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Journal of Energy and Power Technology

Research Article

Significance of Insulation and Heat Pumps in Decarbonising the UK

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Academic Editor: Mohammad Jafari

Special Issue: Optimal Energy Management and Control of Renewable Energy Systems

Journal of Energy and Power Technology
2023, volume 5, issue 1
doi:10.21926/jept.2301003

Received: November 09, 2022
Accepted: January 05, 2023
Published: January 09, 2023

Abstract

This paper examines the economic case for the UK to proceed urgently with the installation of thermal insulation and heat pumps in most UK buildings, in the context of the legal requirement to achieve net-zero carbon emissions by 2050. A recent study by the same authors assumed that such insulation and heat pumps would be in place, and showed how the whole of the UK's energy demand could be met by low carbon electricity generation and appropriate storage. This paper extends the modelling to consider the risk that insulation is not widely installed, fossil gas boilers are retired (as they must be) but are replaced only by resistive heating, which is the pessimistic but likely outcome in the absence of heat pumps. Unsurprisingly, resistive heating and lack of insulation is shown to consume vastly more electricity: an increase of 608% for space heating and 52% overall. The contribution of this paper is in quantifying the seasonal variations and implications for generation and storage, which make the overall costs increase by an even greater proportion: almost doubling. In particular, peak electricity demand is 130% higher and required peak generation is 140% higher without extra insulation and heat pumps. The paper also illustrates the timely return on capital invested in insulation and heat pumps, primarily because they are cheaper than the additional wind turbines and energy storage required otherwise. The additional costs of failing to insulate and install heat pumps escalate to £63bn per year in levelised energy costs alone, and greatly increase the risk of the UK failing to reach net-zero. The financial break-even point for the costs of retrofitting the entire building stock is shown to be just 15 years from the start of a 28-year retrofitting campaign, with increasing cost savings thereafter. The paper shows that it is both necessary and cost effective to retrofit all buildings with proper insulation and heat pumps.

Keywords

Insulation; heat pumps; resistive heating; net zero; grid balancing

1. Introduction

The UK government is legally committed to net zero emissions by 2050 [1], but, according to their own figures [2], 78.3% of the UK's primary energy consumption is still derived from fossil fuels. Heating and hot water in domestic and commercial buildings accounts for 20-25% of emissions [3] and 80% of heating is delivered by fossil gas. The UK's Climate Change Committee [4] says "We will not meet our targets for emissions reduction without near complete decarbonisation of the housing stock". Decarbonising heating is crucial to reaching net-zero.

Additional to the legal requirement is the overwhelming moral duty to future generations. It has been known for decades that greenhouse gasses cause climate change, and yet the UK continues to derive most of its energy from fossil fuels. In 2021 the UK territorial emissions were 424 $MtCO_2e$ [5]. In 2022 the IPCC [6] reported "Globally, GHG emissions continued to rise across all sectors and subsectors".

A recent study by the same authors entitled *Net Zero UK – Generation and Energy Storage Requirements for the UK to Become Carbon Neutral* (NZUK) [7] showed that it is possible for the UK to become completely carbon neutral, operating mainly from wind, solar and the two existing nuclear stations. Electrolytic hydrogen combined with anaerobic digestion provides biomethane for times of low wind and an ongoing energy balance is achieved. A key assumption of NZUK is that all buildings are insulated to a high standard, and fossil fuel boilers are replaced by heat pumps. This paper considers the implications if buildings are not upgraded in this way.

Heat pumps (see Section 2) can deliver more than 3 units of heat from 1 unit of electricity, this ratio, known as the coefficient of performance (CoP), makes heat pumps an attractive proposition whenever electricity is the starting point. Achieving a good CoP however requires large-area heat emitters (radiators or underfloor) and the consideration of the overall installation costs usually points to the benefit of greatly improving the thermal insulation of the whole building at the same time. "Fabric first" emphasises the importance of insulation as an enabler of heat pumps and, if properly installed, the combination is a proven route to warm homes. Running from zero-carbon electricity, they offer the possibility of zero-carbon homes.

A competing proposal is that hydrogen be used as a replacement for fossil gas to fuel central heating boilers. This has the appeal of minimal disruption to the household and is promoted by the incumbent gas distribution and boiler industries. The challenge is in the production of genuine green hydrogen (by electrolysis using green electricity) at the required scale. Assuming an electrolyser efficiency of 80% and a boiler efficiency of 88% gives hydrogen central heating an effective CoP of around 0.7, compared to a CoP of say 3 for heat pumps running directly from wind power, which is available most of the time. This 4-fold difference in heat delivery per unit of electricity is compounded by the risk that the continued use of high-temperature central heating boilers is accompanied by a lack of insulation making the overall electricity consumption higher still.

Cassarino and Barrett [8] studied the potential for hydrogen boilers in comparison to heat pumps and to district heating, using a high-resolution model and looking particularly at the hard winter of 2010, a difficult case for renewables. They showed that "heat pump technology represents the most cost-effective solution, thanks to its efficiency and therefore low electricity consumption". According to their paper 59% of electricity would be used for heating in a network dominated by hydrogen boilers, but only 29% when heat pumps dominate. The system capital and generation costs were highest in the hydrogen heating scenario: the cost per kWh for hydrogen heating was found to be 75% higher than with heat pumps. Cassarino and Barrett do not attempt to cost retrofit measures. Their paper confirms the concerns expressed in the previous paragraph, and hydrogen boilers will not be considered further in this paper.

Insulation and heat pumps are not being deployed anywhere near quickly enough. In 2020 UKERC [9] reported that "at the current rate of heat pump deployment, it would take 700 years to hit net-zero" and "almost all of the UK's 29m homes need energy efficiency upgrades". But the rate of installation of insulation in the UK is in decline, with a 50% reduction recorded in the year to August 2022 [10].

Progress towards net zero in 2050 will require the removal of fossil gas boilers. In the absence of heat pumps, households will be forced to use resistive heating, and in the absence of insulation, they will need a lot of heating. This is a pessimistic scenario that energy researchers normally dismiss as "not an option". The problem is that with the current rates of installation of insulation and heat pumps, it becomes a likely outcome for a great many UK buildings.

