Decarbonising UK Wet Home Heating Effectively

Damon Hart-Davis (6778055)

Supervisors: Dr. Lirong Liu and Prof. Matthew Leach

Confirmation report submitted in partial fulfilment of the requirements for the Degree of Ph.D. in Environment and Sustainability at the University of Surrey.

July 30, 2024

Contents

Chapter 1

Introduction

> We'll go down in history as the first society that
> wouldn't save itself because it wasn't cost-effective.
> Kurt Vonnegut / Donella H. Meadows

1.1 Problem and Background

UK residential heating, largely 'wet' ie gas-fired with radiators, is responsible for as much as 20% of the UK's carbon footprint (Stark & Thompson 2019). This must be almost entirely decarbonised as part of Net Zero goals to tackle climate change. To achieve this, such wet systems in circa 20 million UK dwellings already built that will still be in use in 2050 are likely to be largely replaced with heat pump systems (Stark & Thompson 2019, Piddington et al. 2020, Reguis et al. 2021, LCP Delta 2022, UK DLUHC (Department for Levelling Up Housing and Communities) 2022*a*, UK BEIS 2022, UK National Infrastructure Commission 2023, Hart-Davis 2023*c*). Some current heating systems, especially in dense urban areas, will be replaced with district heating — a majority in London new build (Henretty 2020, Sørensen 2023, Makasis et al. 2023). Some low-demand properties may deploy low-CAPEX simple electric resistive heating with or without storage (Palmer & Terry 2021). In any case, new electric heating will also need to interact well with a grid powered by intermittent renewables (UK DESNZ (Department for Energy Security and Net Zero) 2024*b*). Older and part-occupied UK housing stock will require particular attention to minimise overall carbon emissions.

Retrofit done well is not simply a technical exercise: swapping out one ignored white metal box for another. The swap from gas to heat pump also requires resolving challenges in finance, space for water storage and external units, disruption for possible radiator and pipework replacement, disruption and costs of removal of the gas supply in due course, getting used to old noises and quirks going and new ones in their place, learning to live with demand flexibility such as grid responsiveness, understanding new controls and ways of working with the heating. Retrofit on the required scale is a human, social (Ambrose et al. 2023) and political undertaking too.

Further, replacing tens of millions of heating systems is not an overnight affair. Nor is the process of upgrading the grid generation and transmission and distribution and tariffs to support and massage their load. Nor is scaling up and skilling up the equipment and installation supply chain (Cretu et al. 2022, Preston 2023, Delta 2023, Toleikyte et al. 2023, Woollard et al. 2023, Zanetti 2024). So there will be a transitional period where a combination of technologies and heating fuels will be used, across the country and even in individual homes (Bennett et al. 2021), which has to be managed effectively.

Decarbonising home heating is and will remain a complex process, taking place at accelerating pace across the UK, Europe and worldwide. There has not been much of a dress-rehearsal in terms of the scale required in the locations that have the most to decarbonise. Much will have to be learnt as the process unfolds. This research targets making this process work as well as possible: understanding the issues and solutions, and also conveying the learnings to installers and manufacturers and consumers and policy makers for impact. Working ‘well’ includes (near) maximising carbon-reduction and climate improvements, alongside end-user agency (even to the extent of making basic maintenance cheap and viable for the householder, rather than an exclusive priesthood of expensive engineers) and comfort and health and satisfaction (Donkin & Marmot 2024). This is not a simple single-dimension engineering exercise.

The UK parliament will change at least once during the course of this research, and some salient climate-induced disasters may also land. So public mood may shift decisively away from “not cost-effective” towards something more rational that befits an existential crisis, and the research targets may need to be adjusted accordingly.

1.2 Literature Review

The pressure to decarbonise at speed, learning on the fly, ensures that there are many avenues not yet fully explored, and to which positive contributions are plausible within PhD programme scope. Many possible strands of work have been considered (see Appendix A), given my previous commercial and ‘activist’ experience, and the research conducted so far.

There are many elements that need to be in place to allow decarbonisation, some of which are already present. Firstly the technology, which while we can hope for incremental improvements, already exists and with a basic design the same for about a century (Staffell et al. 2012). Retail heat-pump technology is able to deal with all UK microclimates and building ages and archetypes (UK Energy Systems Catapult 2021), and throughout Europe with the help of different refrigerants (Monschauer & Wetzel 2022, Rosenow et al. 2022). It is already widely understood that the electricity grid (transmission and distribution) will need to be upgraded to deal with significant extra load from heat pumps amongst other things being electrified and work is underway (*Future Energy Scenarios: Bridging the Gap to Net Zero* 2023). The incoming UK Labour government has brought forward to

2030 the target to decarbonise the GB grid (*Great British Energy founding statement* 2024), which would then decarbonise all grid-powered heat-pump space heating. There will likely need to be a rebalancing of system costs, moving green charges away from electricity, possibly in part on to gas, to make OPEX for heat pumps better than gas (UK HMRC (His Majesty's Revenue and Customs) 2023). An army of system designers and installers (and certifiers) of such heat pump systems is needed as noted before. Regulations (such as EPCs and successors) will have to change to acknowledge that heat pumps can and will be zero carbon rather than perverse disincentives that currently can rate homes as *worse* with a heat pump. End users in their homes will need to be able to operate these more complex systems work (ie have agency), as indeed will those who design and install the pumps. The control mechanisms for the heating will need to support these heat pumps better, given their more complex operation than legacy gas, and the need to interact with a renewables-powered grid (UK DESNZ (Department for Energy Security and Net Zero) 2024*b*, Office of Gas and Electricity Markets (Ofgem), UK 2024) and to cost-effectively maximise their climate effectiveness by minimising energy demand especially amongst the majority of homes already built eg Hart-Davis et al. (2024).

Thus core items to investigate and contribute to the optimisation of are various elements of heating system controls, user agency, and the upheaval and process of transition to the coming world of zero-carbon home heat. They are reflected below.

1.2.1 Heating system management and optimisation

The scope of 'controls' for a domestic heating system is wide. Controls start with from the basic detection of a "call for heat" and the management of the generation and delivery of that heat. Also in scope is interaction with the occupants: explicity though thermostat control dials and timers or smartphone applications, and implicitly though occupancy detection and response to static and dynamic energy tariffs and responses to unexpected heat such as from a crowded party. Some of this interacts with user agency and understanding, particular where the system itself is a moving target as it tries to learn and adapt to user behaviour.

Even for gas boilers and wet heating systems with radiators, there is some inverse system efficiency dependence on the flow/return temperature of the water to/from the radiators (efficiency goes up when a system is run cooler) for example to allow condensing mode for modern gas boilers, and stronger temperature effects apply to heat pumps (Maivel & Kurnitski 2015, Jindal et al. 2022). Another issue for such systems is 'cycling' when the boiler heat output power cannot modulate down at all or far enough, and the boiler must cycle off and on to avoid the home overheating (Bagarella et al. 2016). For this reason there exist multiple common control strategies to manage boiler output temperature and power (Table 2.1). It is still controversial if, as part of such a scheme, and as has traditionally been the case with UK gas heating, the entire system should be turned off or at least set back in temperature when the house or individual rooms are unoccupied or occupants are asleep.

While the UK's MCS regulator does almost insist on weather compensation (MCS (UK Microgeneration Certification Scheme) 2020, 2021) it remains unclear exactly what variations such as "room influence" to partly close the control loop (Boait et al. 2011) have been applied in existing UK and EU installations, and what is happening with new installations. Still less does there seem to be good literature on what should be done, nor sufficient verification and re-calibration in situ to physical dwellings, per Marshall et al. (2017). Nor the pros and cons of zoning in older and part-occupied stock, and interaction with cycling, available modulation depth and so on per Oikonomou (2022). Relevant modelling includes Dongellini & Morini (2019) (TRNSYS), Marshall et al. (2017) (Designbuilder), Ji et al. (2019) (IESVE). A holistic grasp of the interplay of these common basic features is surely necessary to maximise the climate gains from decarbonising, while minimising costs and maximising comfort. *These are understanding gaps that I believe would be useful to fill.*

1.2.2 The process of decarbonisation

Though politicians and environmentalists might wish for it, there is no click of the fingers that will instantly decarbonise all UK homes. Per Anna Karenina, every fossil-fuel-heated home is unhappy in its own way. Generally each UK home, or at least each building or block of similar homes, has to be considered on its own merits for effective decarbonisation, ie what subset of the ideal measures to apply and when to stage them (Eyre et al. 2023), and this bespoke approach has costs, including time. It is also the case that some buildings will be harder to decarbonise, and for some buildings some of the preferred tools, such as insulation or improved glazing or storage of electricity or heat, may not be available for reasons of space in smaller homes, or conservation (UK DLUHC (Department for Levelling Up Housing and Communities) et al. 2024, Wollard & Sissons 2024). "Fabric later" will work in many cases. For example, retrofitting a heat pump powered by a grid on a pathway to zero carbon intensity will eliminate such emissions entirely when the grid does, whereas insulating a gas-heated home only *reduces* emissions. Though there is wide agreement (eg Stark & Thompson (2019)) that simple cheap no-regrets measures should be deployed in most cases where possible: draft exclusion, loft insulation and cavity wall insulation. It is also pertinent that many heating system replacements are distress, at which point there is no time for fabric improvement — "waiting until the rain stops to fix your roof" is for many not possible (Hoggett et al. 2011). Dropping in a like-for-like fossil-fuel heat source with a 15-year life due to a rigid insistence on fabric-first does not help achieve Net Zero. A sometimes-fabric-later approach may require availability of heat pumps with enhanced modulation depth (or "turndown ratio"), so that when fabric is improved after a heat pump is installed this does not make the heat pump effectively 'oversized' and force more wasteful and damaging on/off cycling. Increased modulation depth would in any case preserve efficiency through changes of occupancy style, eg with new owners or tenants, and even more mundanely and universally ... better behaviour through the shoulders of every heating season when demands are marginal (Emerson Climate Technologies Inc.

2014, Bagarella et al. 2016, Oikonomou 2022). *The implications of "understanding first" retrofit (Eyre et al. 2023) warrant further study, and dissemination.*

1.2.3 Making decarbonisation work for the occupants

This review section is more preliminary, with further planning and scoping to take place concurrently with the other main research strands. It is focussed on elements that may drive this scoping and the methodology.

Sound appears to have been under-explored as a first-class route to convey information to human users, beyond warning noises. It is rarely an equal partner with visuals. For fully able users and those with visual or attentional or other impairments, or who are simply busy and distracted and not that interested in their heating system per se, we are likely missing a trick.

