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A techno-economic comparison of rural domestic heat decarbonisation fuels and technologies in the UK in energyPro

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Abstract

In the UK 33% of rural households do not use gas from the national grid as a heating fuel. Other fuels such as heating oil, electricity and LPG are the next popular fuels respectively. The technical and policy decisions regarding decarbonising rural off gas housing are considered hard to decarbonise due to a high diversity of housing stock age, fabric, and heating system present. This work utilises high-fidelity energy consumption data from rural UK smart meters to techno-economically model 19 different energy systems which represent the diversity of fuels and technologies used in rural UK homes and low carbon heating systems that are feasible alternatives.

The outputs from the models evaluated are scored and ranked relative to various technical factors such as OPEX, CAPEX and annual emissions in two phases. Finding heat pump and hybrid heat pump/hydrogen heat systems best scoring and coal heating systems the worst scoring when evaluated across 3 rural home archetypes.

Keywords

Rural, heating, fuels, off gas, techno-economic, oil.

Introduction

[1]In the UK Domestic Heating contributes a large part to carbon emissions, partly due to poor building stock energy efficiency which require more heat to be produced (and therefore higher carbon emissions) to reach a comfortable level compared to a more energy efficient building of comparable construction. The other major source of carbon emissions are the fuels used to produce the heat demanded by a domestic property. This presents a challenge towards the goal of decarbonising heating in UK homes via two complementary pathways; first by improving the building's fabric to improve the building energy efficiency, or secondly

by upgrading the heating system of the home by upgrading or converting the heating fuel and technology used. UK government policy decision making changes periodically regarding which decarbonisation pathway is more effective. This work looks at a techno-economic assessment of decarbonising rural UK homes where there is a more complex range of heating fuels, technologies and other factors needed to consider when decarbonising rural homes compared to urban UK homes.

Why look specifically at rural homes? In the UK 78% [2], [3], [4] of homes use grid gas as the primary heating fuel. From this statistic it seems that the UK is near homogeneous in the way it heats its homes. However, this is not the case when broken down into various types of building stock or geographies such as urban and rural. Only 63% of rural homes are heated by grid gas (as seen in Figure 1) with a broader variety of heating fuels used than in an urban setting such as kerosene oil, LPG and wood. As a result, a rural resident will produce 5% more emissions and pay 10% more for the same one kilowatt of heating energy.

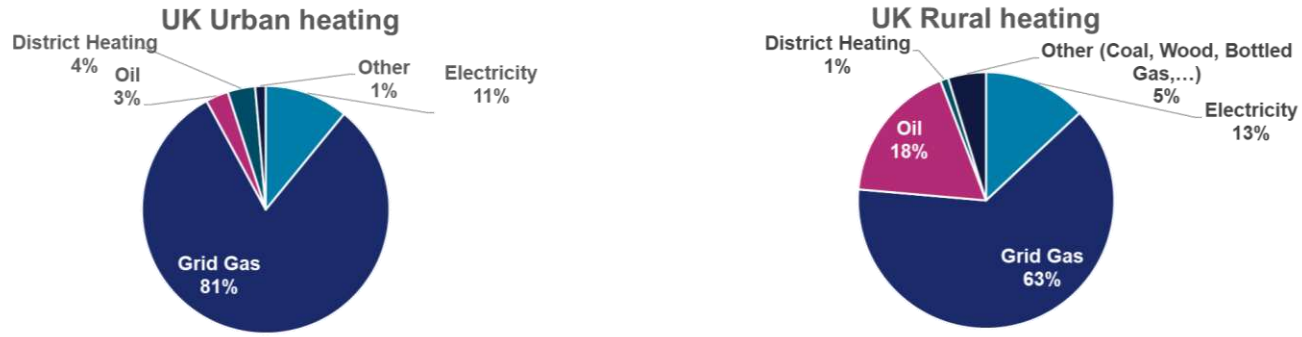


Figure 1: A rural/urban breakdown of domestic heating fuels used in the United Kingdom [2], [3], [4]

Therefore, there are various implications of retrofitting decarbonised heating systems to rural homes. There is not a dominant heating fuel used that enables a broadly consistent and techno-economically predictable and publicly understood decarbonisation pathway, from one fuel to the other such as from grid gas boilers to electricity powered heat pump systems, as the UK and Scottish government policy prefers [1], [5].

There is a greater diversity of rural UK building stock according to age, building fabric, building efficiency, building type, heating fuel and size than UK urban homes. This complexity has made the heat decarbonisation pathways for rural homes more complex and less understood. This work aims to provide greater technoeconomic understanding of existing and low carbon rural heating systems, by modelling over 20 different heating fuel and technology combinations that are currently used to heat rural homes or are cleaner alternatives that could be used using real energy consumption data from rural UK home smart meters.

There has been work evaluating different low carbon technologies for decarbonised heat and therefore researching rural off grid and islanded energy systems with novel energy vectors and technologies. Existing literature focuses on specific individual and limited number of technologies demonstrated or simulated, not comprehensively across various fuels or in a rural UK setting.