Alongside the upfront cost of installing insulation and heat pumps, is the unwelcome change in external building aesthetics and/or loss of indoor floor space and the disruption caused particularly with existing occupied buildings. Even households that could afford the upfront cost may defer the work, perhaps in the hope that green hydrogen will become available or that resistive heating will suffice.

Resistive heaters are cheap and easy to install but, with a CoP of 1, they use at least three times more electricity than heat pumps. Coupled with the absence of good insulation, resistive heating will consume vastly more electricity to achieve the same indoor temperatures. This has been well known for decades. The contribution of this paper is to consider where that extra electricity will come from, its temporal distribution, and how this will affect the required generation and storage capacities.

2. Heat Pumps

Heat pumps transfer heat from the outside to the inside of buildings. Electricity is used to drive the pump rather than to provide the heat. There are three main types of heat pump: air source heat pumps (ASHPs) extract heat from the air, ground source heat pumps (GSHPs) extract heat from underground, and water source heat pumps (WSHPs) extract heat from water such as a lake or river.

The "coefficient of performance" (CoP) of a heat pump is simply heat energy produced divided by the electrical energy used. The CoP for a given heat pump is a function of the difference between the temperature of the heat source and the temperature of the heated medium (typically water). The greater the temperature differential, the lower the CoP. The theoretical maximum CoP is $(T_i/(T_i - T_o))$ where T_i is the indoor temperature and T_o the outdoor temperature in Kelvin.

For best efficiency, radiator temperatures are low (generally 35°C to 45°C), but to compensate, the radiating area is usually large, and underfloor heating is often used. Where heat pumps heat water for washing, again water temperature is typically raised to a lower temperature (<55°C) than would be typical with a gas boiler, where water is often heated to a much higher temperature than necessary, then mixed with cold water for use.

As well as the fitting of the outdoor apparatus, changing from fossil gas central heating often requires substantial indoor work. Additional or larger radiators will be necessary, but more disruptively, the pipework will often need to be upgraded to a wider bore. And of course substantial upgrades to insulation would normally be undertaken.

2.1 Air Source Heat Pumps

ASHPs are the cheapest and most convenient type to fit. The heat exchange unit is small and quiet enough to be installed in most gardens or driveways, or even mounted on walls. Modern units have an overall annual CoP of around 4, but, unhelpfully, the CoP decreases as the outside air becomes colder. Trystan Lea [11, 12], provides an in-depth case study of a recent ASHP installation in an ordinary, terraced house.

2.2 Ground Source Heat Pumps

The heat exchange pipes for GSHPs can be laid in one of two main ways. The cheaper way is to bury in trenches at least 1.5 m deep, but preferably deeper. However, this would not be suitable for most homes since a considerable area of land is required. The other method is to drill one or more vertical boreholes to a depth of 75 m to 200 m, where the ground temperature is at a constant of around 10°C. The footprint is very small, but at present the drilling process is expensive: the total cost is around twice that of a trench-based system. An advantage of GSHPs is that the underground temperature varies much less than the air temperature so, unlike ASHPs, a high CoP is possible even on the coldest days. According to Rybach and Sanner [13] in a borehole-type heat pump, the borehole cools gradually during the first 2 to 3 years of operation and then stabilises at 1°C to 2°C lower than the original temperature. The borehole also cools during the heating season and gradually recharges in the summer. This cooling could be mitigated by running the heat pump in reverse during the warmer months, providing efficient air-conditioning at the same time. Interseasonal thermal storage methods to improve CoP are explored by ICAX [14] and GSHPA [15].

2.3 Water Source Heat Pumps

WSHPs are not widely used since they require a substantial and suitable body of water to be nearby. Where the right conditions exist, WSHPs can be cheaper to install and can enjoy a higher CoP than GSHPs.

2.4 Heat Pumps for Different Housing Types

Rybach and Sanner [13] suggest that with a spacing of 15 m between boreholes for GSHPs, the total area needed for houses with a 7 kW heat load would be around 450 m^2, and, including house, garden and street, is an area "not uncommon in condensed building areas". This implies a borehole depth of about 70 m, though deeper boreholes would reduce the total area requirement.

New build estates could lay trench-based GSHPs under the entire site, including roads, as part of the ground works. Higher density housing could benefit from district heating schemes, using local resources such as lakes, waste heat from industrial processes, or even the sea. New roads could, automatically, be underlaid with piping for community-scale GSHP schemes.

ASHPs should be suitable for most flats when community heating schemes are not available. Small, quiet, wall-mounted units are now available. Depending on price differentials with GSHPs, ASHPs may be the norm for rural dwellings, except those with sufficient, and suitable, land to install trench-based GSHPs. WSHPs are likely to remain niche installations, due to the scarcity of suitable sites, and the ecological dangers of extracting too much heat from standing water, though sea-based community heating schemes may become more common in coastal areas.

It is assumed that some resistive heating systems (electric convector heaters, immersion heaters, IR heaters etc) will still be required – perhaps for top-up heating in the coldest weather, or for buildings in which heat pumps may not be suitable.

3. Methodology

Additional demand for electricity for heat in winter can be met largely by additional wind farms. The problem is that these wind farms may stand idle for extended periods, especially in the summer, and yet still have to be paid for. This raises the overall cost of electricity. Storage can help but again comes at significant cost.

The Python model developed for NZUK and made open source at [16] provides a platform to optimise the capacities of generation and storage, for a given demand scenario. In this paper a revised version, in which heat pumps were more accurately modelled, is used to compare comprehensive installation of insulation and heat pumps (base case) against a lack of insulation and resistive heating.

In both cases we assume that the UK will become carbon neutral by 2050. NZUK retains the two existing nuclear stations, but the vast majority of energy supply is derived from renewables, mainly wind power, the energy from which varies with wind speed. Meanwhile heating demand varies according to outdoor temperature. The NZUK model balances total daily electricity demand against generation from renewables and dispatchable power from stored carbon-neutral biomethane. It uses recorded weather data from 2017 to 2021 and ensures an energy balance for every day of each year. NZUK does not model interconnectors to the continent because, whilst they will be of significant value for short-term balancing, weather systems are often very large, so a deficit of renewables in one country will tend to coincide with a deficit in nearby countries [17]. In particular, long cold spells, and long spells with little wind, which are major concerns of this paper, are likely to be widespread.