Intriguing studies of speech information bandwidth at tens of bits per second (Coupé et al. 2019) as an audio bandwidth floor, and modern video compression getting down to kilobits per second (Oquab et al. 2021) implying an effective visual bandwidth ceiling, and other indications of effective data sensory capacities (Foulds 2004, Stevens 2013), suggest that audio may be being underused as a UI channel. This before considering enhanced comprehension from simultaneous channel use, and accessibility improvement for all.

Householders find heating controls hard to use (Lomas et al. 2018). In general 'folk physics' is poor on how heating systems work and should be improved alongside the UIs to meet comfort and cost (and carbon) goals.

Heating controls such as boiler flow temperature and even room temperature, especially when attempting TTZC (time and temperature zone controls) can be difficult for most users to understand and interact with (low contrast LCD screens near floor level for example). Can we improve accessibility and effectiveness for all users eg Black et al. (2022) with purposeful and cross-manufacturer partly-harmonised design?

The vast majority of UK home heating in 2024 is gas-fired wet heating with radiator heat emitters as previously noted (UK National Infrastructure Commission 2023). UK heating engineers are already bad at specifying such relatively simple gas boiler systems: typically they have been oversized especially for the space-heating role, and oversizing is particularly bad for heat-pumps (Reguis et al. 2021, Harris & Walker 2023). For example my own home boiler can only modulate its own heat output down to about 8 kW, which is about twice the peak demand in the depths of winter, resulting in excess mechanical wear and tear and wasted energy from cycling. Gas boilers are often run so hot that that they cannot run in condensing mode which wastes $\sim$8% of the fuel and a large amount of the clever hardware (Jindal et al. 2022, UK BEIS 2022, Woollard et al. 2023).

Gas boilers, especially 'combi' (combination) gas boilers with instant and effectively limitless hot water have liberated us from finding the space for a storage tank, and planning when to heat and use the water. Both the space and the scheduling will be big stumbling blocks for some retrofits (Stark & Thompson 2019, Terry & Galvin 2023). Somehow we will need to add grid-responsiveness, preferably dynamic — changing daily or hourly to response to weather — to make a zero-carbon grid work reliably and cheaply (*Future Energy Scenarios: Bridging the Gap to Net Zero* 2023, UK DESNZ (Department for Energy Security and Net Zero) 2024*b*).

Retrofits and the green energy supply world they move into will by default be more complicated than now, so we need to actively work to educate and inform installers and users and/or hide some of this complexity eg Berry et al. (2023). Everything gets a little more complex for historic and listed buildings eg UK DLUHC (Department for Levelling Up Housing and Communities) et al. (2024), and those in conservation areas (10% of my local area).

Further, partly because heat pumps space heating is a market still maturing, controls for heat pump systems do not even have a basic level of harmonisation that would improve the likelihood of successful commissioning and operation. Should some basic common subset of controls be mandated for all products? Should novel user interaction (UI) mechanisms be developed in order to convey better some of the more subtle likely results of adjusting controls given slower response and (say) Time-of-Use tariffs, and improve accessibility for all users? Should some of these novel techniques be mandated in product standards across Europe including the UK and EU? *These are more gaps in understanding that I would like to help fill.*

1.3 High-level Research Aims

The key aims of this research programme, in support of making UK home heat decarbonisation work well, are to find answers to:

- What are the practical policies, design rules and end-user guides to get the best outcomes in money, comfort and climate repair outcomes from (UK, wet) heating system retrofits?
- How do we best reduce logistical difficulties of such retrofits — in particular is "understanding first" the best approach, else what is?
- Heat-pump systems are more complex to operate well than the combustion appliances that they will be replacing, and an extra dimension of grid-interaction is likely to be key also; how do we make it easy and cheap and simple for end users to good results and have agency?

Chapter 2

Work to Date: To Zone or Not...

This chapter is the body of (Hart-Davis et al. 2024), “To Zone or Not to Zone When Upgrading a Wet Heating System from Gas to Heat Pump for Maximum Climate Impact: A UK View” published May 2024 in MDPI Sustainability (Hart-Davis et al. 2023, preprint). References are merged into the full report set to avoid redundancy.

2.1 Introduction

UK residential heating, responsible for 10 to 20% of the UK’s carbon footprint (Stark & Thompson 2019), must decarbonise as part of Net Zero goals to tackle climate change. Gas-fired radiator systems in circa 20 million UK dwellings standing now that will still be in use in 2050 are likely to be replaced with heat pump systems (Stark & Thompson 2019, Piddington et al. 2020, Reguis et al. 2021, LCP Delta 2022, UK DLUHC (Department for Levelling Up Housing and Communities) 2022*a*, UK BEIS 2022, UK National Infrastructure Commission 2023, Hart-Davis 2023*c*). Most of those dwellings currently use TRVs (thermostatic radiator valves) to help avoid overheating, improve comfort and save energy, money and thus also carbon emissions, in compliance with building regulation and guidance (UK DLUHC (Department for Levelling Up Housing and Communities) 2014, Bruce-Konuah et al. 2018). The TRVs can provide or implement part of ”zoning” to focus heat where it is needed and reduce losses from where it is not. For older thermally leaky dwellings with partial occupancy (Cockroft et al. 2017, Domestic Building Services Panel 2020), such as “empty nests” when children have left, TRV-driven savings can be particularly significant. Simply heating bedrooms during the day, while only living areas are occupied, is a potential waste that zoning can trim. Smarter and learning TRVs that respond dynamically to occupation patterns and heating system behaviour can further enhance micro-zoning gains (Hart-Davis et al. 2022, Beizaee et al. 2015).

It is reported that only “low-quality” formal evidence for energy savings from TRV (and other zoning) exists (Lomas et al. 2018, Johnson et al. 2021, Xu, Jiang, Chen, Li, Wang & Yan 2023, Terry & Galvin 2023), though claims of over 30% for non-smart mechanical TRVs have some support (Fitton et al. 2016) or more typically around half that (Marshall et al. 2016). A recent study of domestic time and temperature "smart" zonal heating controls showed a saving of 3.5% only over existing controls (Lomas et al. 2022), which in most cases already included TRVs. The first author has seen much larger savings, similar to (Beizaee et al. 2015), over non-smart TRVs in a 100+ home trial in comparable circumstances, but those results are not public, and thus there remains uncertainty. It is however evident that domestic heating controls are hard to use effectively (Lomas et al. 2018).

The explicit literature on interactions of TRVs (or similar micro-zoning and static or dynamic temperature setbacks) with heat pumps is relatively thin and such reality often does not match models mandated by regulation such as SAP (standard assessment procedure) (Fitton 2017), and in any case will likely not be reaching heating professionals designing and implementing gas to heat pump retrofits. Such information should be disseminated explicitly though the industry literature and training in practical forms, and implicitly via regulations and supporting calculation methods such as the "Home Energy Model" for the energy rating of new English homes (UK DLUHC (Department for Levelling Up Housing and Communities) 2023, UK DESNZ (Department for Energy Security and Net Zero) 2023*b*).

This work aims to fill the understanding gap by assessing the energy efficiency benefits of micro-zoning using TRVs with heat pumps and by testing a specific common industry claim therein. It is evident that the worry deterring installers from using TRVs in heat pump retrofits is likely unfounded for most households in practice. Additional energy, money and carbon savings can be had by using them together.

2.1.1 TRV History

Thermostatic radiator valves were invented by Mads Clausen of Danfoss (in 1943 (Andersen 2017), promoted in 1952 as energy saving) for early boiler systems that were run hot, so as to avoid cooled return water damaging the heat exchanger. Such systems had the water flow from the boiler at 80 °C or higher. With a simple tap/resistance valve on the radiator to control the passage of water through it, rooms could quickly and seriously overheat. TRVs avoided that discomfort by capping room temperature. A useful side-effect was saving energy. For a well set-up modern system, setting an appropriate flow temperature (primarily depending on external temperature for weather compensation (Huchtemann & Müller 2013)) will minimise overheating. There will still be occasional solar and appliance and other heat gains that need to be accommodated, and some rooms will benefit from being kept cooler than living areas. TRVs can help in such cases.

2.1.2 How TRVs Work

A TRV enforces a nominal maximum room set-point or target temperature. As the room (and thus air) temperature around the TRV rises, the TRV restricts and eventually stops water flow through the radiator, thus reducing heat input to the room. Simple mechanical TRVs may use a wax- or oil-filled bulb bearing down on a valve pin. As the air around the valve warms, the bulb expands, the pin is pushed down, and the flow of water through the radiator is reduced, thus closing a regulating negative temperature 'thermostatic' feedback loop. As in (Hart-Davis et al. 2022), a "smart" TRV control mechanism may include a microcontroller to react to and anticipate occupancy, for example, to further reduce heat demand in vacant areas. Typically, radiators draw their hot water in parallel from the central heat source; see Figure 2.1.

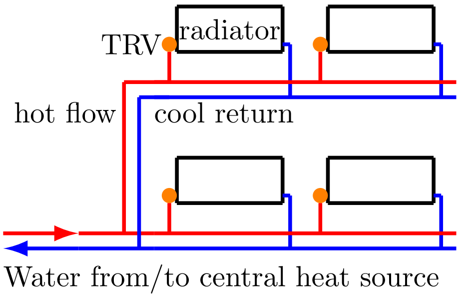


Figure 2.1: Schematic of four radiators in a wet central heating system each regulated by a TRV (the orange device to left of each radiator) drawing hot water in parallel from a common heat source such as a gas boiler or heat pump.

2.1.3 Heating Control Schemes in Europe

EU ErP (energy related products) defines eight control classes (811/2013) per Table 2.1 (European Union n.d.*b*,n). These control schemes can be, and are, applied to heat pump heat generators.

Table 2.1: EU ErP temperature controls classes (European Union n.d.*b*,n).

Class	**Name**
I	On/off room thermostat.
II	Weather compensator control for use with modulating heaters.
III	Weather compensator control, for use with on/off output heaters.
IV	TPI room thermostat, for use with on/off output heaters.
V	Modulating room thermostat, for use with modulating heaters.
VI	Weather compensator and room sensor, for use with modulating heaters.
VII	Weather compensator and room sensor, for use with on/off output heaters.
VIII	Multi-sensor room temperature control, for use with modulating heaters.