Hydrogen energy systems have been demonstrated, where [6] and [7] both demonstrate a completely off grid hydrogen powered home using electric heating through combined heat and power hydrogen fuel cells and hydrogen fuel cell generated electricity systems.
Electric heat pump systems are a relatively mature low carbon heating technology where UK government studies have found this technology to be technically feasible in most UK housing stock across various ages, constructions and energy efficiencies of buildings [8].

Some comparative studies that evaluate different low carbon domestic heating systems, which are key sources of information for informed decisions. [9] evaluated 9 low carbon domestic energy systems across 3 different European city climates, not rural regions. Finding that the biggest factor to reducing energy cost and unit carbon intensity is local solar generation of renewable energy particularly in regions where electricity is generated from high carbon emission generators, where the solar PV and heat pump systems were found to be the most techno economically optimal.
At a national system level [10] techno economically assessed domestic heating and cooling technology mixes related to carbon emissions, efficiency and operating cost and the scope for energy storage to downsize the size and cost of individual heating and cooling generators. This was also comparing optimised technology mixes between northern and southern European climates. Finding on a system scale air to air heat pumps could provide significant provision for low emissions heating due to their low unit cost. However it was notably mentioned practical considerations such as needing potentially multiple air to air heat pumps per home (as a united in needed in each room in a home) mitigates the benefit over air to water heat pumps. This effect might be more prominent in older building types found in rural regions.

Most techno-economic studies of domestic heating system decarbonisation use a refence energy system and technology to come the other systems, methodologies and technologies studied. These reference systems are often grid gas boilers [11] or direct electric [12] resistive heating systems which encompass most urban-type homes. These studies are limited as these are not the only existing energy technologies or energy vectors used to produce domestic heat. Particularly in older buildings and rural regions where fuels such as wood, coal and heating oil are commonly used in the UK and across the world, particularly in developing regions. These are harder to decarbonise buildings and fuels, where a conversion to low carbon heating technologies which would provide an outsized benefit to occupant's health, running costs and emissions. Therefore there are gaps in the existing literature regarding a comprehensive comparative study of rural heating fuels and building archetypes in a single climatic region.

These gaps identified lead to the key novel contributions of the paper:

- The modelling of 19 diverse energy systems, spanning legacy rural fuels and future low-carbon alternatives, specifically mapped to rural building archetypes.

- The integration of real-world energy consumption data from rural UK smart meters to provide representative heat demand profiles for the simulations.
- A dual-iteration analysis framework that demonstrates how the selection of scoring criteria and technical factors influences the perceived viability and ranking of decarbonisation technologies.

This paper was originally proceedings at the 15th International Green Energy Conference (IGEC) 2023, in Glasgow, UK [13]. This is an extended version with further (2nd) data analysis and results presented and compared with the initial 1st analysis.

This paper is structured as follows: Modelling methodology and data inputs, Results: 1st analysis and discussion, Results: 2nd analysis and discussion, Non-modelled barriers to technology implementation, Conclusion.

Methodology

The methodology of the work carried out in this paper is presented in Figure 2. Looking at the scenarios and modelled selection, the modelling software, results, initial analysis of results and secondary extended analysis of results. A key element is the selection and construction of the 19 scenarios modelled, which represent the variety of heating fuels and technologies that are present in existing rural UK homes and low carbon systems that might be used in future. This is important diversity of original energy systems have greater cost and feasibility implications than a relatively typical urban, gas heated home.

This work presents two sets of analyses of the model results and compares the two. An aim of presenting this work is as a decision making tool. This dual analysis and comparison demonstrates the results and ranking of the best technologies can change in the context in considering (or not) of different technical factors.

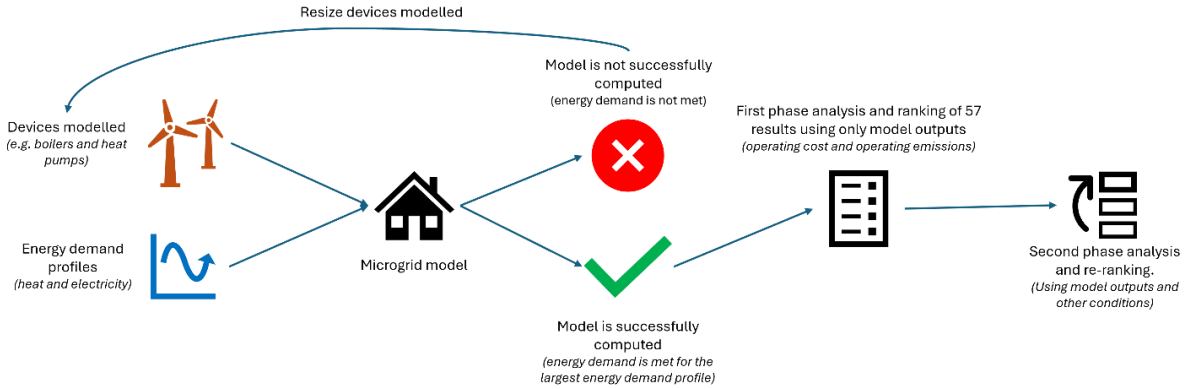


Figure 2: Summary of the modelling methodology process and the results analysis.