The basic operation of the NZUK model is illustrated in Figure 1 which shows an example period of 90 days (taken from a year-long run in late 2021). The cyan shaded area is generation minus demand, and the variations are mainly caused by varying wind and solar generation. There are shortfalls in this generation at the left of the graph, and these are balanced by generating electricity from biomethane power stations (red trace). The orange line tracks the state of the hydrogen buffer store (capacity 5,000 GWh), as hydrogen is made by electrolysis and later used to make biomethane. The black trace is the biomethane store. It depletes rapidly in the first half as it is used to generate electricity.

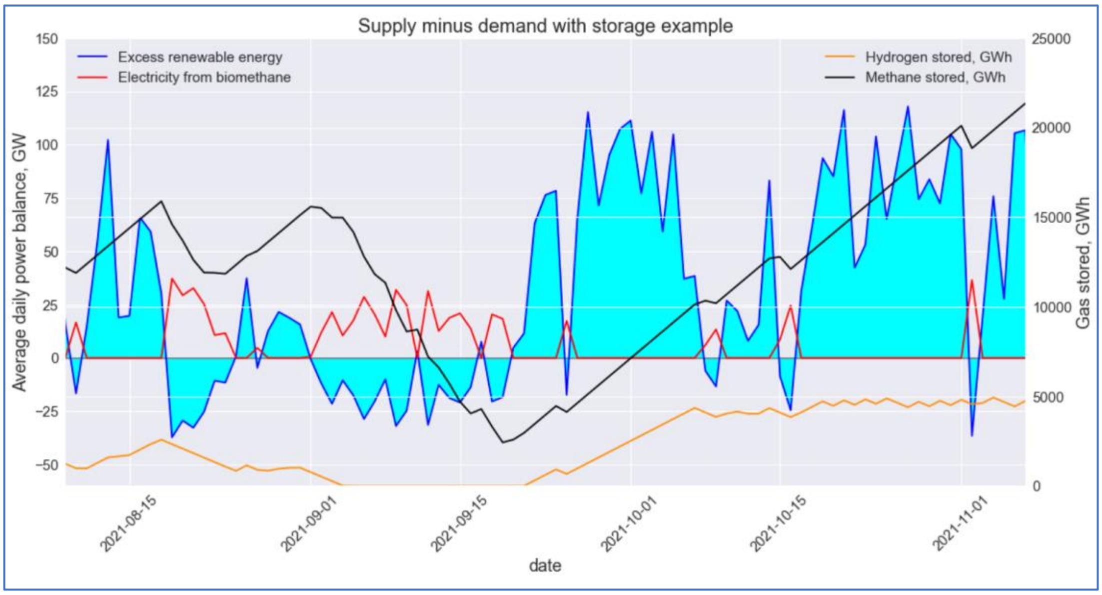

Figure 1 Illustration of energy storage for an example period of 90 days, with NZUK model.

This base-case operation of NZUK assumes comprehensive insulation as used by the Department of Energy and Climate Change (DECC) in "*The 2050 Calculator*" [18] which was published in 2012. Trajectory 4 in the DECC 2050 Pathways Report [19] (pp99-102), details the insulation updates, and shows a 50% decrease in "thermal leakiness" of buildings. This figure was used by the Centre for Alternative Technology (CAT) study [20], as detailed in the CAT methodology papers [21].

In NZUK [7] the following conservative assumptions were made regarding heating:

- 25% of heating would be provided by resistive heating with CoP = 1
- 25% would be via ASHPs with CoP = 2.5
- 50% would be GSHPs with CoP = 4

This gave an overall CoP of 2.9 and this figure was used throughout. The overall hot water CoP was assumed to be 2.0.

For this paper, heating is treated in more detail and with revised assumptions:

- 20% is resistive heating with CoP = 1
- 40% is ASHPs and the CoP will depend on outdoor temperature
- 40% is GSHPs and the CoP will decline over the heating season

For ASHPs the performance of a specific ASHP is used. In the video in Trystan Lea [12] the performance table in Figure 2 was presented. With an outlet temperature of 40°C the characteristic plots to an approximately straight line between T = -7°C and T = 20°C, with the equation: $CoP = 0.085 \times T + 3.2$. This has been substituted into the model, giving CoPs ranging from 3.03 to 5.10.

5.2 Heating performance data
(1)Packaged-type units
■ PUHZ-W50VHA2(-BS)

Water outlet temperature[°C]		25		35		40	
Ambient temperature[°C]		Capacity	COP	Capacity	COP	Capacity	COP
Nominal (Max)	-20	-	-	-	-	-	-
	-15	-	-	3.50	2.44	3.50	2.22
	-10	4.24	3.30	4.13	2.78	4.13	2.51
	-7	5.20	3.60	4.50	3.00	4.50	2.70
	2	5.15	4.20	5.00	3.50	5.00	3.15
	7	5.30	5.48	5.00	4.50	5.00	4.01
	12	5.34	6.20	5.04	4.98	5.03	4.37
	15	5.35	6.65	5.06	5.28	5.06	4.59
	20	5.37	7.41	5.10	5.79	5.09	4.98

Figure 2 Performance data for a Mitsubishi Ecodan ASHP.

For GSHPs, a small level of interseasonal heat storage is assumed. According to ICAX [22], the autumn CoP of GSHPs can be raised to 8 by storing heat in the summer, falling to 5.4 over the course of the heating season. In the model a CoP of 5.5 on 1st October is conservatively assumed, falling linearly to 3.5 on 31st May. The rate of fall is thus 0.00823 K/day. The rate of rise in the warm season is 0.0164 K/day.

For hot water, the space heating CoP values are used, but derated by 10%, the reduction being a result of the higher temperature outlet required. A temperature-related adjustment is also made to the heating required, since water entering the system will be colder in cold weather.

The CoP values for 2021 weather are plotted in Figure 3. Note that the ASHP figures are related to the ambient temperature, while the GSHP CoP is approximated as linear segments, as described above. The grey trace is the overall average CoP – with 40% ASHPs, 40% GSHPs, and 20% resistive heating – while the blue trace is the CoP for hot water. It can be seen that the GSHPs contributed substantially to the overall winter CoP.