Research (Pout 2017) by BRE (Building Research Establishment) into UK domestic boilers (fuelled by gas, oil and LPG), identified four main heating temperature control strategies at the boiler: "on–

off" (also known as "bang-bang", class I) such as with a bi-metallic strip room temperature sensor, advanced controls "weather compensation" (e.g., as class II), "load compensation" (as class V), and "Time Proportional and Integral (TPI)" (as class IV). BRE notes that the "on–off" scheme results in temperature swings of 1 to 1.5 °C, even with modern electronic controls (2 °C with a representative "thermo mechanical thermostat" (Fitton et al. 2016)).

BRE observes that weather compensation uses external temperature to predict dwelling heat demand. That temperature can be an external sensor on the building. It is also possible to source the data from the Internet in real time, and for forecasts. Computed heat demand can be used to set the flow temperature to the radiators. Raising the flow temperature delivers more heating power. Lowering the flow temperature raises the efficiency of the heat generator (for heat pumps and condensing boilers). BRE observes that load compensation uses an internal sensor to determine heat demand. The further that indoor temperature is below target temperature, the higher the heat demand. Again, this can be used to set flow temperature. A variant is "room influence" (e.g., as class VII), with temperature sensed in one room in the house; as the sensor temperature drops, the flow temperature will be raised. This or zoning can help with mixed-construction and mixed-occupancy. TPI control computes heat demand based on how long the building has previously taken to achieve the target temperature and is used once the building is close to target. TPI should achieve "stiffer" temperature control, i.e., maintaining temperature within a narrower band around the target.

These schemes can be blended and can be used in conjunction with a timer and house/room thermostat, and indeed an overall off switch for the central heating outside the heating season to avoid accidental activation or to trim the heating season (Hart-Davis 2023*a*). Other controls and schemes exist.

2.1.4 Heat Pump Experience in Northern Europe

The coldest northern European countries already make extensive use of heat pumps for space heating: in Norway, 60% of homes are so equipped, with over 40% in Sweden and Finland and over 30% in Estonia (Monschauer & Wetzel 2022, Rosenow et al. 2022), though cheaper air-to-air is more common in these countries than air-to-water hydronic systems considered in this paper. The UK figure is only about 1%.

Features sometimes considered special about the UK, such as ASHPs (air-source heat pumps) operating for a significant fraction of their runtime with external temperatures only a little above 0 °C and at high relative humidity, requiring significant defrost energy expenditure, occur elsewhere in Europe too (Vocale et al. 2014).

It is not clear what the most common temperature control schemes are for stand-alone domestic heat pump systems in northern Europe, and the literature apparently has little to say directly. Informal discussions and in-passing comments suggest that on–off may be common (Kelly & Cockroft 2011) (supported by (Fabrizio et al. 2017, Reguis et al. 2021)), with weather compensation (Boait et al. 2011, Huchtemann & Müller 2013, Neubert et al. 2022, Toleikyte et al. 2023) relatively common for newer installations, as already happens for combustion boilers. The UK's relevant standards body, MCS, "requires weather compensation to be available on all space heating systems but does not stipulate how this must be set up," (MCS (UK Microgeneration Certification Scheme) 2020), and "6.3.9. Where it can optimise system efficiency with the maximum possible gradient, weather compensation should be enabled" (MCS (UK Microgeneration Certification Scheme) 2021).

2.1.5 Northern European Housing Stock

Most of the dwellings that will be in use in the UK in 2050 are already built and are quite old with poor fabric compared to the UK's European neighbours (UK DCLG (Department for Communities and Local Government) n.d., Piddington et al. 2020, Miller & Sarshar 2020, UK DLUHC (Department for Levelling Up Housing and Communities) 2022*b*, Fabbri et al. 2023), though much of that continental housing is also quite old (Toleikyte et al. 2023). For example a large fraction of English residential stock is pre-1945 and the majority pre-1965.

Partly because of that age profile, and partly because of the UK's cheap heating fuel sources in more recent times, e.g., abundant North Sea gas, UK homes are markedly less energy efficient than those of neighbouring countries too. Of those existing homes, approximately 80% have gas-fired wet (i.e., hydronic, with radiators) central heating (Henretty 2020, UK DLUHC (Department for Levelling Up Housing and Communities) 2022*a*). The UK range of housing archetypes and ages, and issues such as DHW (domestic hot water) storage and noise regulations for external ASHP units, mean that each inefficient home is inefficient in its own way. That in turn implies customised solutions for each home, which will be slower and more expensive than otherwise.

2.1.6 TRV and Heat Pump Interaction Concerns

The UK has a relatively undersized and inexperienced domestic heat pump industry (Cretu et al. 2022, Zanetti 2024), which will need to scale up fast if it is to meet Net Zero targets. Good habits and lore have not yet been fully formed and bad myths should be nipped in the bud. Not doing so may make those targets unattainable or at least more expensive than need be. Currently, some UK heat pump system designers and installers worry that TRVs and heat pumps can interact badly, and in fact waste energy. Adam Chapman of Heat Geek ("created to give expert advice on all aspects of the heating industry to both end users and industry professionals") stated

> "We wouldn't necessarily advise using TRVs or room stats to turn down unused rooms or spare rooms either. Turning unused rooms right down, or micro zoning, gives a particularly high risk of losing efficiency for heat pumps". Ref. (Chapman 2023) (extracted June 2023).

There are many other similar installer and industry participant comments, and Nicola Terry (environmental consultant) noted

> “ ... if you are in the habit of turning down the radiator in the spare room, you should turn it on again after having a heat pump installed. Either that or insulate the walls and floor/ceiling to minimise heat leakage from the rest of the house. This is an interesting example where what we learned about energy saving with gas boilers has to be modified for heat pumps. They are a different game entirely”. Ref. (Terry 2021) (extracted August 2023).

The MCS domestic heat pump best-practice guide (MCS (UK Microgeneration Certification Scheme) 2020) states that “6.1.2.1 Ideally, some form of temperature control should be available in all rooms either by thermostatic radiator valves (TRVs) in the case of radiators or zone control valves for UFH,” and that TRVs “are a relatively low cost, passive methods of providing user comfort control, whilst also conserving energy by reducing the risk of overheating the space”. It is important not to lose TRVs’ additional low-cost decarbonisation and comfort value when retrofitting heat pumps, simply though installer uncertainty about possible interactions.

2.1.7 Contribution of the Work

This work explores whether particular expressed concerns of those in the industry are well-founded though simple first-order modelling, and shows that TRVs (and micro-zoning) can make additional heating energy demand reductions for Net Zero when switching from gas to heat pump. The exact temperature control regime is, however, perhaps unexpectedly important. This paper therefore provides important new guidance on the overall temperature regulation for heat pump systems, especially in dwellings that already benefit from zoning.

2.2 Methods

The model developed is intended in the first instance to simply reproduce the original installer concerns, and establish how robust they are as-is by testing sensitivity to building construction, room occupancy, archetype and geographic location within the UK. Then, the model is extended to identify the reason for the purported unwanted behaviour and to explore the effects of TRVs and how to maximise savings. The model is a simple, physics-based simulation, and is not intended to capture higher-order behaviour and interactions such as comfort responses to time of day and external conditions, thermal capacitance, central-heating off times, and other time and path dependencies. However, this provides a useful way to explore key effects and helps to identify areas requiring further in-depth analysis. The model application here shows that it is well worth installers (and regulators) being careful about temperature regulation strategies.

2.2.1 Research Path

The research journey in brief was as follows: on discovery of the reported doubts about using TRVs with heat pumps by more than one trade source, and the first author sceptical having spent circa ten years inventing and bringing to market a smart TRV (Hart-Davis et al. 2022), a model was constructed to match the Heat Geek page, tested against a wide range of external temperatures, tested against a representative year (2018) of temperature data for London then Glasgow, tested for sensitivity to internal wall U-values and room occupancy patterns, extended to a more common UK house archetype, then tested against a decade of weather for seven UK locations. A further adjustment of this model to allow weather compensation made the bad setback effect disappear, in return for a small and likely acceptable sag in room temperature. The `SampleComputationsOutput.txt` file at the top of (Hart-Davis 2023*b*) shows most of this development path, as its generation was typically extended at each step above. See Figure 2.2 for a summary flowchart of the final model iteration.

2.2.2 Initial Claim Replication in Model

The main claim of the Heat Geek article (Chapman 2023) re TRVs, heat demand and electricity demand, here described as the “bad setback effect”, was replicated as simply as possible into a single-class (`HGTRVHPMModel`) Java model in (Hart-Davis 2023*b*) with all computations nominally at compile time. The results are verified with JUnit unit tests (`TestHGTRVHPModel`); there is approximately 90% code coverage.

Minor corrections/clarifications were made and versions of the model extended and generalised. These generalised versions were cross-checked with prior versions for unchanged answers in the original cases (Table 2) .

