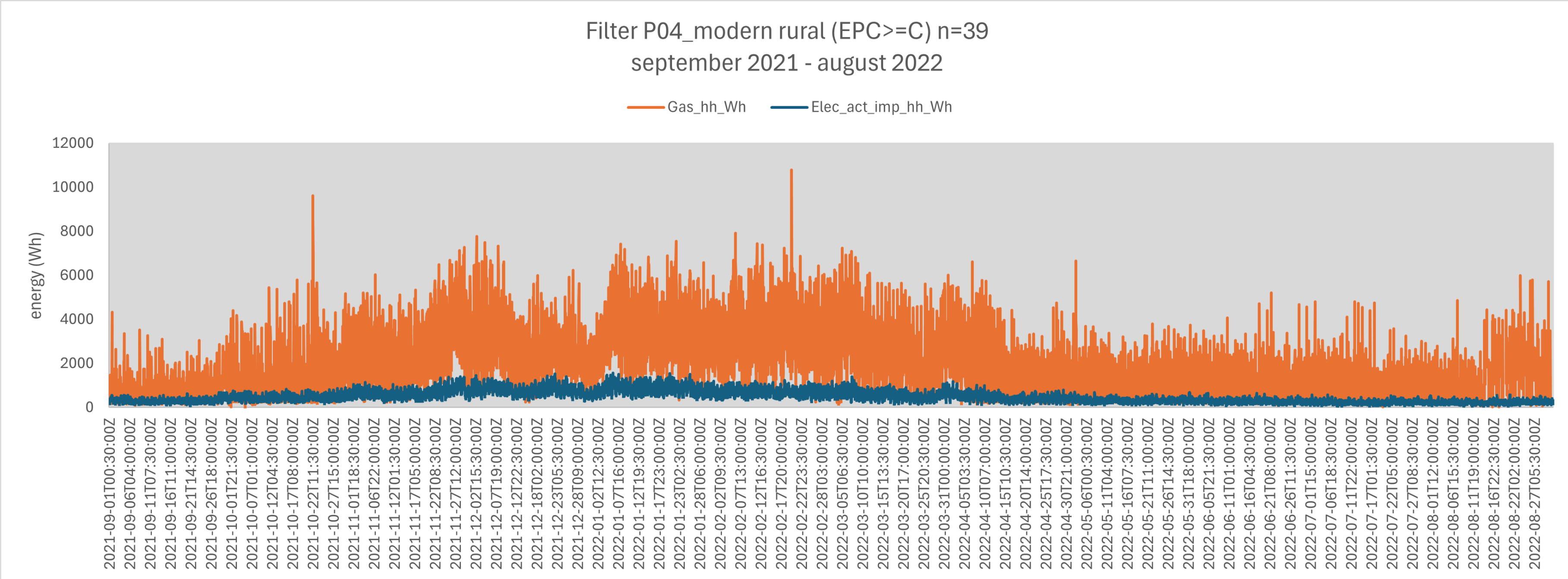


Figure B.18: Average energy demand profile of homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset and filtered according to the energy user profile P04 as defined in chapter 4

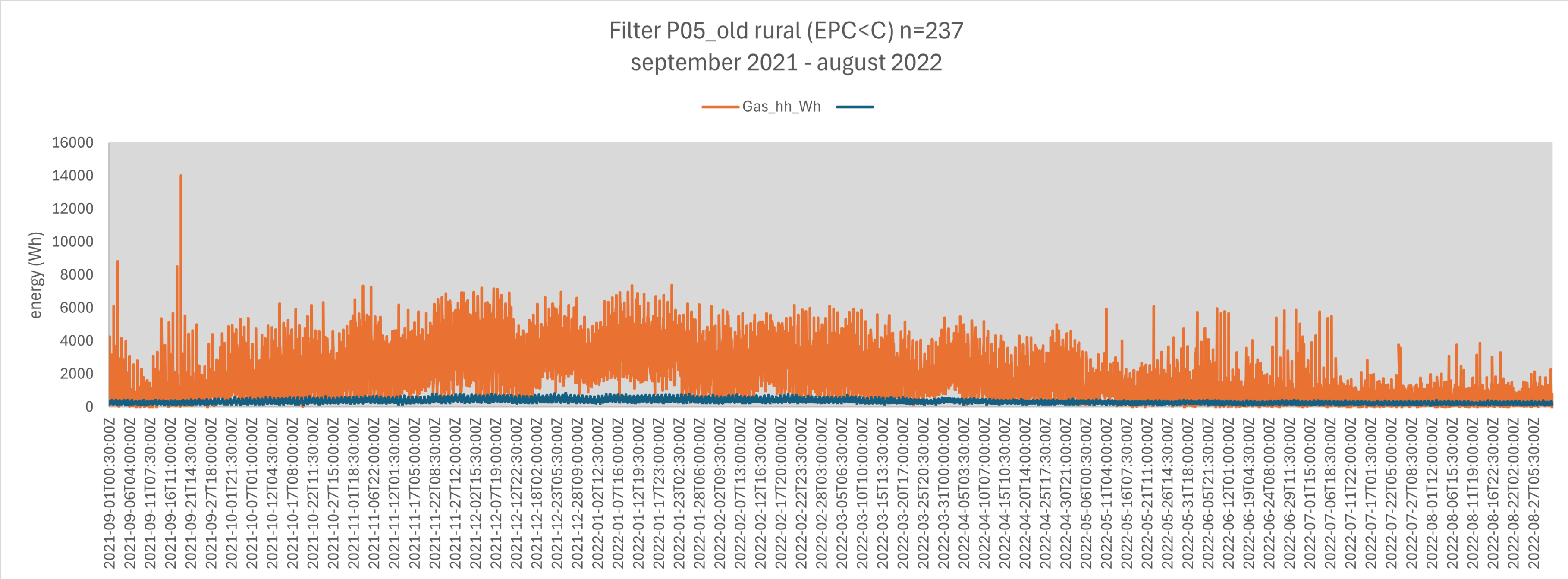


Figure B.19: Average energy demand profile of homes derived from the SERL (Smart Energy Research Lab and University College London n.d.) dataset and filtered according to the energy user profile P05 as defined in chapter 4

B.2 Results and scores from simulations with SERL data

Raw data outputs of each of the 19 simulations and the corresponding normalised min/max score.