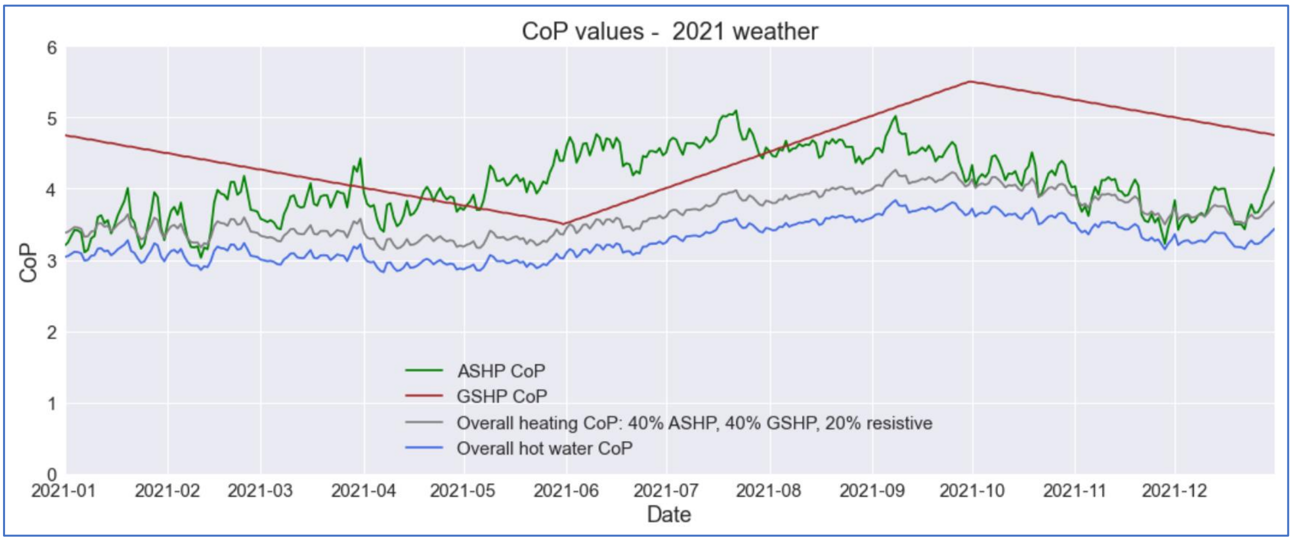

Figure 3 Estimated CoP values for 2021 weather.

The average CoP values for 2021 weather were as follows:

- GSHP, average CoP = 4.51
- ASHP, average CoP = 4.08 (this compares with 4.2 in Lea, [12])
- Overall average CoP = 3.63
- Average hot water CoP = 3.27 (this compares with 4.1 in Lea, [12] for ASHP hot water)

The base (NZUK) simulations were re-run with these new, daily varying, CoP values, calculated from each year's daily temperature data tables. The higher CoP values resulted in an overall demand reduction of 3.8% compared to the original NZUK calculations. Generators were reduced and the total LCOE savings amounted to 4.3%, though the unit electricity cost was barely affected. In Section 4, the updated figures are used throughout.

To investigate operation with no progress on insulation and with mainly resistive heating, the updated NZUK model was adjusted as shown in Table 1, assuming that 5% of buildings will use heat pumps. Cooling load would also be higher without insulation improvements, and especially considering the projected hotter temperatures due to climate change, but cooling is a relatively small load so has not been changed in the model.

Table 1 Changes made to heating requirements.

Parameter	**With insulation and heat pumps (Updated NZUK base case)**	**Resistive heating and lack of insulation**
Space heating CoP	Dynamic: 2021 average 3.63	1.10
Hot water CoP	Dynamic: 2021 average 3.37	1.10
Building heat loss rate (GW/degree)	5.60	12.44

Generation and storage capacities were then increased to supply the additional demand, and ensure energy balance for each day of the last five years of weather data. The model calculates a levelised cost of electricity (LCOE) so that the cheapest mix of primary renewable generation, and generation from stored gas, can be found.

4. Results

The makeup of daily demand, shown in Figure 4, is the case where insulation and heat pumps are fully deployed. 2021 weather was used in this example, though the other years tested, 2017, 2018, 2019 and 2020 are not dissimilar. The main single contributor is industrial demand (red area), with space heating (orange) in fourth place.

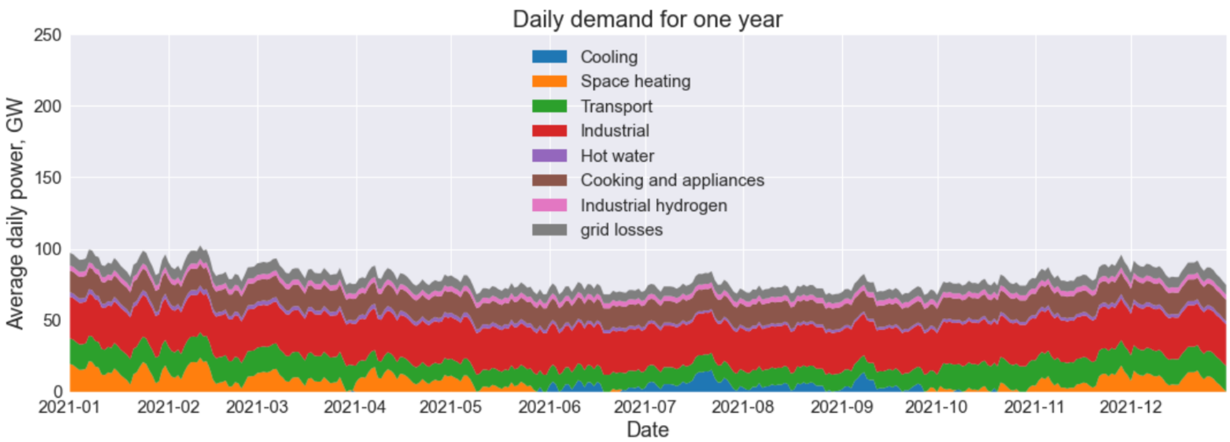

Figure 4 Daily demand with insulation and heat pumps fully deployed, based on 2021 weather.

The case of resistive heating and lack of insulation is shown in Figure 5. As expected, the orange area (space heating) has increased dramatically, and the overall area indicates that a great deal more total energy is required.