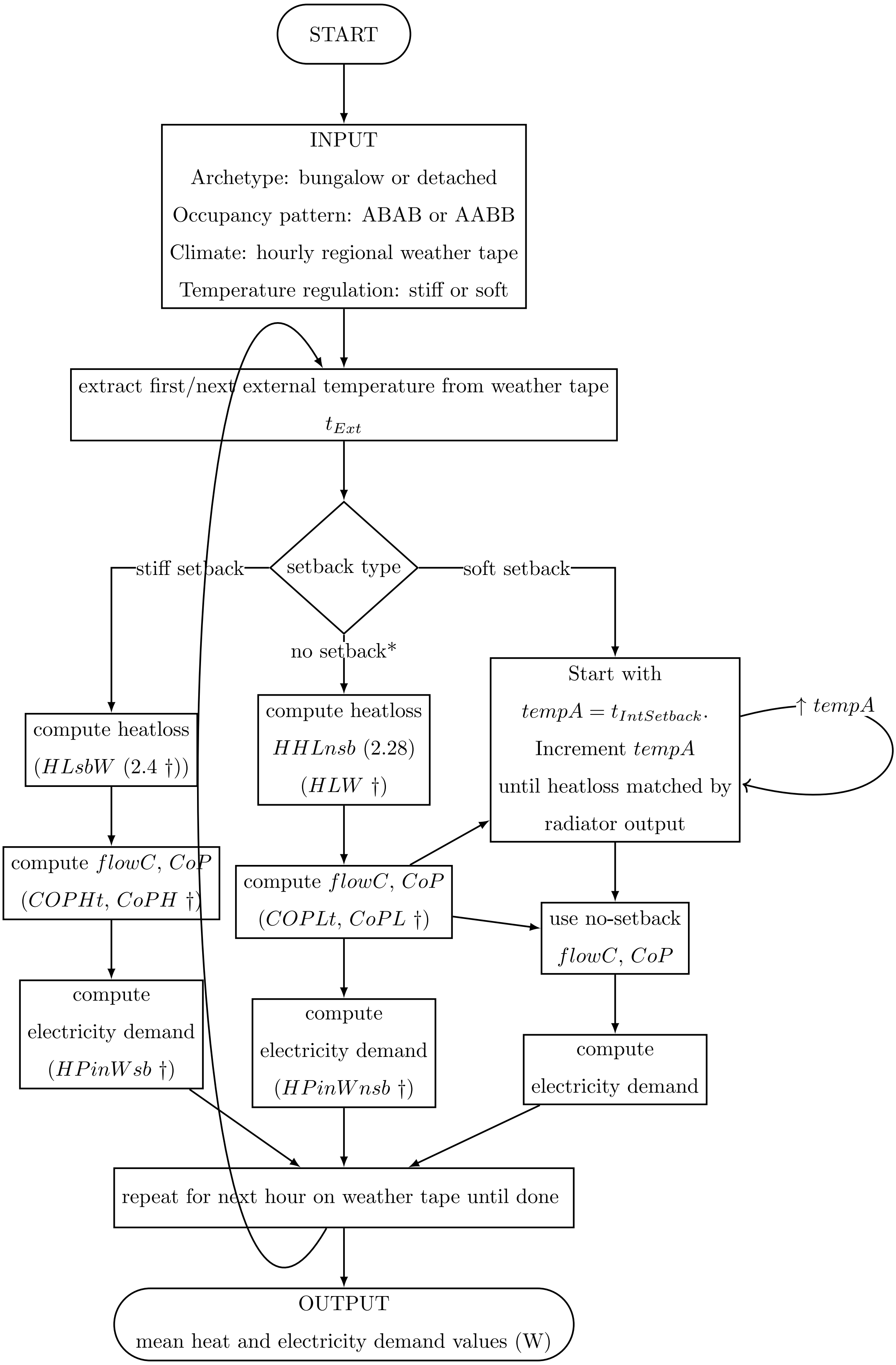


Figure 2.2: Summary flowchart overview of model operation. ”Stiff” regulation and all items marked † are as (Chapman 2023), “soft” regulation is weather compensation. * no-setback computation is used to discover flow temperature (for weather compensation) before soft setback computation.

Table 2.2: Parameters and variables in the model referred to in this paper.

Parameter	**Meaning**
AFA	(A) room floor area (m^2)
CoP	interpolated/extrapolated CoP at flow temperature $flowC$
$CoPDelta$	CoP delta between known CoP points
$CoPH$	CoP sample at higher temperature
$CoPHt$	CoP sample higher temperature (°C)
$CoPL$	CoP sample at lower temperature
$CoPLt$	CoP sample lower temperature (°C)
$detachedExternalArea$	total external roof and wall area (m^2)
$DIFWAabHLW$	detached home heat flow through internal floor/walls from each A room when B rooms set back (W)
$DIWAabHLW$	detached home heat flow through internal walls from each A room when B rooms set back (W)
$dpIW$	mean doors per internal wall
$DradAMWnsb$	detached home radiator mean water temperature in each A room when B not set back (°C)
$EWRU$	derived external wall and roof U-value (W/m^{2}K)
$flowC$	flow temperature of water from heat pump to hot end of radiator for CoP calculation (°C)
$flowMWDeltaK$	difference between mean and flow radiator temperatures for typical heat pump systems (K)
$HHLnsb$	home heat loss to outside with no setbacks (W)
$HLDT$	initial model non-setback home heat loss delta-T interior to exterior (K)
$HLfall$	initial model home heat loss fall from normal to setback conditions
$HLpK$	initial model non-setback home heat loss (W/K)
$HLsbW$	initial model home heat loss to outside when B rooms set back (W)
HLW	initial model whole home heat loss with no setbacks (W)
$HPinWnsb$	initial model heat pump electricity demand with no setbacks (W)
$HPinWsb$	initial model heat pump electricity demand with setbacks (W)

Parameter	**Meaning**
IDA	internal door area of a single door (m^2)
$IDAabHL$	initial model internal door heat loss per A room (W/m^{2}K)
$IDAabHLW$	initial model internal door heat loss per A room (W)
IDU	internal door U-value (W/m^{2}K)
$IDWAabHLW$	initial model internal door and wall heat loss per A room (W)
$IFAabHL$	heat flow via internal floor from each A room when B rooms set back (W/K)
$IFAabHLW$	heat flow via internal floor from each A room when B rooms set back (W)
IWA	internal wall area (m^2)
$IWAab$	internal wall area from each A room to two adjoining B rooms (m^2)
$IWAabHL$	initial model internal wall heat loss per A room (W/m^{2}K)
$IWAabHLW$	initial model internal wall heat loss per A room (W)
$IWAadmd$	internal wall area from each A room to two adjoining B rooms minus one door (m^2)
IWH	internal wall height (m)
IWL	internal wall length (m)
IWU	internal wall U-value (W/m^{2}K)
$MWATP2Dexp$	exponent from power output increase to delta-T increase
$nStories$	number of stories in the building (1 = bungalow, 2 = detached)
$radAdTmultsb$	radiator MW-AT delta-T increase multiplier in each A room when B set back
$radAMWsb$	radiator mean water temperature in each A room when B set back (°C)
$radAdTsb$	radiator MW-AT delta-T in each A room when B set back (K)
$radMWATdT$	radiator mean water-to-air temperature design spec delta-T (K)
$radW$	initial model radiator output all rooms no setbacks (W)
$radWAmultsb$	radiator output increase multiplier in each A room when B set back
$radWAsb$	initial model radiator output power in each A room with B rooms set back (W)
$radWBsb$	initial model radiator output power in each B room with B rooms set back (W)
$roomsAlternatingABAB$	selects ABAB or AABB setback room layout

Table 2.2: *Cont.*

Parameter	**Meaning**
$tempA$	putative/trial temperature of room A with ‘soft’ regulation and B rooms set back (°C)
$TERA$	total external roof area (m^2)
$TEWA$	total external wall area (m^2)
t_{Ext}	exterior temperature (°C)
t_{ExtVar}	variable exterior temperature (°C)
t_{Int}	nominal home/room internal temperature with no setback (°C)
$t_{IntMeanWhenSetback}$	initial model mean room internal temperature when B rooms set back (°C)
$t_{IntSetback}$	room internal temperature when set back (°C)
$VradAdTmultsb$	multiplier in delta-T between A room radiator and room itself with B rooms set back soft vs stiff mode
$VradAdTsb$	delta-T between A room radiator and room itself soft mode with B rooms set back (K)
$VradWAmultsb$	power multiplier of A room radiator output with B rooms set back soft vs stiff mode
$VradWAsb$	increased power from A room radiator in soft mode from increased delta-T with B rooms set back (W)

Table 2.2: *Cont.*

Key points of the scenario as reflected in the initial model:

- The whole system is in equilibrium, i.e., all temperatures are steady.
- The building is a square grid of four equal-size square rooms.
- Room arrangement is treated as a horizontal (e.g., bungalow) plan layout for this work; see Figure 2.3.
- The outside world is at UK winter design temperature (t_{Ext}).
- Normally, all rooms are at a conventional living-space temperature (t_{Int}), and the home then loses a specified total heat flow to the outside (HLW), with one quarter of that heat being supplied by the radiator in each room ($radW$).
- The internal walls between the rooms have a U-value similar to that of a plasterboard-on-stud wall (IWU) and a door with a U-value that can be taken at face value or maybe lower but partly open (Cockroft et al. 2017) (IDU).
- The radiators are sized just large enough to emit $radW$ when their mean water-to-air temperature is a specified delta-T above room temperature, and there is a non-linear relationship between that delta and the heating power.
- During setback, two of the diagonally opposite rooms are allowed to drop to a cooler setback temperature good for sleeping and less-occupied rooms ($t_{IntSetback}$), see Figure 2.4, using TRVs that reduce flow rate as needed, and the flow temperature of the heat source is adjusted (upwards) as necessary to maintain the other two rooms at t_{Int} as they leak heat through the internal walls/doors into the setback rooms.
- Raising the flow temperature reduces the CoP (coefficient of performance) of the heat pump (with data points from a real device) by a greater factor than the heat demand reduction caused by the TRVs, thus the electricity demand of the heat pump goes up while the two rooms are set back.

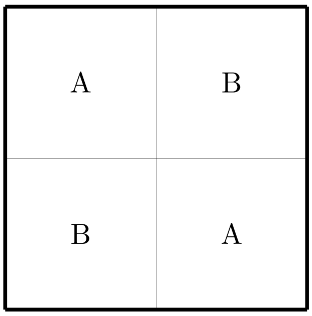


Figure 2.3: "ABAB" layout of rooms in the initial model "bungalow" as seen from above. A rooms are always at 21 °C. B rooms can have their temperature set back to 18 °C. B rooms may be unoccupied, or bedrooms kept cooler for sleeping comfort. All external walls around the perimeter are identical, and all internal walls are identical and less well insulated than external walls.

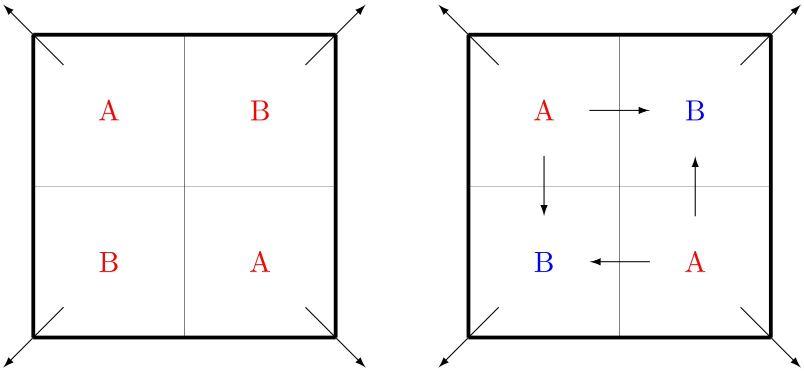


Figure 2.4: "ABAB" layout heat flows: (**left**) without B rooms set back (all warm, coloured red), (**right**) when set back (cooler rooms coloured blue); arrows indicate heat flows.

The basic physics entailed by this description corresponds to just the fabric-loss component of (Najjar et al. 2019) for example, i.e., heat transfer through (say) a wall is proportional to the product of the U-value of, and temperature difference across, and area of, that wall, and as stated is usually the major part of building heat loss.