Scenarios

19 different domestic microgrid energy systems are modelled in Table 1, representing various heating fuels and technologies that are used in UK rural homes and low carbon heating and energy systems could replace legacy fuels and technologies. Broken down into two groups of systems of 'Existing fuels' and 'Renewable' for ease of simulation. The renewable models also feature across models in this group a 3kWp solar photovoltaic array, a 1.2kWp solar thermal array and a 6kWp wind turbine to represent a future rural remote property best case scenario in the UK, that has capacity and space for all domestically available renewable energy technologies.

Table 1: List of the 19 modelled microgrid systems of varying fuels and technologies. With key energy storage and energy conversion devices noted.

Existing fuels models: **11 fuels and heating technologies**	**Renewable models:** **9 fuels/technologies** *+ Solar PV, Solar Thermal, Wind Turbine for all models below*
1. **Grid Gas** – *combi boiler*	**12. Grid Gas** – *combi boiler*
2. **Heating Oil** – *combi boiler*	**13. Biomass (Dry Wood Logs)** (w/ hot water tank) – biomass boiler and feed system
3. **House Coal** (w/ hot water tank) – *fireplace and back boiler*	**14. Electrolysed green Hydrogen** *with a combi boiler*
4. **Dry Wood Logs** (w/ hot water tank) *– fireplace and back boiler*	**15. Electrolysed green Hydrogen** *with a fuel cell*
5. **Electric boiler**	**16. Electric immersion heater** (in hot water tank)
6. **LPG bottle** – *combi boiler*	**17. Heat pump** (w/ hot water tank)
7. **Electric immersion heater (**in hot water tank)	**18. Hybrid heat pump and electrolysed green hydrogen boiler** (w/ hot water tank) – combi boiler
8. **Heat pump** (w/ hot water tank)	**19. Hybrid heat pump and blue hydrogen bottle boiler** (w/ hot water tank) – combi boiler
9. **Electric storage heater** – *resistive heating*	
10. **Grey hydrogen Bottled** – *combi boiler*	
11. **Blue hydrogen Bottled** – *combi boiler [SMR with CCS (90% capture)]*	

Modelling

The modelling of the 19 different systems presented in Table 1was completed in energyPro, a multivector energy system modelling software with dedicated electricity, heating and other fuel 'networks'. With premade energy devices and the ability to make custom energy devices not yet present in the software such as hydrogen fuel cells. The models were constructed and specified with modules representing energy conversion devices and energy storage devices that are commercially and publicly available in the UK, with the technical specifications and costs of these devices inputted into the model. Some devices and fuels, particularly hydrogen fuels and devices do not have accessible costs and specifications, these are derived from informed academic papers and enquiries with colleagues at the University of Nottingham Hydrogen Research Group.

The 19 models created are simulated against an electrical demand profile representing day to day uses of appliances in the home (except any electrical heating appliance) and 3 different heat demand profiles from [14], which represents the electricity and heat consumption of a home on the Isle of Gigha in Scotland across three representative buildings and levels of insulation that are found on the island and across rural UK. Referred to as: *Old and uninsulated*, *Old and insulated* and *New Build* as seen in Figure *3*.

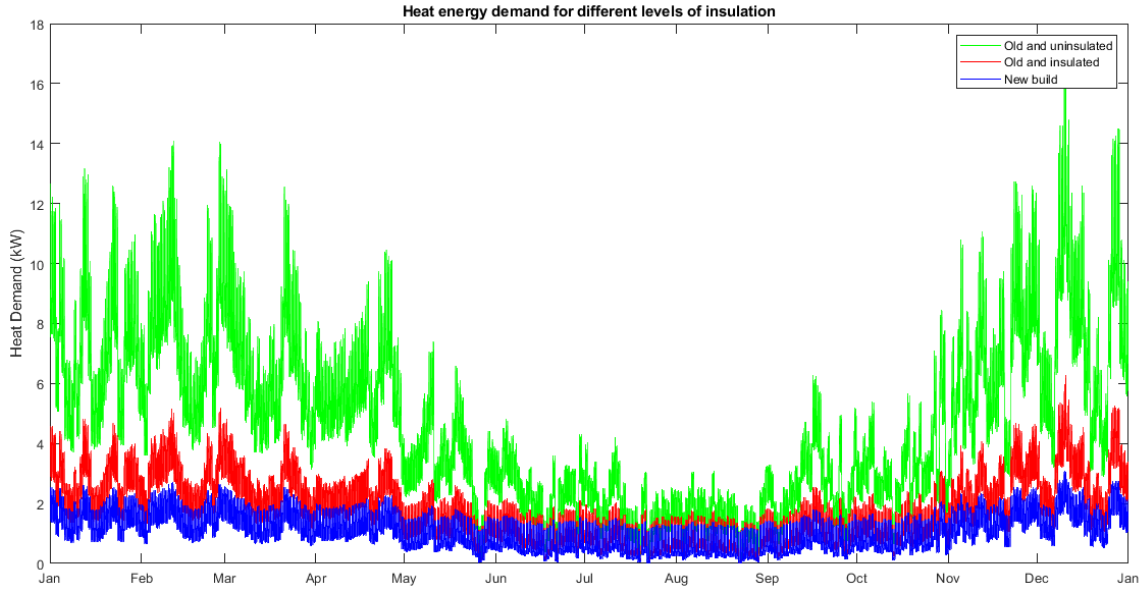


Figure 3: Heat demand profile data plotted from [14]

All the energy conversion devices in the 19 models are sized to satisfy the largest energy demand profile, "Old and Uninsulated". This decision was made to streamline the modelling time required. Other data inputted into the energyPro models are economic and emissions

data regarding each fuel modelled. All fuels other than the hydrogen fuels are used from the SAP 10.2 methodology as seen in Table *2*.