Table B.1: All the results and scores for the existing fuels model simulations.

Iteration	Energy demand profile	Total score	Total rank	Total system efficiency		Operational cost (£/year) (£/kWh)		CO2 emissions (kg CO2e/year) (CO2e/kWh)		Capital cost of system (total) - for a new installation	
				Result	Score	Result	Score	Result	Score	Result	Score
Heat Pump	P01	***1.000***	**1**	3.5 COP	*0.0000*	£ 1,069.00	*0.0000*	671	*0.0000*	£ 15,763.92	*1.0000*
Heat Pump	P05	***1.281***	**2**	3 COP	*0.1847*	£ 1,228.00	*0.0789*	802	*0.0172*	£ 15,763.92	*1.0000*
Mains Gas	P01	***1.349***	**3**	97%	*0.9280*	£ 1,139.00	*0.0348*	3,586	*0.3833*	£ 2,787.50	*0.0029*
Mains Gas	P05	***1.427***	**4**	98%	*0.9274*	£ 1,297.00	*0.1132*	3,585	*0.3831*	£ 2,787.50	*0.0029*
Mains Gas	P04	***1.523***	**5**	98%	*0.9267*	£ 1,490.00	*0.2090*	3,594	*0.3843*	£ 2,787.50	*0.0029*
Heat Pump	P04	***1.563***	**6**	2.56 COP	*0.3450*	£ 1,429.00	*0.1787*	967	*0.0389*	£ 15,763.92	*1.0000*
Blue hydrogen	P01	***1.635***	**7**	97%	*0.9280*	£ 2,264.00	*0.5933*	913	*0.0318*	£ 3,816.67	*0.0820*
Blue hydrogen	P05	***1.701***	**8**	98%	*0.9274*	£ 2,366.00	*0.6440*	1,034	*0.0477*	£ 3,816.67	*0.0820*
Blue hydrogen	P04	***1.784***	**9**	98%	*0.9267*	£ 2,495.00	*0.7080*	1,184	*0.0674*	£ 3,816.67	*0.0820*
LPG Bottle	P01	***1.888***	**10**	97%	*0.9280*	£ 1,973.00	*0.4489*	4,079	*0.4481*	£ 3,567.51	*0.0628*
Wood	P01	***1.921***	**11**	78%	*1.0000*	£ 1,511.00	*0.2195*	815	*0.0189*	£ 11,632.82	*0.6826*
LPG Bottle	P05	***1.941***	**12**	98%	*0.9274*	£ 2,088.00	*0.5060*	4,056	*0.4450*	£ 3,567.51	*0.0628*
Wood	P05	***2.001***	**13**	79%	*0.9956*	£ 1,647.00	*0.2870*	941	*0.0355*	£ 11,632.82	*0.6826*
LPG Bottle	P04	***2.010***	**14**	98%	*0.9267*	£ 2,233.00	*0.5780*	4,038	*0.4427*	£ 3,567.51	*0.0628*
Electric boiler	P01	***2.015***	**15**	104%	*0.9021*	£ 2,894.00	*0.9062*	2,246	*0.2071*	£ 2,750.00	*0.0000*
Electric boiler	P05	***2.061***	**16**	104%	*0.9032*	£ 2,967.00	*0.9424*	2,306	*0.2150*	£ 2,750.00	*0.0000*
Wood	P04	***2.100***	**17**	80%	*0.9905*	£ 1,816.00	*0.3709*	1,096	*0.0559*	£ 11,632.82	*0.6826*
Electric boiler	P04	***2.120***	**18**	104%	*0.9046*	£ 3,063.00	*0.9901*	2,385	*0.2253*	£ 2,750.00	*0.0000*
Oil	P01	***2.181***	**19**	97%	*0.9297*	£ 1,258.00	*0.0938*	5,010	*0.5705*	£ 10,387.68	*0.5869*
Storage heater	P01	***2.241***	**20**	95%	*0.9384*	£ 1,930.00	*0.4275*	2,480	*0.2378*	£ 11,045.00	*0.6374*
Oil	P05	***2.245***	**21**	97%	*0.9290*	£ 1,406.00	*0.1673*	4,945	*0.5619*	£ 10,387.68	*0.5869*
Storage heater	P05	***2.299***	**22**	95%	*0.9371*	£ 2,036.00	*0.4801*	2,530	*0.2444*	£ 11,045.00	*0.6374*
Oil	P04	***2.326***	**23**	97%	*0.9282*	£ 1,588.00	*0.2577*	4,878	*0.5531*	£ 10,387.68	*0.5869*
Storage heater	P04	***2.360***	**24**	96%	*0.9343*	£ 2,150.00	*0.5367*	2,587	*0.2519*	£ 11,045.00	*0.6374*
Elec Tank	P01	***2.472***	**25**	100%	*0.9185*	£ 2,926.00	*0.9220*	2,346	*0.2202*	£ 8,103.13	*0.4113*
Elec Tank	P05	***2.513***	**26**	100%	*0.9185*	£ 2,993.00	*0.9553*	2,402	*0.2276*	£ 8,103.13	*0.4113*
Elec Tank	P04	***2.567***	**27**	100%	*0.9186*	£ 3,083.00	*1.0000*	2,476	*0.2373*	£ 8,103.13	*0.4113*
Grey Hydrogen	P01	***2.603***	**28**	97%	*0.9280*	£ 2,264.00	*0.5933*	8,277	*1.0000*	£ 3,816.67	*0.0820*
Grey Hydrogen	P05	***2.625***	**29**	98%	*0.9274*	£ 2,366.00	*0.6440*	8,064	*0.9720*	£ 3,816.67	*0.0820*
Grey Hydrogen	P04	***2.657***	**30**	98%	*0.9267*	£ 2,495.00	*0.7080*	7,823	*0.9403*	£ 3,816.67	*0.0820*
Coal	P01	***2.937***	**31**	79%	*0.9966*	£ 1,676.00	*0.3014*	7,980	*0.9610*	£ 11,573.16	*0.6780*
Coal	P05	***2.977***	**32**	79%	*0.9954*	£ 1,736.00	*0.3312*	8,066	*0.9723*	£ 11,573.16	*0.6780*
Coal	P04	***3.022***	**33**	80%	*0.9903*	£ 1,900.00	*0.4126*	7,828	*0.9410*	£ 11,573.16	*0.6780*