Note that there are two distinct delta-T (temperature difference) values in the model: the temperature difference between the water entering a radiator ('flow') and leaving it ('return'), and between the mean of those two ('mean water') and the room temperature.

The heat loss $HLpK$ from the home in W/K given the difference between (non-setback) internal and external temperatures can be computed as

$$HLDT = t_{Int} - t_{ExT} \tag{2.1}$$

$$HLpK = HLW/HLDT \tag{2.2}$$

Because of the simple geometry and symmetry of this model dwelling, when B rooms are set back, the reduced home losses to outside ($HLsbW$) and thus the reduction ($HLfall$) can be computed using the new mean home temperature ($t_{IntMeanWhenSetback}$)

$$t_{IntMeanWhenSetback} = (t_{Int} + t_{IntSetback})/2 \tag{2.3}$$

$$HLsbW = HLpK.(t_{IntMeanWhenSetback} - t_{Ext}) \tag{2.4}$$

$$HLfall = (HLW - HLsbW)/HLW) \tag{2.5}$$

The internal door area (IDA) and U-value (IDU), and internal wall area (IWA, from length IWL and height IWH) and U-value (IWU) for each intra-room wall, are used to compute losses from A rooms into B rooms when set back.

The original article suggests that each room has a single door to just one adjacent room, i.e., one for the pair of internal walls that it has. Slightly more plausible is a door to each of the two adjacent rooms. To ensure that the initial investigation matches the setup for the original Heat Geek claims, the calculations show the former. The extended model allows for adjustment to the latter.

The internal wall area from each A room to its two adjoining B rooms (in ABAB layout) is $IWAab$, and minus the area of one door is $IWAabmd$.

$$IWA = IWL.IWH \tag{2.6}$$

$$IWAab = 2.IWA \tag{2.7}$$

$$IWAabmd = IWAab - IDA \tag{2.8}$$

This allows computation of internal wall and door heat loss per A room ($IDWAabHLW$) when B rooms are set back.

$$IWAabHL = IWAabmd.IWU \tag{2.9}$$

$$IWAabHLW = IWAabHL.(t_{Int} - t_{IntSetback}) \tag{2.10}$$

$$IDAabHL = IDA.IDU \tag{2.11}$$

$$IDAabHLW = IDAabHL.(t_{Int} - t_{IntSetback}) \tag{2.12}$$

$$IDWAabHLW = IWAabHLW + IDAabHLW \tag{2.13}$$

From this, the radiator output power in each A room ($radWAsb$) and B room ($radWBsb$) when B rooms are set back can be calculated.

$$radWAsb = radW + IDWAabHLW \tag{2.14}$$

$$radWBsb = (HLsbW - 2.radWAsb)/2 \tag{2.15}$$

From this is computed the amount that the heat output of room A radiators needs to be multiplied by to make up the shortfall from the non-setback case. Given the stated exponent from power output increase to delta-T increase ($MWATP2Dexp$), the required delta-T mean radiator temperature to room temperature is computed ($radAdTsb$) and thus the new A room radiator mean water temperature itself ($radAMWsb$).

$$radWAmultsb = radWAsb/radW \tag{2.16}$$

$$radAdTmultsb = radWAmultsb^{MWATP2Dexp} \tag{2.17}$$

$$radAdTsb = radMWATdT.radAdTmultsb \tag{2.18}$$

$$radAMWsb = t_{Int} + radAdTsb \tag{2.19}$$

The radiators in this model are specified as mean water-to-air temperature DT25, i.e., they emit $radW$ when their mean surface temperature is 25 °C ($radMWATdT$) above room temperature.

From this point, the original article uses the mean radiator temperature as the flow temperature from the heat source to the hot end of the radiators. The immediately following calculations replicate this, but the extended model version described later allows for this small discrepancy to be corrected.

Using the supplied example heat pump CoPs (coefficients of performance) in the non-setback case and the setback case allows calculation of the electricity demand for the heat pump in each case; no setback ($HPinWnsb$) and setback ($HPinWsb$).

$$HPinWnsb = HLW/CoPL \tag{2.20}$$

$$HPinWsb = HLsbW/CoPH \tag{2.21}$$

If with B rooms set back and heat demand *down*, electricity demand goes *up*, this would be the "bad setback" effect that installers are currently assuming.

2.2.3 Extended Model

An extended (parameterised) version of the model was developed to allow for the following:

- Clarification of the minor issues in the original article (doors per internal wall and radiator flow vs mean adjustment);
- Allowing different interior room setback arrangements (allowing alternative "AABB" arrangement as a sensitivity test);
- Allowing different external temperatures;
- Allowing an alternative building archetype (generalised method to calculate for bungalow or 2-storey detached).

The initial model was extended in stages, with the facility to model a detached 2-storey building, and then "soft" temperature regulation added last. Each extension to the model can reproduce the results from previous iterations, and indeed reproduce the original article results if required. This extended model performs most of its computations at runtime, unlike the initial model implementation.

Fixes

To allow doors per internal wall ($dpIW$) to be adjusted, from the original half to a more plausible one, one Equation (2.8) is reimplemented in the extended models:

$$IWAabmd = IWAab - (2.dpIW.IDA) \tag{2.22}$$

The original article (and thus the initial model) uses flow temperature as the mean radiator temperature. More realistically for a heat pump system, with a fix applied, the radiators are assumed to run with a temperature drop of 5 K from flow to return, and thus with the mean 2.5 K below the flow ($flowMWDeltaK$).

This in turn means that the supplied sample CoP values are not directly usable when this correction is applied. The extended model uses a simple linear interpolation and extrapolation from the two sample points to compute the new CoP as a reasonable monotone approximation for the flow temperature ($flowC$) range covered:

$$tempDeltaK = CoPHt - CoPLt \tag{2.23}$$

$$CoPDelta = CoPH - CoPL \tag{2.24}$$

$$CoP = CoPL + ((flowC - CoPLt).(CoPDelta/tempDeltaK) \tag{2.25}$$

Note that $CoPDelta$ is negative, i.e., CoP falls as flow temperature rises.

Layout

The initial model maximises internal heat flow/loss with the ABAB layout. With the same 50% of rooms set back an "AABB" layout (Figure 2.5) minimises internal heat flow by minimising (halving) the number of shared surfaces between A and B rooms (Figure 2.6).

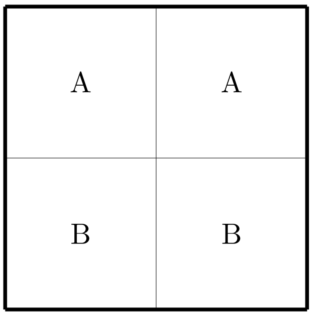


Figure 2.5: "AABB" layout of rooms minimising internal heat flows compared to the "ABAB" layout shown in Figure 2.3.

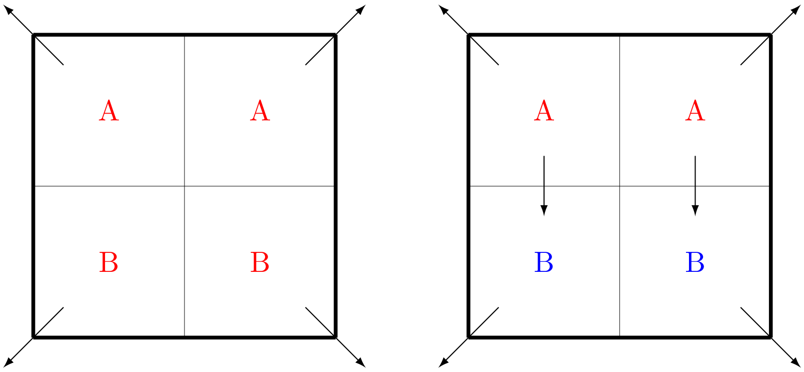


Figure 2.6: "AABB" layout heat flows: (**left**) without B rooms set back (all warm, coloured red), (**right**) when set back (cooler rooms coloured blue); arrows indicate heat flows.

Switching between ABAB and AABB layouts tests sensitivity to the juxtaposition of setback (e.g., unoccupied) and non-setback rooms. (Also, equivalently, the level of insulation in the internal walls.) Switching to AABB layout halves the internal wall heat loss, so requiring adjustment of Equation (2.13), internal wall heat loss per A room to B room(s).

$$IDWAabHLW = (IWAabHLW + (2.dpIW.IDAabHLW)).\begin{cases} 1 & \text{if } roomsAlternatingABAB \\ 0.5 & \text{otherwise} \end{cases} \tag{2.26}$$

Note that AABB layout *eliminates* inter-floor 2-storey heat loss, see later.

Varying External Temperature and Building Archetype

The initial model scenario uses an external temperature (t_{Ext}) which is a reasonable outdoor (winter minimum) design temperature for the Midlands and Wales (approximately 53 °N), and thus the UK (up to 50 m above sea level) (UK NHBC (National House-Building Council) 2023). It is useful to test this bad setback effect for sensitivity against a range of design temperatures that might be encountered in different parts of the UK a degree or so either way. This also allows simple weather tape testing against hourly external temperatures in the above locations, though ignoring thermal capacitance of the building and contents.

For the bungalow, the overall building heat loss per K difference between inside (mean) temperature and external temperature is already known ($HLpK$). To allow generalisation to an additional building archetype, this loss to the outside is treated as evenly lost through wall ($TEWA$) and roof, i.e., ceiling in the top storey ($TERA$), with a derived uniform U-value of $EWRU$. For simplicity, there are no losses to the ground.

To explore sensitivity of the bad setback effect to building shape (and heated floor-space to external surface-area ratio), the model was extended to allow a 2-storey variant, with a second identical storey.

For the 2-storey detached home, the external area increases to

$$detachedExternalArea = TERA + 2.TEWA, \tag{2.27}$$

i.e., doubling the heated floor area with the second storey does not double the losses to outside for a given temperature differential.

Thus, the heat loss (W) to outside for a given external temperature t_{ExtVar}, and with number of stories $nStories$, is, without setbacks,

$$HHLnsb = (t_{Int} - t_{ExtVar}).(TERA + nStories.TEWA).EWRU. \tag{2.28}$$

The default ABAB setback room distribution is extended so that each A room has a B room beneath/above it, and vice versa. In the AABB variant each room has the same (A or B) type beneath/above it, and thus there are no vertical internal heat flows in this case.