Table 2: 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	[15]
Heating oil	0.298	4.94	[15]
House coal	0.395	5.58	[15]
Dry wood log	0.028	5.12	[15]
Grey Hydrogen	0.5049	9.57	[16] Cost @ £49.97 per bottle of hydrogen when data was captured [17]
Electric boiler	0.136	16.49	[15]
LPG Bottle	0.241	9.46	[15]
Electric Tank	0.136	16.49	[15]
Heat Pump	0.136	16.49	[15]
Storage heater	0.136	16.49	[15]
Blue hydrogen	0.042	9.57	[16] Cost @ £49.97 per bottle of hydrogen when data was captured [17]

Results

The outputs of the energyPro models are technical and economic, the following are used in later results analysis. Providing if the model is successfully computed (if all energy demand was satisfied); the *total annual operational running cost*, the *total annual operational emissions*, the *total amount of imported/exported energy to/from the system,* the *amount of electricity renewably generated* and the *amount of heat renewably generated*. Two iterations of results analysis are presented, the first analysis only considers the annual operational running cost and the annual operational emissions. The second analysis considers all the outputs listed above, these are not the only outputs provided from energyPro but the outputs used in this work. Two sets of analysis is presented to compare and contrast the impact of different scoring metrics on the final total score for a technology. This has also enabled a narrowing down of viable energy systems of heat pump, hybrid heat pump and biomass fuels to be further considered in detail.

The results from the models are presented and processed separately in the “existing fuels” and “renewable” model groups due to limitations in the computer hardware used and software capability to compute 19 models in one session. Therefore this required this required the models to be split into two groups. Results are presented with two iterations of analysis to demonstrate how by only using a limited number of scoring criteria and simple ranking methodology affects the rankings of the models compared to a more complex and detailed ranking methodology.

1st Analysis

The initial analysis of the results finds to assign a score and rank of each of the 19 models computed across the three different building heat demand profiles, 57 results in total. Each of these numeric results are found by ranking the output annual emissions and annual running cost separately for each model as seen in Table 3 and Table 4. The rank for each model output is a 1-11 score (1-8 for the renewable model), where 1 is the best performing and 11 (or 8) is the worst performing model for that criteria. The aim is to minimise emissions and cost, so the best scores are assigned to the models with the lowest emissions and lowest running cost.

The final score is derived buy summing each model's rank across annual emissions and annual running cost as seen in and Table 6. Tables 4 – 6 have highlighted in green and the worst performing models highlighted in red.

Table 3: Results of existing fuel energy model comparing the energy bill and emissions of different fuels or technologies. Where highlighted in green are the best performing model and red the worst performing.

Model version name	Annual running cost (£) Building heat profile type			Annual emissions (kg CO2e) 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	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

Table 4: Results of renewable energy model showing the annual energy bill and annual emissions broken down by building type and technology. Where highlighted in green are the best performing model and red the worst performing.

Model version name	Annual running cost (£) Building heat profile type			Annual emissions (kg CO2e) 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

The outputs for the renewable group of models as seen in Table 4 include negative running costs, this is due to the renewable models are additionally configured to export and sell electricity at the same cost of purchasing electricity. In the UK currently the purchase price of electricity from a distributed generator (exporting domestically produced renewable electricity) varies depending on the tariff the domestic distributed generator has and can range from 5-30p/kWh [18]. Using the electricity import price of 16.49 p/kWh for exports is just under the average export price for this quoted range.

Table 5: 1st analysis ranked result of different heating fuels when combining the ranking for cost and emissions of each technology/fuel for the existing fuels model. Where highlighted in green are the best performing model and red the worst performing.

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*

Table 6: 1st analysis ranked result of different heating fuels when combining the ranking for cost and emissions of each technology/fuel for the renewable energy system model. Where highlighted in green are the best performing model and red the worst performing.

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

Comparing the best and worst results for the existing fuels models across Table 3 and finds that heat pump systems are the best scoring systems for the Old and Insulated and New Build energy demand profiles, whereas the wood heated system (fireplace with a back boiler) has the lowest total score for the Old and Uninsulated heat demand profile with a median running cost score and the lowest emissions score.

The results for the renewable models are found in Table 4 and Table 6, finding that the highest scoring model is the Green hydrogen Fuel Cell and the lowest scoring system are Biomass. Biomass consistently produced the lowest cost and emissions results closely followed by mains gas in terms of low cost and heat pumps were often second or first when

considering annual emissions. Median results and scores are achieved by the two hybrid heat pump and hydrogen boiler systems and by the mains gas reference model.

This primary analysis method is optimal for initial range finding of the techno-economic suitability of a technology. Iterating this to test the robustness of the initial rankings against a wider set of technical constraints statistical analysis provides greater detail and fine tuning in a scoring and ranking methodology as seen in the 2nd analysis section following.