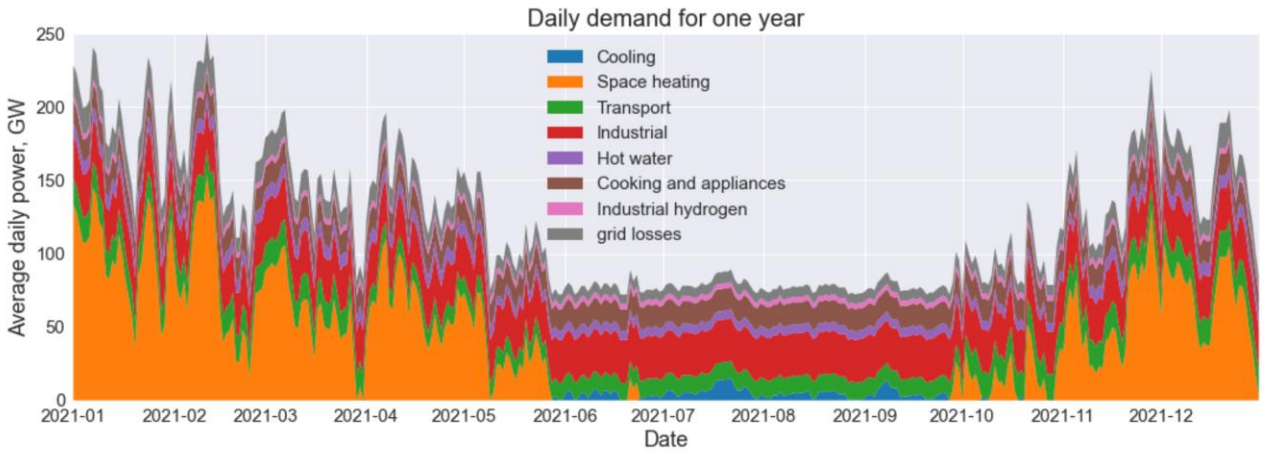

Figure 5 Daily demand with resistive heating and lack of insulation, based on 2021 weather.

The next major difference is the seasonality. Figure 4 (with insulation and heat pumps) is relatively flat throughout the year, whereas Figure 5, shows the total demand is much higher during the heating season than in the summer.

Lastly, Figure 5 is far more peaky. It peaks at up to 250 GW, from a minimum of about 70 GW, whereas Figure 4 peaks at only 105 GW, from a similar baseline.

Further details of the comparison are presented in Table 2. The figures for space heating confirm the orange areas of the graphs. Electricity consumption for hot water has trebled due to the reduced CoP of resistive heating. Total demand is the total areas of the graphs.

Table 2 Numeric comparison of the two cases.

Generation and demand *All figures are averages of 2017, 2018, 2019, 2020 and 2021 data*	**With insulation and heat pumps (updated NZUK base case)**	**Resistive heating and lack of insulation**	**Increase**
Space heating demand (TWh/y)	46	327	608%
Hot water (TWh)	21	64	205%
Total demand (TWh/y)	692	1049	52%
Wind generation (TWh/y)	734	1869	155%
Solar generation (TWh/y)	137	39	-72%
Total generation (TWh/y)	942	1979	110%
Spillage (curtailment) (TWh/y)	180	749	316%
Power station capacity needed (GW)	70	165	135%
Biomass needed (TWh/y)	117	178	52%
Gas fired generation (TWh/y)	58	99	48%
Electrolysis capacity needed (GW)	28	53	89%
Hydrogen storage capacity (TWh)	5	10	100%
Biomethane storage capacity (TWh)	30	60	100%

The rest of Table 2 shows the generation capacities required to meet the respective demands. These capacities are adjusted to achieve a minimum overall LCOE. The greatly increased spillage in the case of resistive heating and lack of insulation is due to the highly seasonal nature of the demand. When calculating the increased generation needed, hydrogen and biomethane storage capacities were doubled. This would be an extremely expensive upgrade, and the cost is not reflected in the LCOE figures. In practice there would be an optimum storage capacity increase for hydrogen and biomethane in terms of cost - the more storage that was available, the lower the spillage, and the lower the total generation needed. However, the calculation of storage costs is beyond the scope of this paper, so storage capacities were simply doubled. The large increase in (biomethane) power station capacity is due to the peakiness of the demand.

Comparison of the generation required for the two cases is shown in Figure 6 and Figure 7. The black traces are total demand as per the previous graphs. The graphs are on the same scale and the huge increase in wind generation (brown area) reiterates the data already shown in Table 2. Some seasonal correlation between supply and demand is apparent in Figure 7, but overall, it can be seen that the supply greatly exceeds demand on average. This implies significant spillage, and yet there is no scope to reduce the generation without causing shortfalls at other times (including in other years). These graphs of generation mix are the result of careful adjustment to minimise LCOE. An interesting but minor observation is the reduced role for solar power shown in Figure 7.

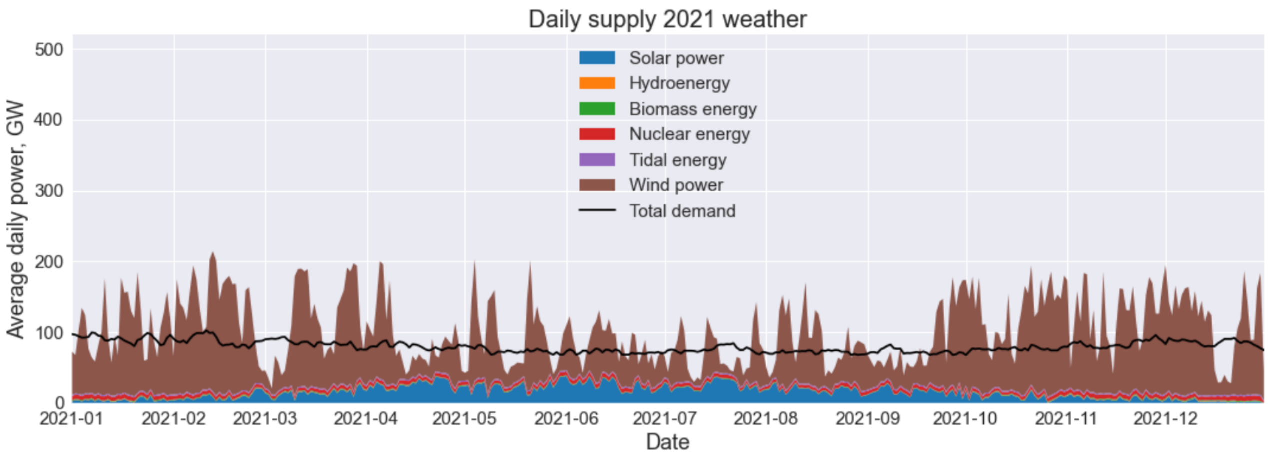

Figure 6 Generation mix with insulation and heat pumps fully deployed.