Heat flow between A and setback B rooms on adjacent stories is modelled as symmetric (though air leakage and other factors would typically make real-world flows up slightly higher) and internal floor U-values are taken to be the same as internal wall values ($IFU = IWU$), which is a reasonable simplifying approximation. (Internal floor U-values, therefore, approximately match that of plasterboard/8-inch joist space/tongue-and-groove floorboards construction, consistent with a late 1970s build or thereabouts).

Internal heat flows from each A room when B rooms are set back:

$$IFAabHL = (AFA.IFU) \tag{2.29}$$

$$IFAabHLW = (t_{Int} - t_{IntSetback}).IFAabHL \tag{2.30}$$

$$DIWAabHLW = \begin{cases} 0 & \text{if nStories=1 or is AABB} \\ IFAabHLW & \text{otherwise} \end{cases} \tag{2.31}$$

$$DIFWAabHLW = DIWAabHLW + DIFAabHLW, \tag{2.32}$$

with A room temperatures held ‘stiff’ at t_{Int}.

Simulation of Different UK Locations

To establish whether the reported bad setback effect was an isolated problem that might only apply in particular microclimates or at particular times of year, the model is tested against hourly weather temperature data for ten years for several heavily populated areas of the UK (BizEE Software n.d.). For a given location and time-span, the model is re-run against the exterior temperature for each hour. The (arithmetic) mean heat and heat pump electrical demand is computed, as well as the fraction of hours in which heat pump demand is increased when B rooms were set back. This hourly computation is performed with a simple loop over the location-specific exterior temperature data read from a CSV file captured within the model project, for both non-setback and setback situations. The value computed is for equilibrium, and not path-dependent as it does not consider factors such as thermal capacitance. Thus, it would only be necessary to compute once for each parameter set, most obviously each (limited-precision) external temperature for a given archetype and ABAB/AABB layout, assuming that the "fixes" parameters are applied. The complexity of this potential optimisation (and opportunity for introducing errors) was avoided as the model runtime is barely noticeable.

Simulation of "Soft" Temperature Regulation

To simulate "soft" temperature regulation in A rooms, i.e., pure "weather compensation", the model is first run without setbacks for the various parameters, in particular, external temperature. The adjusted flow temperature required to maintain all rooms at the non-setback temperature, overcoming all home losses to outside, is noted. This in effect computes one point on the weather compensation curve, mapping external temperature to flow temperature. The model is then re-run with B rooms set back, maintaining the flow temperature just computed above. Putative A room temperatures are tested in small ($tempStepK$) steps from the setback temperature ($t_{IntSetback}$) up to nominally just above the "normal" temperature (t_{Int}) to find the lowest at which the flows into the room from the radiator are exceeded by the losses internally and externally. This "found" equilibrium temperature is thus slightly conservative/high. A small refinement is to compensate both for the reduced losses to B rooms and outside at lower A room putative temperature ($tempA$), e.g., floor losses

$$IFAabHLW = (tempA - t_{IntSetback}).IFAabHL, \tag{2.33}$$

and the increased power output from the radiator ($VradWAsb$) given the increased delta-T ($VradAdTsb$) between it and the A room for any given flow temperature

$$VradAdTsb = DradAMWnsb - tempA \tag{2.34}$$

$$VradAdTmultsb = VradAdTsb/DradAdTsb \tag{2.35}$$

$$VradWAmultsb = VradAdTmultsb.VradAdTmultsb^{1/MWATP2Dexp} \tag{2.36}$$

$$VradWAsb = VradWAmultsb.DradWnsb \tag{2.37}$$

For simplicity, any second-order rise in delta-T from flow to return, and thus dip in mean water temperature, given more heat being drawn from the A room radiators, is ignored.

2.2.4 Scenarios

Several scenarios are explored in this paper from the initial model onwards. Key input parameters and key calculated values are listed below to produce the results described in this section. The Table 2.3 parameter values apply across all scenarios, having been inherited from the initial model and thus the original article. Some are inputs and some are calculated/derived.

Table 2.3: Input parameters and select calculated values across all scenarios.

Parameter	Value
AFA	16 m^2 (calculated)
$CoPH$	2.3
$CoPHt$	51.5 °C
$CoPL$	2.6
$CoPLt$	46.0 °C
IDA	2 m^2
IDU	8 $\mathrm{W/m^2K}$
IWH	2.3 m
IWL	4 m
IWU	2 $\mathrm{W/m^2K}$ (cf plasterboard-on-stud wall at approximately 1.7 $\mathrm{W/m^2K}$)
$MWATP2Dexp$	0.77
$radMWATdT$	25 K
$tempDeltaK$	5.5 K (calculated)
t_{Int}	21 °C
$t_{IntSetback}$	18 °C

Table 2.3: *Cont.*

Initial Model

The Table 2.4 parameter values apply only to the initial model, prior to any fixes and extensions.

Table 2.4: Input parameters and select calculated values for the initial model only.

Parameter	Value
$dpIW$	0.5
$HLDT$	24 K (calculated)
$HLfall$	6.25% (calculated)
$HLpK$	83 W/K (calculated)
$HLsbW$	1875 W (calculated)
$HPinWnsb$	769 W (calculated)
$HPinWsb$	815 W (calculated)
$IDWAabHLW$	146 W (calculated)
$radAdTsb$	30.5 K (calculated)
$radW$	500 W
$radWAsb$	646 W (calculated)
$radWBsb$	291 W (calculated)
$radAMWsb$	51.5 °C (calculated)
t_{Ext}	−3 °C (outdoor winter minimum design temperature for the UK ∼ 53 °N (UK NHBC (National House-Building Council) 2023))
$t_{IntMeanWhenSetback}$	19.5 °C (calculated)

Initial Model with Corrections

These fixes allow increasing the doors per internal wall from 0.5 and adding the expected difference between radiator mean and flow temperature to the flow temperature to compute a more accurate CoP. See Table 2.5.

Table 2.5: Input parameters and select calculated values for fixes.

Parameter	Value
$dpIW$	0.5 or 1.0 (preferred)
$flowMWDeltaK$	0 or 2.5 K (preferred)

AABB Layout

This flag allows rearranging the set back (B) rooms to minimise internal heat flows. See Table 2.6.

Table 2.6: Input parameters and select calculated values for varying setback room layout.

Parameter	Value
$roomsAlternatingABAB$	true if ABAB layout, false otherwise

Varying External Temperature

This parameter allows an external temperature other than the default (UK-wide) to be used. Locations cover a selection of UK microclimates and population centres. See Table 2.7.

Table 2.7: Input parameters and select calculated values for varying external temperature and weather.

Parameter	Value
location	Belfast, Cardiff, Edinburgh, Glasgow, London, Manchester, Newcastle
t_{ExtVar}	varies, e.g., by hour for weather

Detached 2-Storey

This allows generalising the building model to two stories, attributing heat loss across extra exterior wall surface in a way that is compatible with the initial model. See Table 2.8.

Table 2.8: Input parameters and select calculated values across scenarios.

Parameter	Value
$EWRU$	0.61 W/m^{2}K (calculated)
$nStories$	number of stories in the building (1 = bungalow, 2 = detached)
$TERA$	64 m^2 (calculated)
$TEWA$	73.6 m^2 (calculated)

The initial model example home is being treated here as a bungalow, i.e., four rooms on one level. At approximately 64 m^2 heated floor area, it would be in a moderately common size category as can be seen in Table 2.9, though Table 2.10 indicates that bungalows themselves make up a small part of the housing stock.

Table 2.9: English 2020 dwelling stock profile: usable floor area m^2. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey (UK DCLG (Department for Communities and Local Government) n.d.).

Parameter	**Value**
less than 50	2340
50–69	5113
70–89	6390
90–109	3579
110 or more	6111

Table 2.10: English 2020 dwelling stock profile: archetype. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey (UK DCLG (Department for Communities and Local Government) n.d.).

Parameter	**Value**
all terrace	6417
semi-detached	5810
detached	4137
bungalow	1753
converted flat	1028
purpose built flat, low rise	3764
purpose built flat, high rise	625

Table 2.11: English 2020 dwelling stock profile: age. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey (UK DCLG (Department for Communities and Local Government) n.d.).

Parameter	**Value**
pre-1919	4684
1919–44	3450
1945–64	4106
1965–80	4604
1981–90	1745
post-1990	4946

The simplest extrapolation from this home archetype is to a detached home, with two floors identical to the bungalow on top of one another. This tests sensitivity to the archetype shape, in particular, the ratio of usable heated floor area to exterior surface area. Such detached homes are the third most common according to Table 2.10, and at 128 m^2, is the second most common size category as shown in Table 2.9. To capture some of this shape effect as simply as possible, the initial model non-setback 2 kW heat loss (HLW) was treated as entirely lost through the external walls and roof, with those two elements having the same U-value. That implies a U-value of approximately 1.13 W/m^2K. Looking at the progression of U-values in building regulations since the 1960s (Davies 2016), that would imply a late 1970s build or thereabouts, another reasonably common slice of the English stock according to Table 2.11. So, the initial model bungalow and detached variants are plausibly partially representative of UK housing stock.

Note that in ABAB mode, on each floor an A room has a B room above/below and vice versa. In AABB mode, each room type has a matching type above/below. The U-value of the inter-storey floor/ceiling was taken to be the same as the internal walls for simplicity (2 W/m^2K). This is reasonably close to reality for plasterboard/8-inch joist space/tongue-and-groove floorboards. Heat flow was taken to be symmetric up and down, though in reality, air leakage and other factors typically make flows up slightly higher.

Soft Temperature Regulation

This emulates an open loop weather compensation system, fixing the flow temperature at that for the no setback state, searching for a new equilibrium A room temperature when B rooms set back. See Table 2.12.

Table 2.12: Input parameters and select calculated values for soft temperature regulation.

Parameter	Value
tempStepK	0.01 K

2.2.5 Model Runtime

All code and temperature data used for this paper is available open source at (Hart-Davis 2023*b*).

The model runtime to compute and output all the numbers discussed in this paper is trivial: for the main calculations, a few seconds on a 2020 Apple MacBook Air M1 laptop, running GraalVM 19 Java, in an Eclipse IDE. Thus, no effort was made to optimise code, though easy optimisations are available.

2.3 Results

This work confirmed that the thrust of the original article claim is true in the specific equilibrium situation described, at typical UK exterior winter temperature and assuming that radiators are not at all oversized (Chapman 2023). There are some possibly unintended elements in the original piece, but once adjusted, the “bad setback” effect is even more pronounced than the original claim.