2nd Analysis

This subsequent extended analysis of the same computed results from the energyPro models with a more detailed statistical method of analysing the model results and incorporating other techno economic factors such as capital cost, system efficiency and the proportion energy consumed that is renewably generated, in addition to operational cost and operational emissions already used in the initial analysis.

A new ranking methodology was used to measure the relative spread of the results in each factor assessed. Using the min-max statistical method to produce a relative result from 0 to 1 where the best score is 0 and the worst score is 1. This allows a dimensionless unweighted measure of spread between each type of result (e.g. capital cost, annual emissions, …) seen in equation (1) below.

$$Score = \frac{x - minimum}{maximum - minimum} \qquad (1)$$

This method produces a fractional score for each for each factor for each model according to each energy demand profile. All the scores for a specific model are summed together. Producing a final score that can provide a more considered result as seen in Figure *4* and Figure *5*, where the lowest score is considered the best.

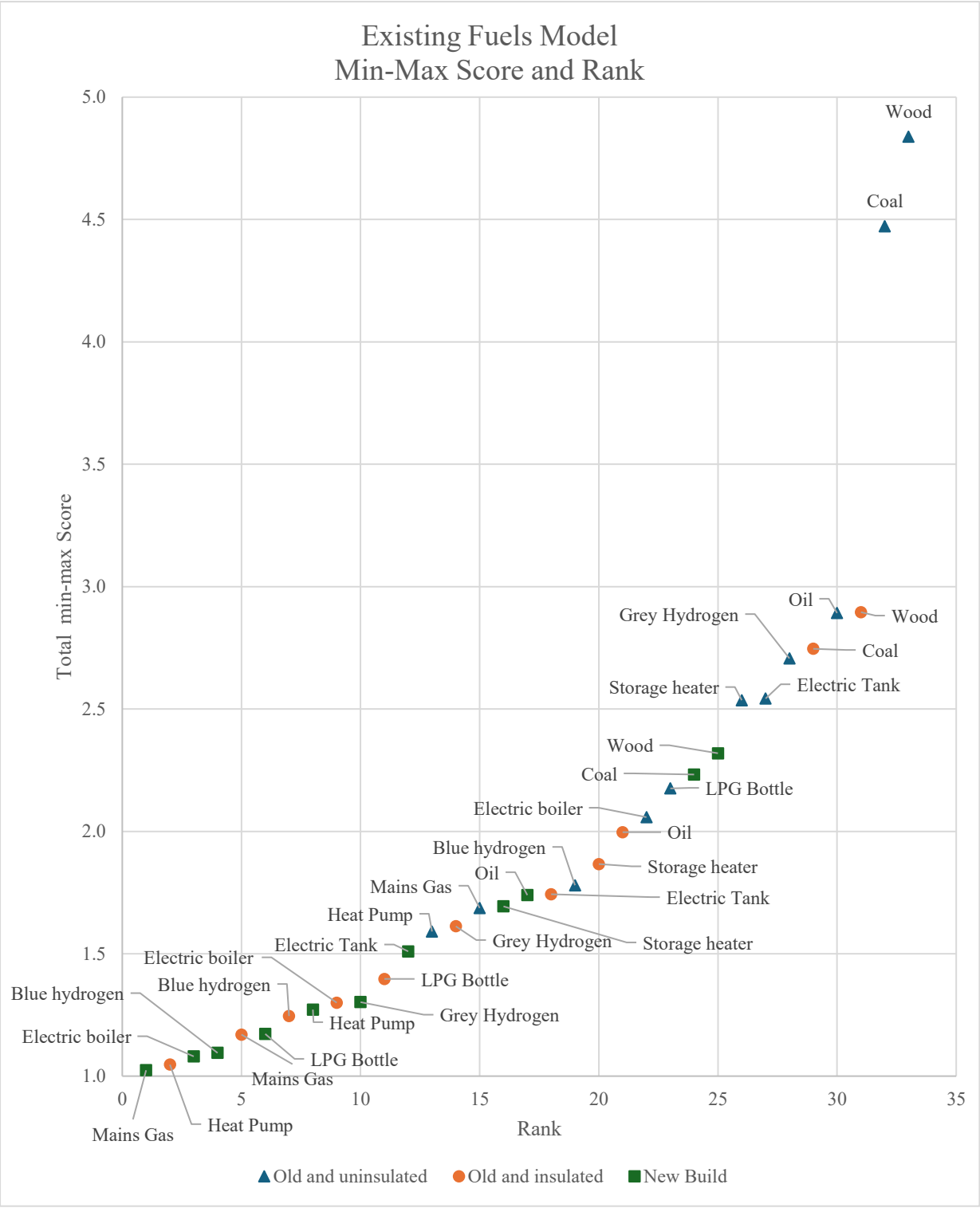


Figure 4: The total min-max normalised score for all 33 iterations of the existing fuels model across three different levels of insulation showing the relative spread of the scores of the iterations.