Table B.2: All the results and scores for the renewable model simulations.

Iteration	Energy demand profile	Total score	Total rank	Total system efficiency		Operational cost (£/year) (£/kWh)		CO2 emissions (kg CO2e/year) (CO2e/kWh)		Capital cost of system (total) - for a new installation	
				Result	Score	Result	Score	Result	Score	Result	Score
Heat Pump	P01	***0.302***	**1**	2.82 COP	*0.0000*	£ 1,554.00	*0.1607*	1,725	*0.0812*	£ 46,571.42	*0.0588*
Heat Pump	P05	***0.354***	**2**	2.49 COP	*0.1301*	-£ 821.00	*0.0105*	452	*0.0016*	£ 46,571.42	*0.0588*
Hybrid HP Bottled h2	P05	***0.402***	**3**	249%	*0.1293*	-£ 725.00	*0.0166*	967	*0.0338*	£ 48,084.11	*0.0705*
Hybrid HP Bottled H2	P01	***0.507***	**4**	282%	*0.0000*	£ 1,169.00	*0.1364*	5,227	*0.3002*	£ 48,084.11	*0.0705*
Heat Pump	P04	***0.643***	**5**	2.18 COP	*0.2510*	-£ 520.00	*0.0295*	571	*0.0090*	£ 46,571.42	*0.0588*
Hybrid HP Bottled h2	P04	***0.680***	**6**	219%	*0.2481*	-£ 437.00	*0.0348*	996	*0.0356*	£ 48,084.11	*0.0705*
Hybrid HP GH2 Boiler	P05	***0.715***	**7**	214%	*0.2697*	-£ 470.00	*0.0327*	706	*0.0174*	£ 53,029.11	*0.1084*
Hybrid HP GH2 Boiler	P04	***0.971***	**8**	186%	*0.3779*	-£ 226.00	*0.0481*	780	*0.0221*	£ 53,029.11	*0.1084*
Hybrid HP GH2 Boiler	P01	***1.024***	**9**	221%	*0.2415*	£ 3,221.00	*0.2662*	3,127	*0.1688*	£ 53,029.11	*0.1084*
Biomass	P05	***1.497***	**10**	97%	*0.7308*	-£ 987.00	*0.0000*	427	*0.0000*	£ 48,865.31	*0.0765*
Biomass	P04	***1.533***	**11**	98%	*0.7273*	-£ 687.00	*0.0190*	597	*0.0106*	£ 48,865.31	*0.0765*
Elec Tank	P05	***1.561***	**12**	100%	*0.7188*	-£ 83.00	*0.0572*	1,329	*0.0564*	£ 38,910.63	*0.0000*
Reference (Mains Gas)	P05	***1.569***	**13**	98%	*0.7272*	-£ 916.00	*0.0045*	2,010	*0.0990*	£ 39,312.50	*0.0031*
Biomass	P01	***1.601***	**14**	97%	*0.7293*	£ 266.00	*0.0793*	1,094	*0.0417*	£ 48,865.31	*0.0765*
Reference (Mains Gas)	P04	***1.691***	**15**	98%	*0.7264*	-£ 650.00	*0.0213*	3,540	*0.1947*	£ 39,312.50	*0.0031*
Elec Tank	P04	***1.707***	**16**	100%	*0.7187*	£ 1,153.00	*0.1354*	2,227	*0.1126*	£ 38,910.63	*0.0000*
Reference (Mains Gas)	P01	***2.070***	**17**	98%	*0.7279*	£ 284.00	*0.0804*	8,928	*0.5316*	£ 39,312.50	*0.0031*
Elec Tank	P01	***2.146***	**18**	100%	*0.7188*	£ 5,411.00	*0.4047*	5,264	*0.3025*	£ 38,910.63	*0.0000*
Green H2 Boiler	P05	***2.333***	**19**	55%	*0.8973*	£ 1,374.00	*0.1493*	2,492	*0.1291*	£ 72,136.67	*0.2552*
Green H2 Boiler	P04	***2.607***	**20**	57%	*0.8882*	£ 3,867.00	*0.3070*	4,538	*0.2571*	£ 72,136.67	*0.2552*
Green H2 Boiler	P01	***3.405***	**21**	53%	*0.9048*	£ 10,742.00	*0.7419*	9,997	*0.5984*	£ 72,136.67	*0.2552*
Green H2 FC	P05	***3.543***	**22**	30%	*0.9938*	£ 2,955.00	*0.2493*	5,272	*0.3030*	£ 169,099.17	*1.0000*
Green H2 FC	P04	***3.971***	**23**	32%	*0.9857*	£ 6,306.00	*0.4613*	8,922	*0.5312*	£ 169,099.17	*1.0000*
Green H2 FC	P01	***5.000***	**24**	29%	*1.0000*	£ 14,823.00	*1.0000*	16,419	*1.0000*	£ 169,099.17	*1.0000*