The numbers in the original article suggest half a door per internal wall. Parameterising the model to allow a more probable one door per internal wall increased internal heat flows and the bad setback effect. The original article treats interchangeably the mean radiator temperature and the flow temperature to the radiator. Parameterising as discussed in Methods to add the typical difference between the two also increased the bad setback effect. Before these two adjustments, the heat pump demand was 769 W with no B room setbacks, and with setbacks 815 W. With the updated parameters, those became 812 W and 895 W. A 6% rise in heat pump demand with B rooms set back became 10% with the adjustments.

2.3.1 Internal Heat Flow Sensitivity

The ABAB arrangement of rooms maximises internal heat transfer from A rooms to B rooms, and this maximises the bad setback effect. A flag in the model parameters allows a room arrangement AABB that minimises such internal flows, changing nothing else. With the flag set, the heat pump demand during setback dropped from 895 W to 824 W, i.e., the setback heat pump electricity increase reduced from 10% to 1.5%. This indicates that the bad setback effect is sensitive to, for example, the insulation in such internal walls, and how much the doors are left open (Cockroft et al. 2017) into rooms that are set back. (It is good practice to ensure that doors are closed into such rooms to reduce moisture flow along with heat.)

2.3.2 External Air Temperature

See Table 2.13 for bungalow behaviour at a range of external temperatures, including the −3 °C original scenario. Note that above a 10 °C threshold, using the TRVs saves heat pump electricity also, i.e., the bad setback effect goes away. This is all steady state, and ignores complicating factors such as wind and solar gain and building thermal capacitance and variable occupancy, and assumes that the heating is nominally on all day.

Table 2.13: Extended model with fixes and sample external temperatures showing heat pump electrical demand without and with B room setback and the delta increase with setback. −3 °C is the initial model scenario. The lowest temperature is well below that generally expected in the UK, and the highest is just below the B room setback temperature so that heat continues to flow from inside to outside. The bad setback effect stops at and above 10 °C.

External °C	Pump Demand Normal (W)	Pump Demand with B Setback (W)	Change
−13	1386	1593	15%
−3	812	895	10%
0	674	733	9%
3	549	586	7%
10	298	298	0%
13	206	194	−6%
17	96	70	−27%

2.3.3 Alternative Building Archetype

Taking the original bungalow with fixes applied, the heat demand was 812 W. For the detached house, though twice the heated floor area, demand was 1131 W, only about 39% more. For the bungalow, the bad setback effect was 10%. For the detached house, the bad setback effect was 19%, a marked magnification.

2.3.4 Multi-Year Multi-City Multi-Archetype Behaviour

To establish how robust this bad setback effect would be across various parts of the UK, especially heavily populated areas, 10 years of recent hourly temperature data from (BizEE Software n.d.), years 2010 to 2019 inclusive (avoiding the somewhat abnormal 2020), across seven reasonably representative UK towns and cities, was used. Both ABAB and AABB configurations of both bungalow and detached archetypes were used as a simple indicator of sensitivity to the internal construction and occupancy and zoning pattern. The summary results are in Table 2.14.

Table 2.14: Stiff mode: summary of mean power change with selected-room setback of (1) stiff temperature regulation in A rooms (2) whole-home heat demand and of (3) heat pump electrical demand in high ABAB and low AABB internal loss room setback arrangements (4) for 1- and 2-storey (bungalow and detached) archetypes, for 7 UK locations. Based on hourly temperature data for the ten years 2010 to 2019 inclusive. When B rooms were set back, overall home heat demand did fall, but in the ABAB layout that maximises internal losses, heat pump electricity demand rose, in all scenarios, especially in the detached house cases.

Location (Weather Station)	**Archetype**	**Home Heat Demand Delta**	**ABAB Heat-Pump Demand Delta**	**AABB Heat-Pump Demand Delta**
Belfast (EGAA)	bungalow	−11.7%	3.1%	−4.5%
	detached		11.5%	−4.6%
Manchester (EGCC)	bungalow	−11.8%	3.1%	−4.5%
	detached		11.5%	−4.6%
Cardiff (EGFF)	bungalow	−12.5%	2.1%	−5.4%
	detached		10.4%	−5.5%
London (EGLL)	bungalow	−12.3%	2.5%	−5.1%
	detached		10.8%	−5.2%
Newcastle (EGNT)	bungalow	−11.4%	3.6%	−4.1%
	detached		12.0%	−4.2%
Glasgow (EGPF)	bungalow	−11.5%	3.5%	−4.2%
	detached		11.9%	−4.3%
Edinburgh (EGPH)	bungalow	−11.4%	3.6%	−4.1%
	detached		12.0%	−4.2%

With the ABAB layout the bad setback effect was visible in all locations, and was much stronger in the detached property with greater internal heat flow compared to its losses to outside. This ABAB bad setback effect was robust across all UK locations tested. It can be largely defeated by, for example, some combination of choosing carefully which rooms to occupy or set back, keeping internal doors closed between areas with different temperatures and better insulating internal walls and floors.

With the AABB layout, the bad setback effect was partly suppressed. Somewhat over half of the TRV-based heat savings were lost but electricity consumption *fell* with setbacks in place. The fraction of hours in which a setback caused heat pump power to rise fell from tens of percent for ABAB to single-digit percent for AABB.

2.3.5 Regulation Strategy

A critical part of the initial model scenario is that temperature regulation in the A rooms is "stiff". The A rooms stay fixed at the 21 °C setpoint. The flow temperature is raised as necessary to achieve this. Even in a conventional gas-fired system with a thermostat on the wall (and "on–off" aka "bang-bang" control), temperature may easily fluctuate by 1–2 °C around the temperature setpoint (Pout 2017).

A more common scheme in heat pump installations is to use weather compensation to set the radiator flow temperature based on the outside temperature (Huchtemann & Müller 2013) (the heat pump turns down or off if the building gets too hot). When flow temperature was driven entirely by weather compensation, A room temperatures fell a little towards the B room 18 °C setback.

Similar behaviour was observed in a Chinese apartment block (Xu, Chen, Wang & Jiang 2023). Heated room temperatures fell at most approximately 1.5 °C, and 0.7 °C on average. These are more steady offsets from the target temperature than the "bang-bang" control fluctuations.

When B rooms were then allowed to set back with "soft" regulation, in the initial model bungalow, the worst temperature sag was approximately 1.5 K. For the detached house version, it was approximately 1.9 K. These sags were smaller with a less extreme zoning pattern such as AABB (approximately 1.0 K/approximately 1.1 K). In other words, when this (small) A room temperature sag was allowed, heat pump electricity demand went down in step with heat demand, see Table 2.15.

Table 2.15: Soft mode: summary of mean power change with selected-room setback of (1) soft temperature regulation in A rooms (2) whole-home heat demand and of (3) heat-pump electrical demand in high ABAB and low AABB internal loss room setback arrangements (4) for 1- and 2-storey (bungalow and detached) archetypes, for 7 UK locations. Based on hourly temperature data for the ten years 2010 to 2019 inclusive. Contrast with "stiff" temperature regulation in Table 2.14.

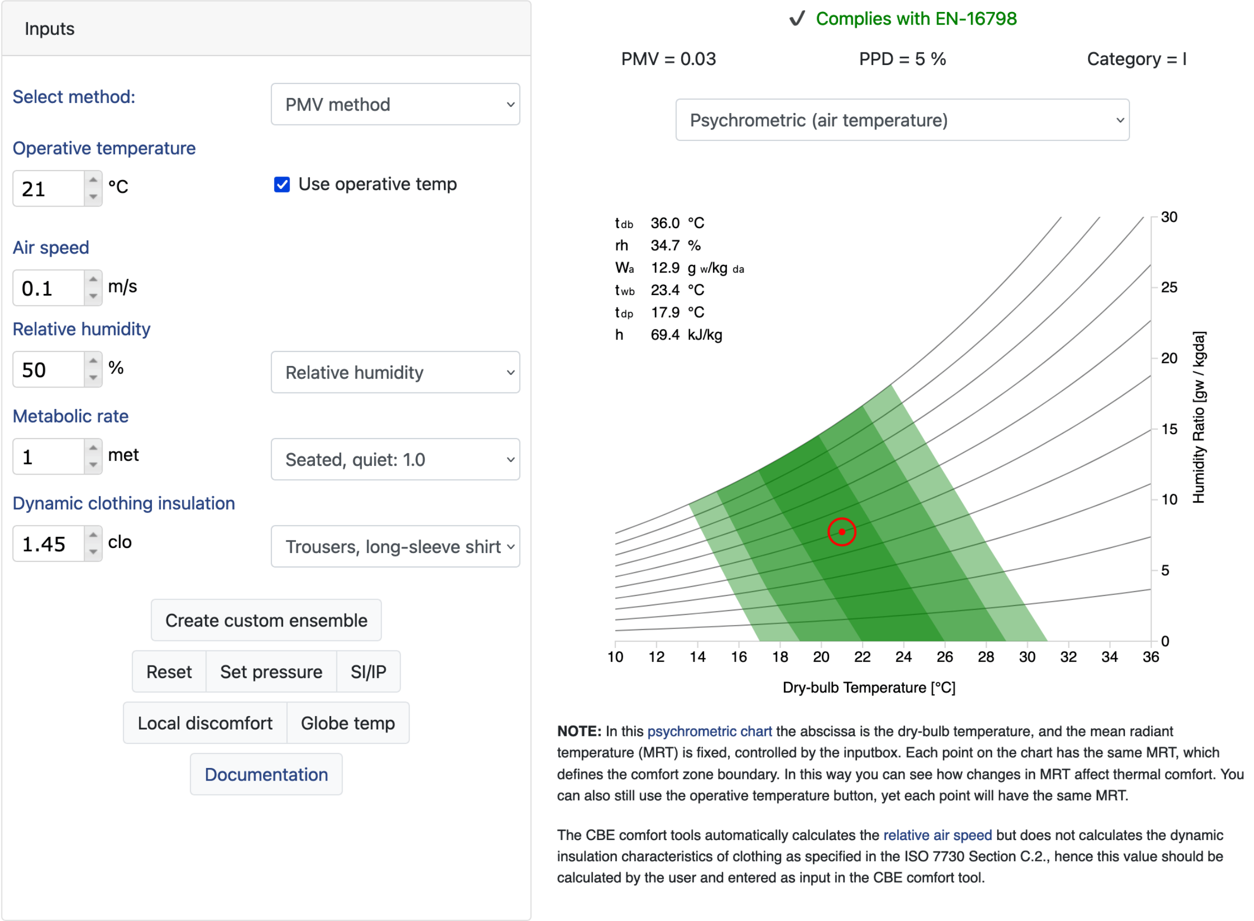
Location (Weather Station)	**Archetype**	**Home Heat Demand Delta**	**ABAB Heat-Pump Demand Delta**	**AABB Heat-Pump Demand Delta**
Belfast (EGAA)	bungalow	−17.5%	−17.1%	−15.2%
	detached		−18.6%	−15.6%
Manchester (EGCC)	bungalow	−17.6%	−17.1%	−15.2%
	detached		−18.7%	−15.6%
Cardiff (EGFF)	bungalow	−18.7%	−18.3%	−16.3%
	detached		−20.0%	−16.7%
London (EGLL)	bungalow	−18.3%	−17.9%	−15.9%
	detached		−19.5%	−16.3%
Newcastle (EGNT)	bungalow	−17.0%	−16.5%	−14.7%
	detached		−18.1%	−15.1%
Glasgow (EGPF)	bungalow	−17.2%	−16.6%	−14.8%
	detached		−18.2%	−15.2%
Edinburgh (EGPH)	bungalow	−17.0%	−16.5%	−14.7%
	detached		−18.1%	−15.1%

Thus, with simple weather compensation, the "bad setback effect" does not occur.