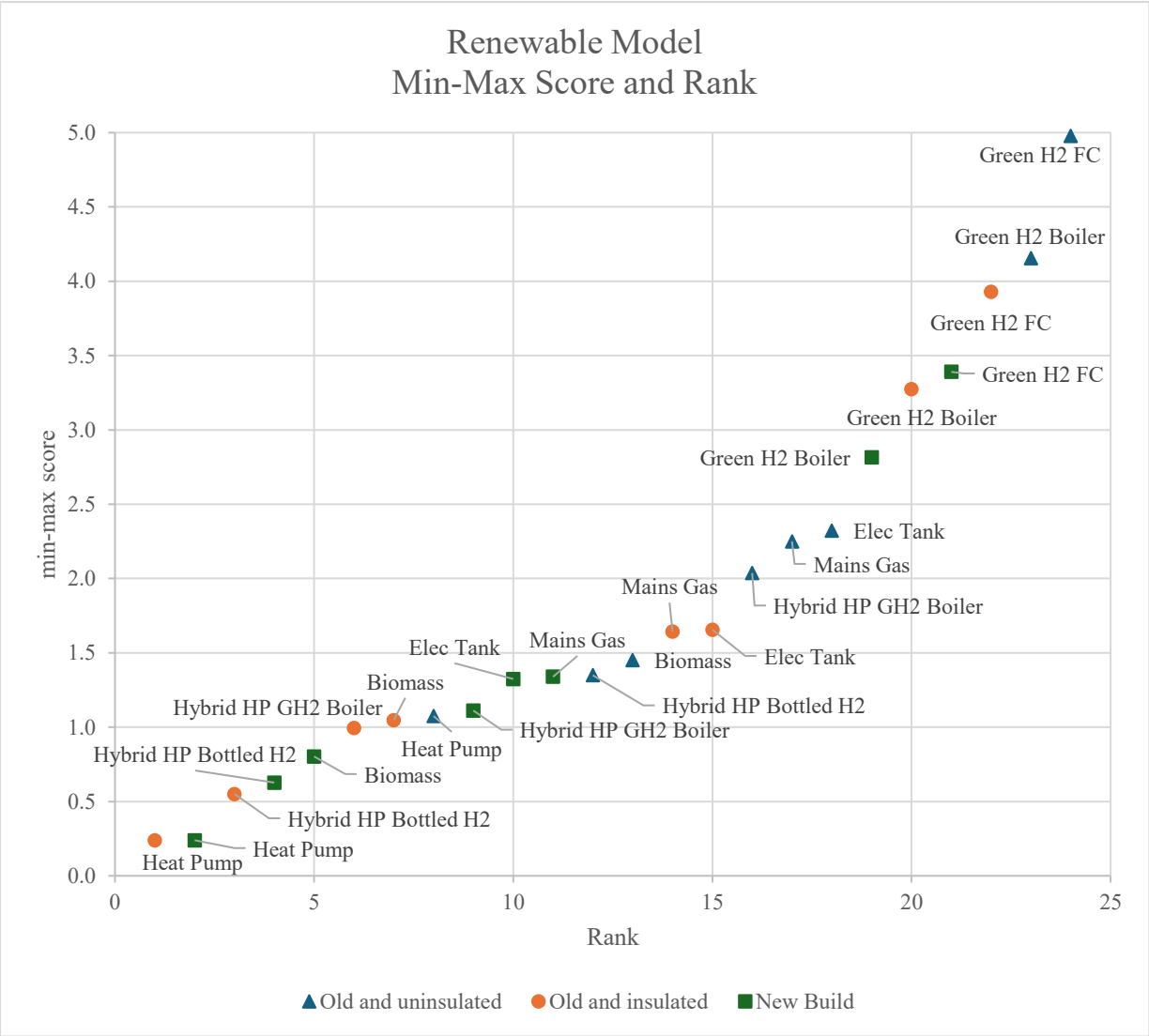


Figure 5: The total min-max normalised score for all 27 iterations of the renewables model across three different levels of insulation showing the relative spread of the scores of the iterations.

When using the relative spread of results to assess the ranking of different models there is a trend of a large gap produced from two outlier results of wood and coal and the remainder of the models in each energy demand profile in Figure *4*. The gap is largest for the Old and Uninsulated results where Oil scores 2.892 and Coal scores 4.473. The lowest scoring results for the existing fuels group are heat pump and mains gas across the three energy demand profiles.

The highest scoring renewable model is Green Hydrogen (electrolysed) + fuel cell followed by Green hydrogen (electrolysed) + boiler. In the renewable set of results there are multiple clusters of results in each energy demand profile rather than a more cohesive set of in the existing fuels grouping.

The outputs of this extended result analysis finds some variation of the final ranking of the models categorised.

Discussion

Comparing the results from the first and second analysis as seen in Table 7 and Table 8 finds 81% of the 57 unique models computed changed rank, 52% moved up in rank and 26% moved down in rank. This large change in rank is primarily due to fossil fuels such as wood, biomass, oil and coal scoring poorly in the energy efficiency category. As these models shift down in rank consequently a cascade of the remaining models shifting up occurs. The green hydrogen systems in Table 8 remain unchanged in their rank due to having poor roundtrip energy efficiency and emissions scores due to a large amount of grid imported electricity as there is insufficient renewable energy produced within the microgrid.