B.3 Comparing scores

Comparing the scores of results from the energyPro microgrid simulations using smart meter data from SERL (Smart Energy Research Lab and University College London n.d.). Comparing the individual scores for factors such as operational cost, capital cost, operational emissions, proportion of energy used that is locally renewably generated and potential health cost using data from (Vries et al. 2022).

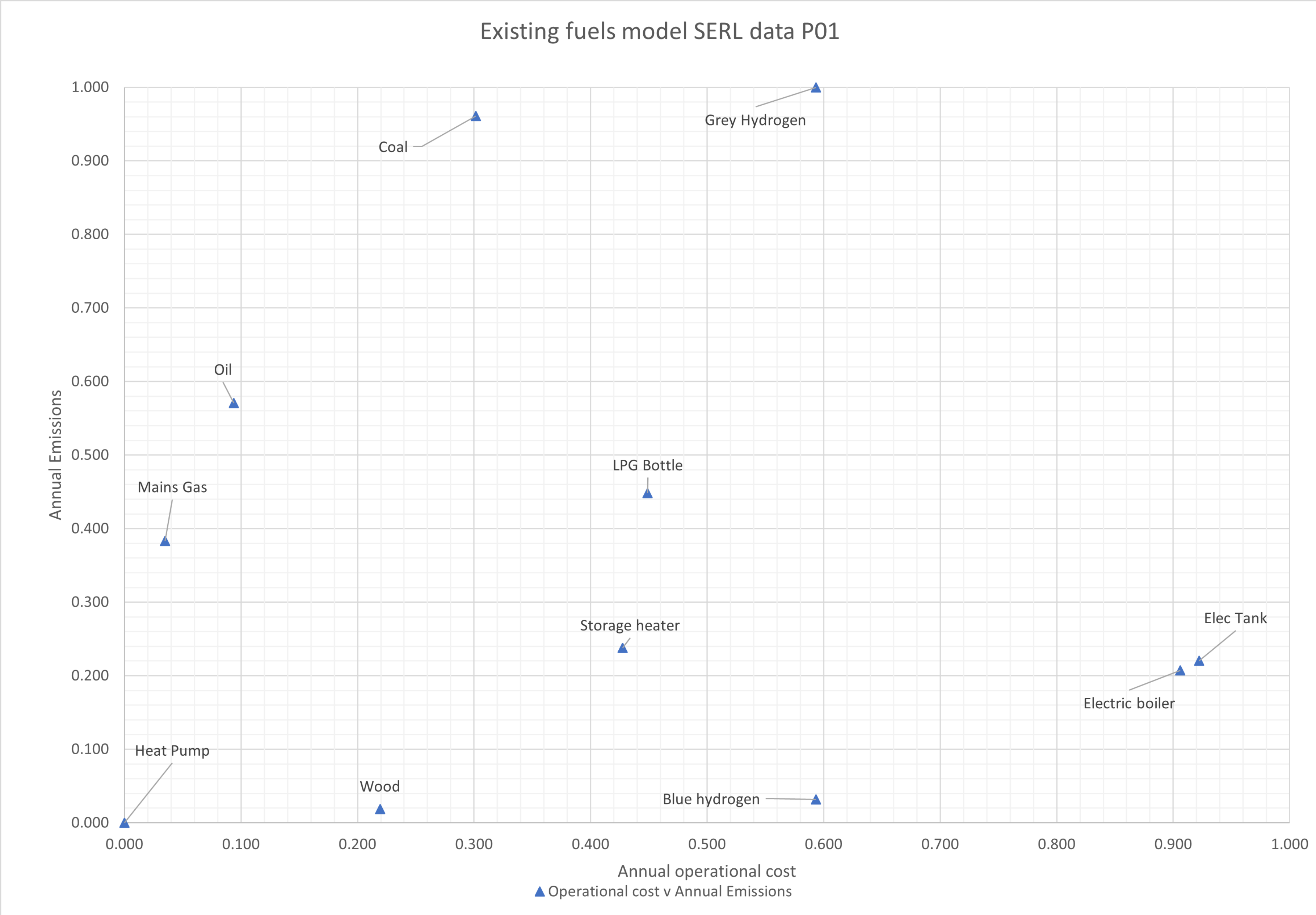


Figure B.20: Comparing annual operational cost and annual emissions scores from the existing fuels model