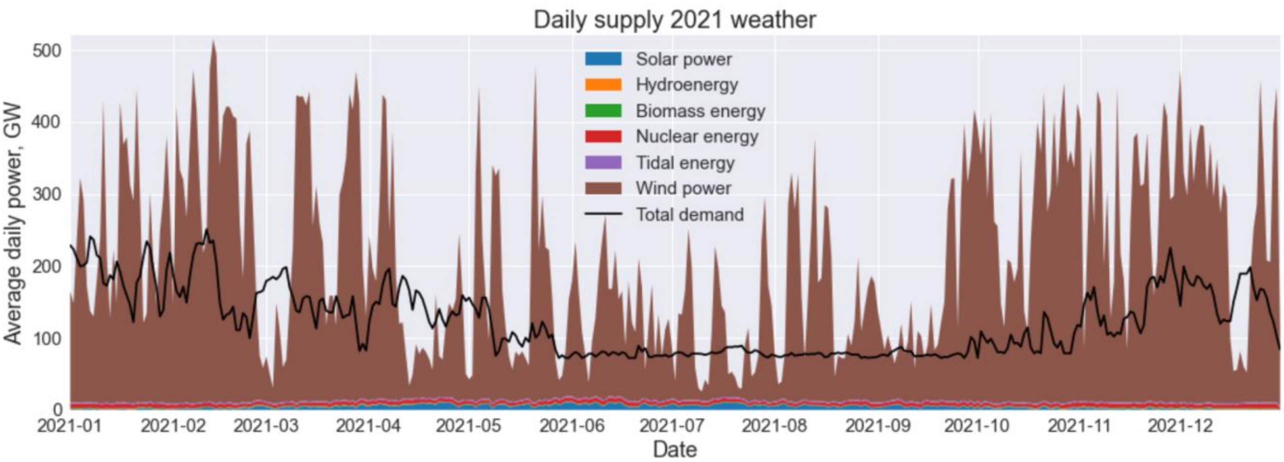

Figure 7 Generation mix with resistive heating and lack of insulation.

The resulting cost differences are shown in Table 3, again averaged over five years. The 34% increase in unit electricity cost is due to the increased spillage and increased role of biomethane power stations. This causes the overall total cost of energy to increase by 98% - an even greater proportion than the 52% increase in volume of energy used. The total LCOE is over £60bn per year higher.

Table 3 Electricity cost comparison.

	With insulation and heat pumps (updated NZUK base case)	**Resistive heating and lack of insulation**	**Increase**
Electricity used (TWh/y)	692	1049	52%
LCOE (£/MWh)	£91	£122	34%
Total LCOE (£/y)	£64bn	£127bn	98%

5. Transition Costs Comparison

The data already presented in Table 3 shows the position in 2050, when it is assumed that the transition to net-zero is complete. This section looks at the year-on-year costs between 2022 and 2050. In both cases, steady progress is assumed towards net-zero, including general demand reduction. In each of the next 28 years, $^{1}/_{28}$ of the required progress towards net zero is made.

- In the case with insulation and heat pumps, $^{1}/_{28}$ of the required generation is installed, and costed together with $^{1}/_{28}$ of cost of the required insulation and heat pumps.
- In the case without insulation and heat pumps, their costs are omitted but $^{1}/_{28}$ of the increased generation required to supply resistive heating with a lack of insulation is included.

The typical cost of insulating and installing a heat pump to an individual house is around £18,000 [23] or £21,600 for the “maximum energy efficiency case” [24]. The higher figure was used here. According to the ONS [25] there are 29,548,000 dwellings in the UK (2020 figures) so the total retrofitting cost for dwellings would be £638bn. Uplifting this to include service and industry buildings, which account for 38% of the total heat loss [21], requires a multiplier of 1.6 and gives a total of £1021bn, or £36.5bn per year from 2022 until 2050. In practice, however, not all buildings will be retrofitted. Many buildings will be demolished before 2050, having reached the end of their useful lives, and will be replaced with new, more energy efficient, buildings. In this paper we assume that 80% of buildings will need to be retrofitted with good insulation and heat pumps, at an annual cost for 28 years of £30bn.

Further assumptions were made to enable the comparison of transition costs:

- All present energy vectors – including oil – have the same retail cost per MWh as that paid by the average consumer for a balanced mix of gas and electricity in October 2022. All energy has to be accommodated in the calculation because by 2050 almost all energy will have transitioned to electricity.
- October 2022 fossil-based retail costs will continue to hold as the transition to renewables is made.

Retail cost of energy, rather than LCOE, is used in the comparison. According to Ofgem [26] £55/MWh of a typical dual-fuel bill is non-fuel costs. LCOE in 2050 for the case with insulation and heat pumps was calculated as £91/MWh (see Table 3). It could be assumed that wholesale energy costs would be 10% higher than this to provide a profit margin for the producers. The retail price would include the non-fuel costs, so £155/MWh in total. Similarly, the retail electricity price in the case without insulation and heat pumps would be £122 + 10% + £55 = £189/MWh. This is illustrated in Figure 8.