Table 7: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**	↑	**Electric Tank**	9
Electric 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**	↑	**Electric Tank**	7
Storage heater	8	↓	**change**	↓	**Oil**	8
Coal	9.5	↓	**change**	↓	**Wood**	9
Electric 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**	↑	**Electric Tank**	7
Electric Tank	8	↑	**change**	↓	**Oil**	8
Storage heater	8	=	match	=	**Storage heater**	9
Coal	10	↓	**change**	↓	**Wood**	10
Grey Hydrogen	11	↑	**change**	↓	**Coal**	11

Table 8: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						
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
Electric Tank	6	=	match	=	**Electric 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
Electric Tank	6	=	match	=	**Electric 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**	↑	**Electric Tank**	5

Electric Tank	6	↑	**change**	↓	**Mains Gas**	6
Green H2 Boiler	7	=	match	=	**Green H2 Boiler**	7
Green H2 FC	8	=	match	=	**Green H2 FC**	8

The change in results of the second analysis results compared to the initial analysis is a vivid example of the scoring and ranging of a technology is highly conditional on the criteria used to calculate the score. This implication is a clear example and reminder of the influence of selective use of data to influence decision making and decision makers. Furthermore, this example highlights the benefit of using more data of different relevant factors if accessible to provide a more informed score and decision making.

Non-modelled barriers to technology implementation

While undertaking this study a keen awareness has been made to acknowledge there are important and high-risk factors that are not captured and quantified due to their specific geographic or subjective nature. A term that can encompass much of this is the 'rural accessibility factor'. Where the level of rurality of a home can impact the cost, emissions and timescale of installing an energy system at a home or affecting fuel delivery logistics and electricity costs to a property. A balance is needed to be struck between modelling detailed and specific rural scenarios and a broadly applicable methodology applicable to any UK rural setting. In this study two assessment methodologies have been developed one iterating on the other blind to geography beyond a generic UK archetype. Further work can be had to further iterate with a contextual geographic 'rural accessibility factor'.

How could a 'rural accessibility factor' be implemented? Such a metric would comprise of various factors that will each vary depending on geography and jurisdiction, such as the level of rurality (the definition of which varies across the UK), the cost of fuels (electricity, wood, oil, LPG, etc.), the delivery cost of such fuels, labour costs associated with installation of the energy system (CAPEX is already modelled in this study) and government grants or subsidies that might be available in different jurisdictions. Hyper-local factors such as permitting or individual case studies would be too specific to be considered in this detailed methodology. All of the above would need to be iterated across each level of rurality and geography to an appropriate resolution depending on the scope of a later study.

An understood example are heat pumps, where it is best practice to upgrade building insulation alongside heat pump installations, potentially replacing all the hot water circuitry (using larger diameter piping that boiler heating properties), replace heat emitters resized to the heat pump outputs and ensure there is sufficient electrical capacity in the home for a heat pump [19][20], this can significantly increase the cost for a viable heat pump installation. Each energy technology has their own unique prerequisites that need to be considered that are complex to capture in a study like this. These non modelled factors will significantly contribute to the technical and economic viability of deploying a technology.

Conclusion

This study showcases a broad techno-economic modelling scenario encompassing almost every heating fuel and technology used in rural UK and showcasing various low carbon technologies considered to be used in future rural microgrids.

This work is important as rural domestic heat decarbonisation is a lot more complex and unique to carry out due to a greater variety of fuels, building types and other local considerations than in an urban setting. Yet in the UK policy and awareness is limited, rural heat decarbonisation policy is one sentence. This work provides an initial baseline comparative context for policy makers, communities and researchers to enable technological and social parity with urn heat decarbonisation.

The results of this modelling is then presented over two iterations of analysis with different methodologies and tertiary factors considered. This multi iteration of analysis was presented to showcase the evolution of the research carried out and to provide an example of how technology selection and policy decision making relies highly on the quantity and quality of the assessing factors. Between the first and second iteration of analysis a large majority of rankings changed, where fossil fuels primarily dropped in rank.

Across both analyses a trend of the consistently top scoring technologies were found to be heat pump, mains gas, blue hydrogen and hybrid heat pump/hydrogen systems. Mains gas and heat pump electric heating systems make up the vast majority of urban UK heating consistently scoring the best compared to typical rural fuels such as wood, oil and LPG aligns with the statement at the beginning of the study “A rural resident will produce **5% more emissions** and **pay 10% more** for the same 1kW of heating energy”, as the results of this techno economic study considers multiple cost and emission factors.

Hybrid heating systems also rank highly and provide opportunities for further research and modelling of different hybrid heating system ratios between fuel and technology to minimise cost, emissions and efficiency. As the continued policy and UK governmental work towards low carbon heating large and upcoming hurdles towards decarbonised (by primarily heat pump) electrified heating will become a technical impossibility alongside transport electrification and the large and unspecified UK electric grid upgrades planned by UK government. Therefore hybrid heat pump/mains gas/hydrogen heating will become a medium term necessity to enable heat decarbonisation not just in the domestic sector but in the commercial and industrial building sectors.

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Credit contribution
Soares: Conceptualisation, Methodology, Analysis, Writing
Gillott: Supervision
Stuart: Supervision

Data availability
The data used can be found at [14].