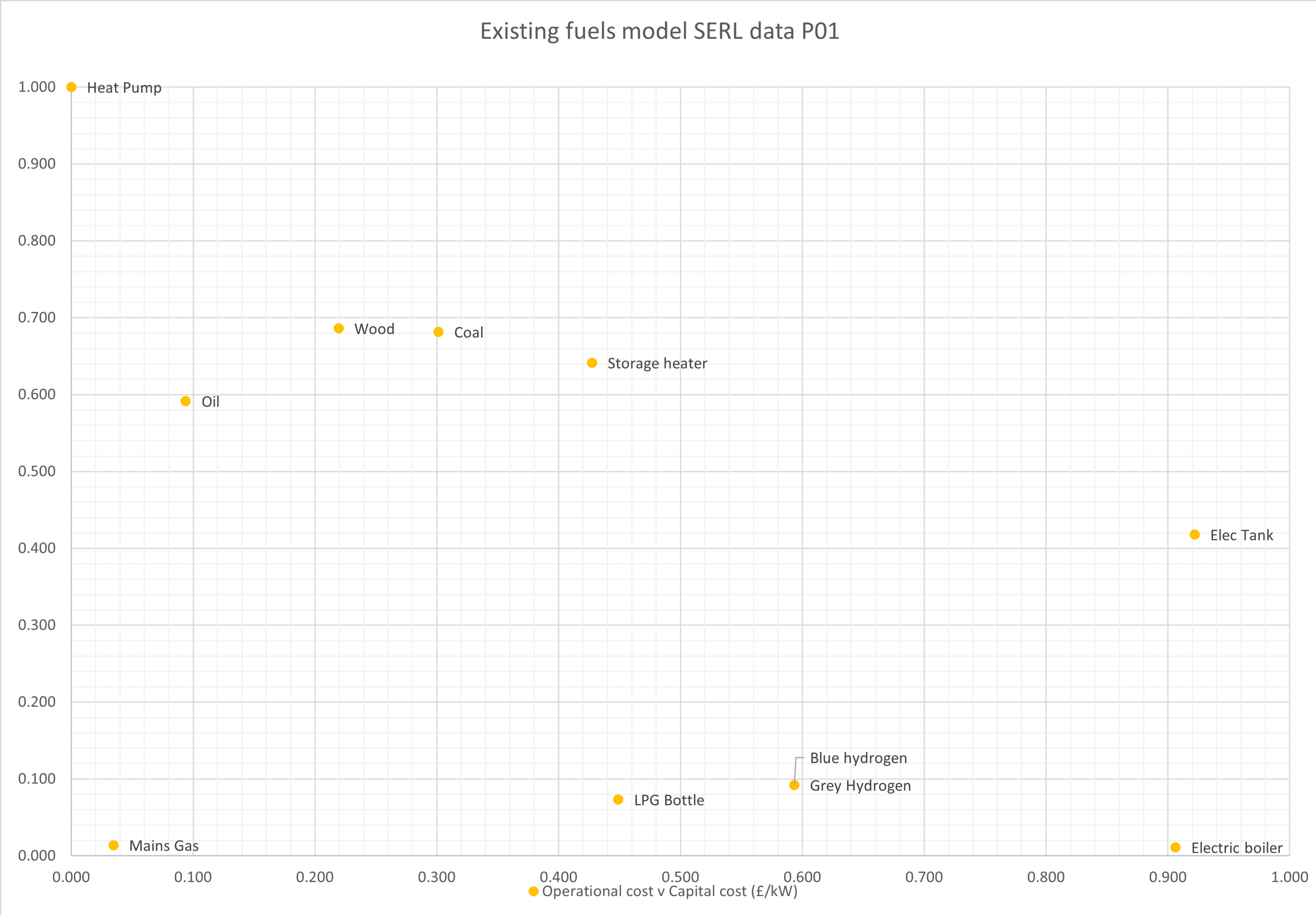


Figure B.21: Comparing annual operational cost and capital cost scores from the existing fuels model