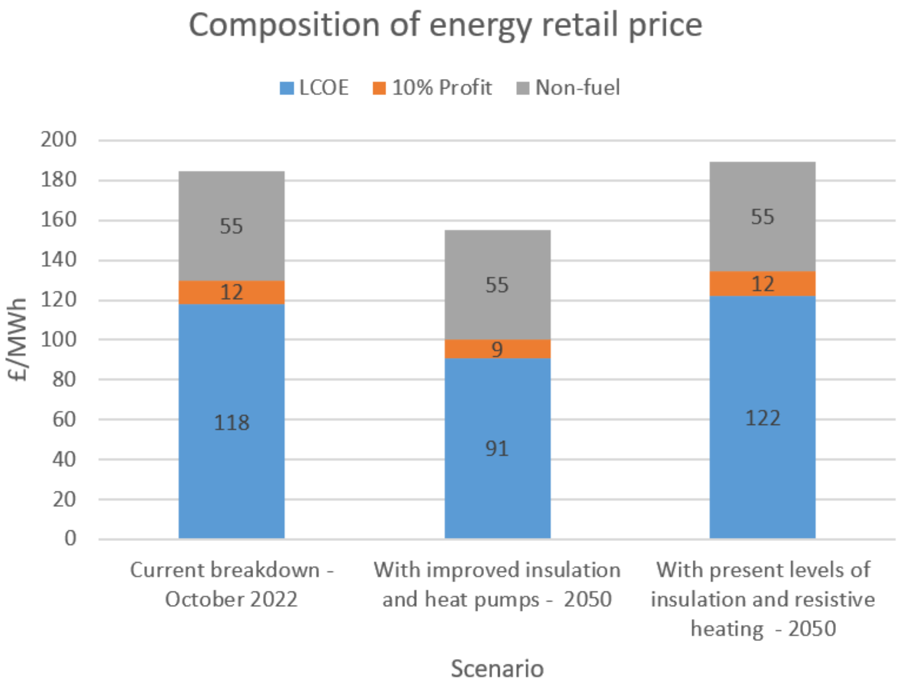

Figure 8 Comparison of energy retail prices.

For the comparison, the starting point for both cases is the 2022 energy price and demand. According to Ofgem [26] the typical dual-fuel bill from October 2022 will be £3,549 for 19.1 MWh/y, giving an average unit energy price of £186/MWh, (though government subsidies were later applied to reduce this figure for consumers). For comparison purposes it will be assumed that *all* energy at present costs £186/MWh, and according to DUKES 2022 [2] total energy consumption in 2021 was 1,978 TWh. These figures are summarised in Table 4.

Table 4 Parameters for cost comparison curve.

Item	**With insulation and heat pumps (NZUK base case)**	**Resistive heating and lack of insulation**
Energy demand 2022 (TWh)	1978	1978
Energy (electricity) demand 2050 (TWh)	693	1049
Unit retail cost of energy 2022 (£/MWh)	186	186
Unit retail cost of energy (electricity) 2050 (£/MWh)	155	189
Annual insulation and heat pump retrofit cost (£bn)	30	0

The curve in Figure 9 plots the cumulative cost difference, subtracting annual energy plus retrofitting costs from the equivalent non-retrofitting costs. Annual figures were found by interpolating between the 2022 and 2050 terminal points in Table 4. The cost difference reaches its minimum in 2029, but after that, the energy savings begin to outweigh the annual retrofitting costs. The break-even point comes in 2036 and thereafter there would be increasing net gains as a result of installing insulation and heat pumps.

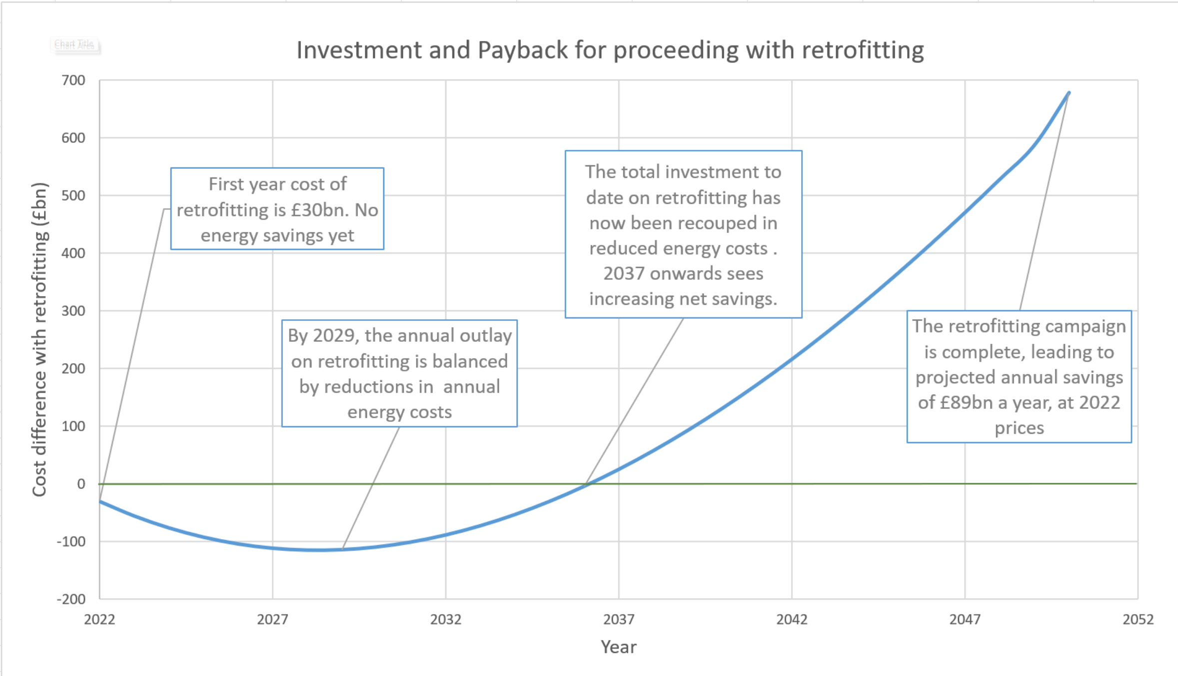

Figure 9 Cumulative cost difference between cases.

6. Discussion

This paper has focussed on the economic costs of reaching net-zero emissions for the UK without retrofitting effective insulation and heat pumps. We have shown that it is theoretically possible, but it would be far more expensive than including insulation and heat pump installation.