Also with the following link
https://www.esru.strath.ac.uk/EandE/Web_sites/17-18/gigha/heat-demand-profile.html

[14]
A. Baumanis, D. Lee, N. Marinos, and F. Ross, "Energy Future of Gigha - Heat Demand Profile," wayback machine. Accessed: Jun. 22, 2022. [Online]. Available: https://web.archive.org/web/20200205114649/http:/www.esru.strath.ac.uk:80/EandE/Web_sites/17-18/gigha/heat-demand-profile.html

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[1] H. Government, “Heat and Buildings Strategy,” 2021.

[2] Office for National Statistics, “Energy efficiency of housing in England and Wales - Office for National Statistics,” 2021. Accessed: May 30, 2022. [Online]. Available: https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/energyefficiencyofhousinginenglandandwales/2021

[3] Scottish Government, “Scottish house condition survey: 2019 key findings,” 2020. Accessed: Jun. 22, 2022. [Online]. Available: https://www.gov.scot/publications/scottish-house-condition-survey-2019-key-findings/

[4] Northern Ireland Housing Executive, “House Condition Survey Main Report 2016,” 2016.

[5] Scottish Government, “Heat In Buildings Strategy: Achieving Net Zero Emissions in Scotland’s Buildings,” 2022. Accessed: May 24, 2022. [Online]. Available: https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/

[6] P. Puranen, A. Kosonen, and J. Ahola, “Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates,” *Solar Energy*, vol. 213, pp. 246–259, Jan. 2021, doi: 10.1016/j.solener.2020.10.089.

[7] Hydrogen House Project, “Hydrogen House Project - Hydrogen House Project: Home.” Accessed: Jun. 13, 2022. [Online]. Available: https://www.hydrogenhouseproject.org/index.html

[8] BEIS and Delta, “Technical Feasibility of Electric Heating in Rural Off-Gas Grid Dwellings Final report BEIS Research Series Number 0024,” 2018.

[9] M. Kurses, A. V. Olympios, A. A. Harraz, and J. Xu, “Comparative analysis of heating and cooling solutions for residential use: Energy, environmental, and economic perspectives,” *Appl. Energy*, vol. 399, p. 126511, Dec. 2025, doi: 10.1016/J.APENERGY.2025.126511.

[10] M. Aunedi, A. V. Olympios, A. M. Pantaleo, M. Mersch, and C. N. Markides, “System-level techno-economic comparison of residential low-carbon heating and cooling solutions,” *Energy*, vol. 317, p. 134602, Feb. 2025, doi: 10.1016/J.ENERGY.2025.134602.

[11] A. Vijay and A. Hawkes, “The Techno-Economics of Small-Scale Residential Heating in Low Carbon Futures,” *Energies 2017, Vol. 10, Page 1915*, vol. 10, no. 11, p. 1915, Nov. 2017, doi: 10.3390/EN10111915.

[12] E. Venturi, G. Dermentzis, M. Magni, and F. Ochs, “Techno-Economic Analysis of the Heating System Robustness,” *International Sustainable Energy Conference - Proceedings*, vol. 1, Apr. 2024, doi: 10.52825/ISEC.V1I.1171.

[13] J. Zhao, S. Kadam, Z. Yu, and X. Li, Eds., “IGEC Transactions, Volume 1: Energy Conversion and Management,” 2024, doi: 10.1007/978-3-031-48902-0.

[14] A. Baumanis, D. Lee, N. Marinos, and F. Ross, “Energy Future of Gigha - Heat Demand Profile,” wayback machine. Accessed: Jun. 22, 2022. [Online]. Available: https://web.archive.org/web/20200205114649/http:/www.esru.strath.ac.uk:80/EandE/Web_sites/17-18/gigha/heat-demand-profile.html

[15] BRE, Garston, and Watford, “The Government’s Standard Assessment Procedure for Energy Rating of Dwellings,” Apr. 2023, doi: 10.2.

[16] “UK BOC Online Shop: High Purity Hydrogen Cylinder.” Accessed: Mar. 15, 2023. [Online]. Available: https://www.boconline.co.uk/shop/en/uk/gas-a-z/hydrogen/high-purity-hydrogen-cylinder

[17] R. W. Howarth and M. Z. Jacobson, “How green is blue hydrogen?,” *Energy Sci. Eng.*, vol. 9, no. 10, pp. 1676–1687, Oct. 2021, doi: 10.1002/ese3.956.

[18] “Solar panels: How to get paid top rates for electricity you export – MoneySavingExpert.” Accessed: Jun. 05, 2026. [Online]. Available: https://www.moneysavingexpert.com/utilities/best-solar-rates-seg-tariffs/

[19] Daniel Mousdell, “Pipe Sizing for Heat Pump Systems (Includes a Worked Example),” h2x engineering. Accessed: Nov. 17, 2025. [Online]. Available: https://www.h2xengineering.com/blogs/pipe-sizing-for-heat-pump-systems-worked-example/

[20] Ryan Williams, “Heat pump installation: a step-by-step guide - Energy Saving Trust,” energy saving trust. Accessed: Nov. 17, 2025. [Online]. Available: https://energysavingtrust.org.uk/heat-pump-installation-a-step-by-step-guide/