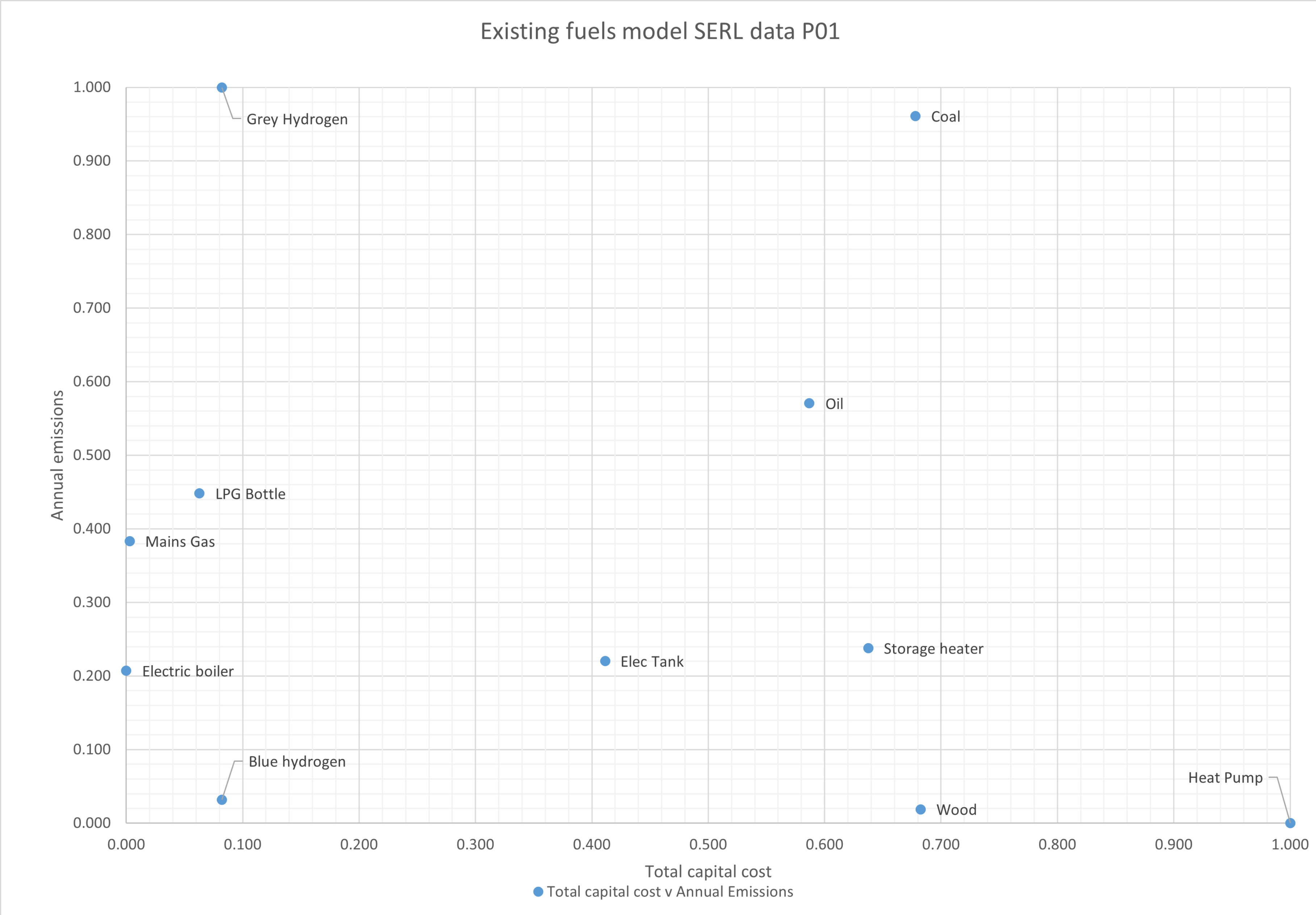


Figure B.22: Comparing annual emissions and capital cost scores from the existing fuels model