The extra direct energy costs incurred by not fitting insulation and heat pumps are a result of:

- A great deal more renewable generators being required to meet the much heavier, and much peakier, electricity demand during the heating season. The base NZUK case required a very challenging 11 times more wind turbine capacity than existed in 2021. This would have to increase by a further 155%.
- Much more biomethane-fired generation is required to balance the grid, as a result of large differences between wind power and demand. Gas-fired generation is expensive due to large efficiency losses, and low capacity factors of the power stations.
- Substantial curtailment or spillage due to excess generation: four times more spillage than in the base case. The electrolysis capacity and gas storage facilities are already greatly increased in an attempt to make better use of the energy generated.

But the calculated LCOE figures do not include much of the extra infrastructure required. Figure 5 shows that peak demand would more than double without retrofit, implying that the transmission and distribution grids would have to be twice as strong. Also the hydrogen and biomethane storage capacities have been doubled. No attempt has been made to cost these items, though they would represent significant extra expense. Table 5 provides a summary of what is included in the LCOE figures and what is not. The curve in Figure 9 would show an even faster payback if these costs were accounted for. As Table 2 shows, 52% more biomass is required. This is included in the costings, but it might be difficult to source this large increase.

Table 5 Indication of which additional costs are included, and not included, in LCOE pricing.

Included in LCOE cost calculations	Not included in LCOE cost calculations
Capital and running costs of all generators	Hydrogen storage and pipework
Cost of hydrogen production (inc electrolysers)	Biomethane storage and pipework
Cost of biomethane production (inc AD)	Electricity transmission grid strengthening
Capital and running costs of power stations	Electricity distribution network strengthening

Figure 9 shows that in the first years of a retrofit campaign there would be initial net outlays, totalling up to £115bn by 2029. The break-even point – where total retrofit costs are balanced by total energy savings – comes seven years later. By 2050, the UK would have saved £674bn by retrofitting, with annual savings of £87bn thereafter. Even if retrofitting costs were 33% higher than expected – at £40bn per year for 28 years – the scheme would still break even by 2042, with net savings of £394bn by 2050.

The total net outlay of £115bn up to 2029 is considerable, but when set against the £85bn that the government was prepared to borrow in September 2022 to hold energy prices at their current very high levels for just two years, it begins to look reasonable, especially as fitting insulation and heat pumps is a one-off investment which will lead to permanently lower energy costs.

As shown in Figure 8, zero carbon electricity would cost 15.5 p/kWh if insulation and heat pumps are fitted, and 18.9 p/kWh otherwise. That compares with October 2022 energy at 18.5 p/kWh, which includes nearly 80% fossil fuels. Cassarino and Barrett [8] also projects lower future energy prices, but gives much cheaper figures than this paper: 10.2 p/kWh for heating for their heat pump scenario. There is not enough detail in their paper to see how this figure was derived, but according to BEIS [27], electricity from offshore wind projects installed in 2030 will cost 4.7 p/kWh. With non-energy costs currently at 5.5 p/kWh, the retail energy price would be 10.2 p/kWh *only* if all energy was from primary renewables (i.e. none from biomethane power stations), there was no profit margin, and there was no spillage.

The subject of who would pay for the required retrofitting would be a policy decision, but some commentators have suggested that the government should fund retrofitting of government and local authority owned buildings, while loans would be available for private owners and companies to update their properties to a required standard.

In a 2019 report, the Climate Change Committee said, “Simply put, there is no way in which the UK can meet the legally-binding climate change targets that Parliament has determined unless we take the [retrofitting] measures outlined in this report.” [28].

If the mass roll-out of insulation and heat pump installations had started in 2012, when the DECC report [18] was published, the cumulative savings graph would have passed its nadir by now, and there would be far fewer people unable to keep warm in the coming winter. According to E3G [29], 57,288 people died in the UK in the 5 years to 2018 due to cold housing conditions, while NEA [30] reported that there were 8,500 deaths due to cold homes in the winter of 2019. Many would argue that 8,500 avoidable deaths a year due to cold is unacceptable in a wealthy country, but with energy prices rising and real incomes declining, the death toll is unlikely to fall until a concerted retrofit campaign gets underway.

There is a very real danger that if a large-scale retrofitting campaign does not begin immediately, the UK might fail to achieve net zero by 2050. The UK cannot expect poorer countries to work hard towards a carbon neutral future (and they must if there is to be any chance of avoiding a complete climate breakdown), if it is not seen to be taking the first steps itself. Greenhouse gases from poorer countries are as much against the UK's national interest as home-produced emissions. According to the IPCC [6], "The global wealthiest 10% contribute about 36-45% of global GHG emissions". It is vital that the UK, along with other wealthy countries, take the lead.

This paper has assumed that retrofitting will take 28 years to complete, but the total savings will be greater, the lives lost fewer, and the greenhouse gas emissions diminished, if the retrofit rate was increased. And many would argue that carbon-neutrality must be achieved long before 2050: "Cumulative net CO_2 emissions of the last decade (2010-2019) are about the same size as the remaining carbon budget for keeping warming to 1.5°C" [6] and yet emissions are still rising. Insulating buildings is a necessary, and cost-effective, first step to reducing emissions.

7. Conclusions

The pessimistic proposition that the UK retires fossil gas boilers (as it must) but fails to install heat pumps or insulation, forcing the use of resistive heating in poorly insulated buildings, has been modelled.

The space heating electricity demand is seven times higher than the case with good insulation, and heat pumps and resistive heating dominates all electricity demand. Moreover, it is very seasonal and peaky, making it difficult to supply directly from renewable, or indeed nuclear, sources.

In the present fossil gas economy, a similarly seasonal and peaky heat demand is easily served by the enormous energy storage inherent in fossil gas. It is easy to overlook the scale of that storage until trying to replace it with any alternative. The challenge here is not so much to do with the variability of renewables, much more with the variability and scale of the thermal demand.

Whilst it is theoretically possible to meet this demand "simply" by building yet more wind farms and electrolysers, the scale and cost of that proposition only points to the urgency of reducing the thermal demand. The effectiveness and economic sense of comprehensive installation of insulation and heat pumps has been shown.

As well as making net zero a practical possibility for the UK, insulation has immediate benefits for almost all its citizens: warmer living spaces and reduced energy bills.

Author Contributions

A Williams: preparation of Python model, data collection and analysis, report writing. Dr M Thomson: project guidance and direction, report writing and editing.

Funding

The research for this paper did not receive any funding.

Competing Interests

The authors have declared that no competing interests exist.

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