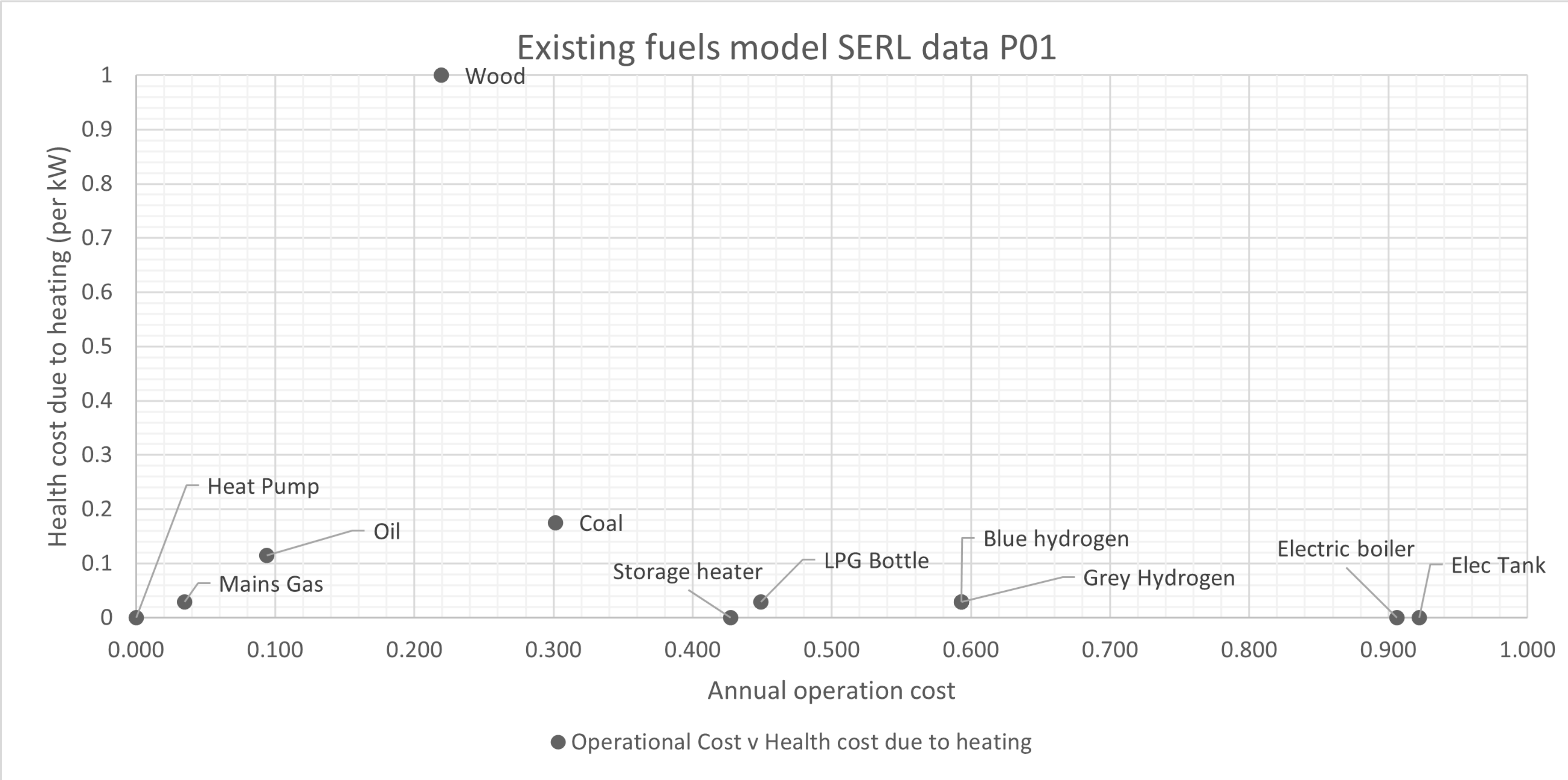
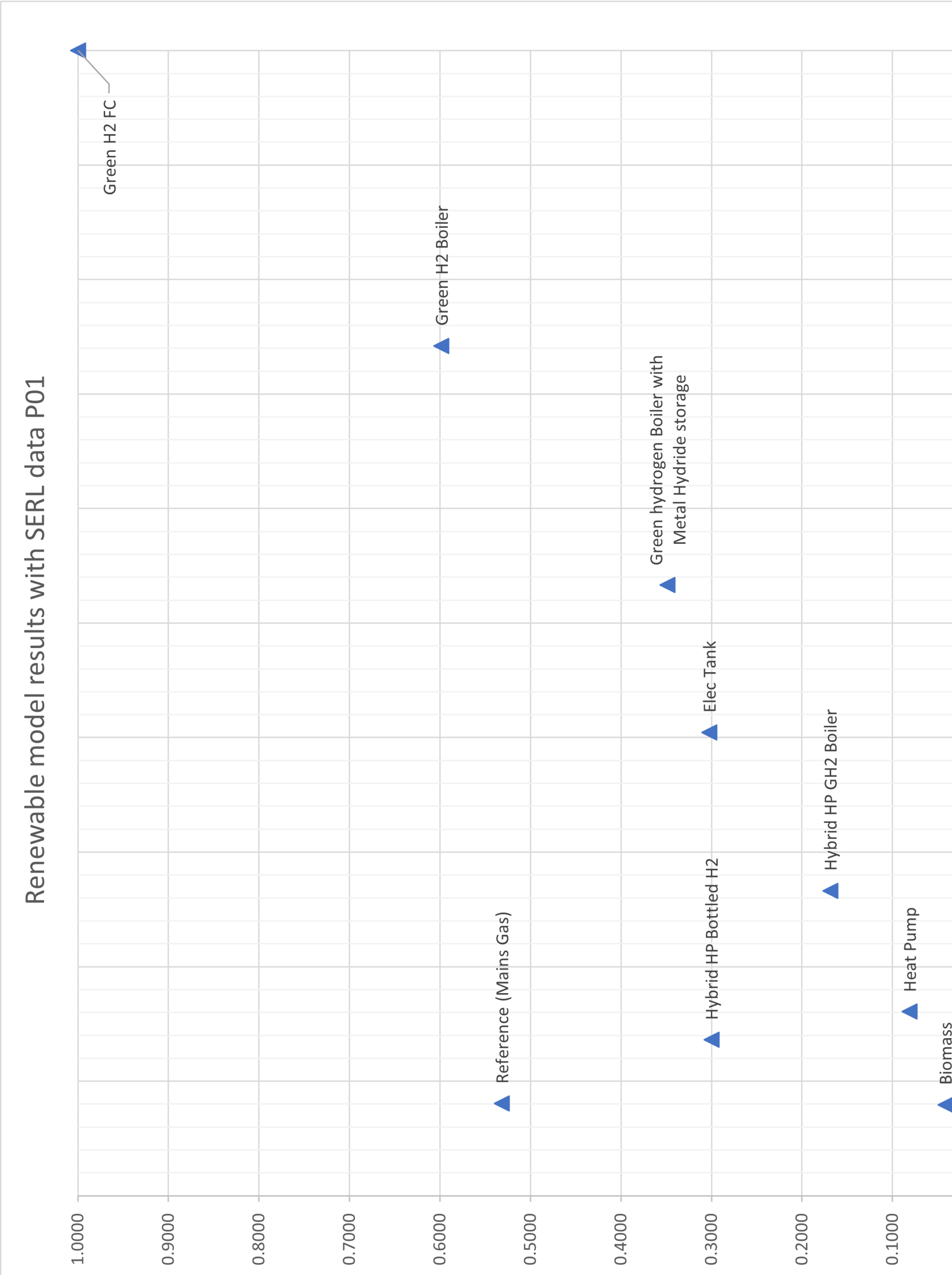
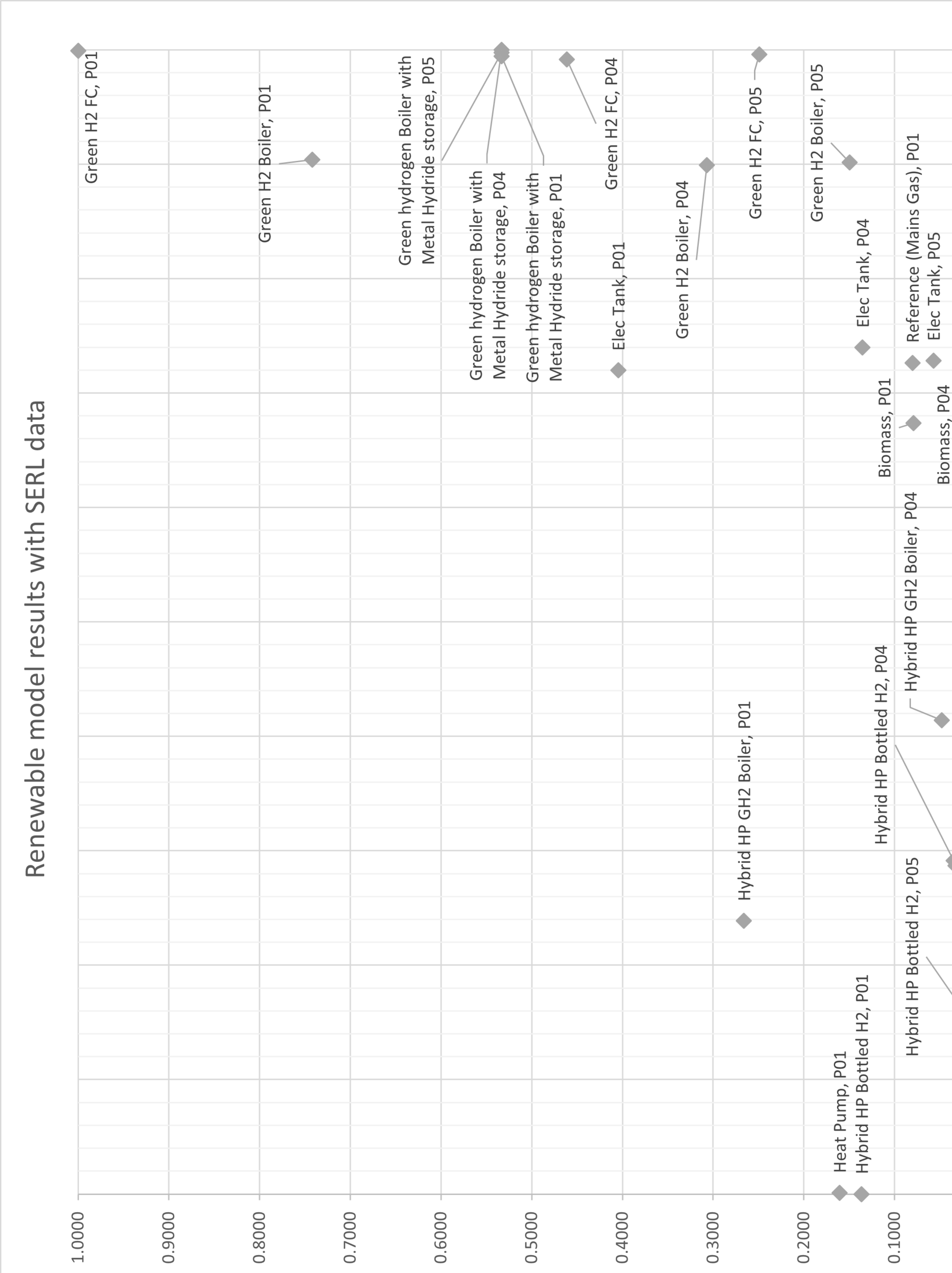


Figure B.23: Comparing annual operational cost and health cost due to heating scores from the existing fuels model



Renewable model results with SERL data P01
Green H2 FC
Green H2 Boiler
Green hydrogen Boiler with Metal Hydride storage
Elec Tank
Hybrid HP GH2 Boiler
Reference (Mains Gas)
Hybrid HP Bottled H2
Heat Pump
Biomass
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000



Renewable model results with SERL data
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
Green H2 FC, P01
Green H2 Boiler, P01
Green hydrogen Boiler with Metal Hydride storage, P05
Green hydrogen Boiler with Metal Hydride storage, P04
Green hydrogen Boiler with Metal Hydride storage, P01
Green H2 FC, P04
Elec Tank, P01
Green H2 Boiler, P04
Green H2 FC, P05
Green H2 Boiler, P05
Elec Tank, P04
Reference (Mains Gas), P01
Elec Tank, P05
Biomass, P01
Biomass, P04
Hybrid HP GH2 Boiler, P04
Hybrid HP Bottled H2, P04
Hybrid HP GH2 Boiler, P01
Hybrid HP Bottled H2, P05
Heat Pump, P01
Hybrid HP Bottled H2, P01

Appendix C

Other appendices

C.1 Calculation of the rural cost and emissions of energy

Table C.1: Calculation of the increased cost and increased emissions a rural resident would incur for one unit of energy compared to an urban resident

Urban		**United Kingdom**	**Rural**	
82%	54,671,710	Population (67,081,000)	19%	12,410,290
11%	5,975,099	Electricity	13%	1,617,587
81%	44,354,174	Grid Gas	63%	7,860,942
3%	1,629,000	Oil	18%	2,211,348
4%	1,964,945	Communal	1%	125,759
1%	748,246	Other	5%	594,736
100.00%	**54,671,463**	**Total**	**100.00%**	**12,410,371**

* assume communal fuel is mains gas
* assume other is average cost/emissions of coal, wood, LPG

			Urban fuel mix			**Rural fuel mix**		
Source	(BRE, Garston, and Watford 2023) Emissions (kg CO2e/kWh)	Cost (p/kWh)		Emissions kg CO2e /100kwh	Cost p/100kwh		Emissions kg CO2e /100kwh	Cost p/100kwh
Electricity	0.136	16.49	11%	1.49	180.22	13%	1.77	214.93
Grid Gas	0.21	3.64	81%	17.04	295.31	63%	13.30	230.57
Oil	0.298	4.94	3%	0.89	14.72	18%	5.31	88.02
Communal	0.21	3.64	4%	0.75	13.08	1%	0.21	3.69
Other	0.221	6.72	1%	0.30	9.20	5%	1.06	32.20
		Total	100%	**20.47**	**512.53**	100%	**21.66**	**569.42**

Rural increase	
Emissions	**Cost**
5%	**10%**

C.2 Extended table of time to charge and adsorb hydrogen into metal hydride tank.

Table C.2: Time and median time to reach 80% and 100% state of charge of GH2 store tank.

Operational cycle	Adsorption 1	Adsorption 2	Adsorption 3	Adsorption 4	Adsorption 5
Time to 80% (min)	171	291	168	147	149
Median (min)	**168**	**Median (excluding adsorption 2)**			**158**
Time to 100% (min)	448	641	424	402	403
Median (min)	**424**	**Median (excluding adsorption 2)**			**414**