A recent study indicates that occupants have temperature tolerances of at least 2 °C (Berry et al. 2023). Steady deviations such as in (Xu, Chen, Wang & Jiang 2023) also seem to be tolerated. A detailed assessment of thermal comfort is a complex and nuanced subject beyond the scope of this work, but (Tartarini et al. 2020, CBE 2020, ASHRAE & ANSI 2023) suggest that approximately 2 °C of temperature sag may be tolerable; see Figure 2.7 for an indication. Thus, a temperature sag such as seen above in A rooms with soft regulation may be entirely acceptable to householders.

2.3.6 Annual Energy Savings

Energy savings from retaining TRVs in a heat-pump retrofitted UK home are here estimated for a system with weather compensation, given Typical Domestic Consumption Values (TDCV) (Milligan 2023) from Ofgem, the UK energy regulator, and that where a UK home has gas, typically 80% is used for space heating (the balance is used for hot water (DHW) and cooking in the main) (Schuetz et al. 2020, Miller & Sarshar 2020, UK DESNZ (Department for Energy Security and Net Zero) 2024*a*). Given a medium gas TDCV of 11,500 kWh/year, that indicates approximately 9000 kWh/year of gas for space heat demand per UK home on average. Allowing for real-world gas boiler efficiencies of approximately 90% implies approximately 8000 kWh/year actual space heat demand per home. Applying the heat demand delta in London of −18.3%, for example, from Table 2.15 indicates a reduced heat demand of approximately 1500 kWh/year. The reduction in heat-pump electricity demand is fairly similar seen in the right-hand columns of the table, in the range 15.9% to 19.5%. Given a recent median measured UK ASHP seasonal CoP of 2.8 (UK Energy Systems Catapult 2023), that would suggest a reduction in electricity demand of approximately 500 kWh/year per home.



Inputs

Select method: PMV method

Operative temperature: 21 °C ☑ Use operative temp

Air speed: 0.1 m/s

Relative humidity: 50 % Relative humidity

Metabolic rate: 1 met Seated, quiet: 1.0

Dynamic clothing insulation: 1.45 clo Trousers, long-sleeve shirt

✓ Complies with EN-16798

PMV = 0.03 PPD = 5 % Category = I

Psychrometric (air temperature)

t db 36.0 °C
rh 34.7 %
Wa 12.9 g w/kg da
t wb 23.4 °C
t dp 17.9 °C
h 69.4 kJ/kg

NOTE: In this psychrometric chart the abscissa is the dry-bulb temperature, and the mean radiant temperature (MRT) is fixed, controlled by the inputbox. Each point on the chart has the same MRT, which defines the comfort zone boundary. In this way you can see how changes in MRT affect thermal comfort. You can also still use the operative temperature button, yet each point will have the same MRT.

The CBE comfort tools automatically calculates the relative air speed but does not calculates the dynamic insulation characteristics of clothing as specified in the ISO 7730 Section C.2., hence this value should be calculated by the user and entered as input in the CBE comfort tool.

Figure 2.7: Example EN-16798 Ref. [69] visualisation with operative temperature at 21 °C and clo bumped up to 1.45 to roughly centre the bullseye (red circle) in the darkest green ”good” band; there is approximately 2 °C of temperature sag possible before dropping out of the central band. Screenshot used with permission (CBE 2020, Tartarini et al. 2020).

Examining a specific case of the modelled bungalow in London with ”soft” regulation (i.e., pure weather compensation) and optional TRV-maintained setbacks using the hourly external temperatures for the representative 2018 year, mean heat demand in the ABAB configuration is 719 W without setbacks and 591 W with, corresponding to heat pump electric demand of 246 W (2155 kWh/year) without and 203 W (1778 kWh/year) with, saving 377 kWh/year, −17.4%. In the AABB configuration, mean heat demand is 719 W without setbacks and 605 W with, corresponding to heat pump electric demand of 246 W (2155 kWh/year) without and 208 W (1822 kWh/year) with, saving 333 kWh/year, −15.5%. The non-setback case shows a heat demand of approximately 6300 kWh/year, so a little under the TDCV-derived medium figure, as might be expected for a relatively small home at the warmer end of the UK. This reasonable agreement serves as one validation of the model's operation.

2.3.7 Economics

The economic benefits of retaining TRVs in a UK home in 2024 being retrofitted from gas boiler to heat pump can be estimated. Example domestic retail energy prices used for this calculation are for May 2024 from Ecotricity for a London home on a "green" single rate (no time-of-use), though technically in the "South East" pricing region, and from the Ofgem (the UK regulator) energy price cap in force at May 2024, both standing charges and per-kWh charges; see Table 2.16. These prices are down from peaks induced by the war in Ukraine. It is assumed that gas will not be used in the property at all, and thus no "dual-fuel" discount or similar would apply.

For the Ofgem medium TDCV home in London with an estimated electricity saving of 500 kWh/year and a nominal unit cap of 25.72 p/kWh, the annual saving from having TRVs installed or updated is projected to be approximately GBP130 per year. With typical TRVs priced retail at around GBP20, even for smart TRVs such as (Hart-Davis et al. 2022), that medium TDCV home could have full payback within a year or two. For the modelled bungalow in London with estimated electricity savings of approximately 350 kWh/year, thus approximately GBP90, TRVs for its four radiators could pay back within a year, though this allows for no off times (e.g., overnight) for the space heating. Thus, there is a strong economic case for retaining or installing TRVs, on top of comfort and climate motivations.

Table 2.16: Sample UK domestic retail electricity costs in May 2024, rounded to 2 decimal places.

Source	**Standing Charge p/day**	**Unit Cost p/kWh**
Ecotricity "South East" domestic retail "Green Electricity" standard variable single rate including VAT at 5% taken from first author's utility bill, see also tariff sheet (Ecotricity Limited 2024), not subject to the Ofgem price cap	56.90	32.09
Ofgem price cap for "South East" region in force 1 April to 30 June 2024, paid by Direct Debit, single rate (Office of Gas and Electricity Markets (Ofgem), UK n.d.)	56.90	25.29
Ofgem price cap for "London" region in force 1 April to 30 June 2024, paid by Direct Debit, single rate (Office of Gas and Electricity Markets (Ofgem), UK n.d.)	40.79	25.72
Ofgem price cap average for England, Scotland and Wales in force 1 April to 30 June 2024 (Office of Gas and Electricity Markets (Ofgem), UK n.d.)	60.10	24.50

2.4 Discussion

Unexpectedly, the Heat Geek concern was shown initially to be supported and robust across the original single-temperature scenario, and across a decade's external temperature data at various population centres across the UK. It was also unexpected that reconciling this with the actual experience of a user of a heat pump and TRVs who did not find the original article and initial model to reflect their reality, would depend on the detail of radiator sizing and temperature regulation.

Using common open-loop weather compensation (radiator flow temperature driven by external temperature only) eliminates the bad setback effect, and indeed saves a little extra energy. This is in return for a small sag in temperature for A rooms, though likely well within tolerable bounds. At the very least, heat pump system designers/installers and users should be made aware of the additional significant energy saving benefits of this regulation scheme: 17% or more in the locations and archetypes modelled over and above the direct climate footprint savings from switching to a heat pump.

However, comfort-seeking occupants demanding tight (”stiff”) temperature control with such alternative regulation schemes may indeed see their heat pump interact badly with TRVs and waste energy, as Heat Geek flags up, and the modelling demonstrates. Some such occupants will neither care to know nor act on this (Vu et al. 2023), but it is likely that most would. Even apparently innocuous fiddling with the settings panel for some systems (in response to someone complaining that they are too cold on a very cold day) may shift the control regime, e.g., by increasing ”room influence”, and have a disproportionate effect on energy consumption and footprint. In these circumstances, it may be best to omit or remove TRVs, or have them all set to a non-setback target temperature so that they only serve to trim true overheating such as from solar gain, and will not cause inward heat flows from surrounding rooms. Because a change of occupants or occupancy pattern may mean that setbacks would again be beneficial, it may be better to leave TRVs in place but educate as to their best use.

Note also that the control regime is not a binary: a mixture of weather compensation with a little bit of ”room influence” or similar can be used to retain all the savings from reduced zoned heat demand while trimming temperature sags a little and closing the control loop.

There remain other legitimate reasons to consider reducing zoning and the number of TRVs when upgrading from gas to heat-pump, including raising flow rates and for ASHPs ensuring enough water volume to steal heat from during defrost cycles.

2.4.1 Limitations

The modelling in this work is simple and does not include losses such as through the ground, nor through ventilation. Nor does it include solar nor appliance nor other gains, nor more detailed weather effects. Also missing is any effect of thermal capacity of the building, and other path dependencies, i.e., the hourly modelling treats each hour independently and in equilibrium.

2.4.2 Future Research

It would be useful to explore the effects of control alternatives beyond simple weather compensation and the original article approaches, looking at schemes that are typical for the UK and other areas. Additionally these could use higher-fidelity or regulatory-standard models (such as in EnergyPlus, or EWASP (Johnson et al. 2021), or HEM (UK DESNZ (Department for Energy Security and Net Zero) 2023*b*)), a weighted range of dwelling archetypes, and physical dwellings. Another avenue is exploring how TRVs or other zoning might be made to work better with heat pumps, including over a range of control strategies, to maximise carbon savings, comfort, and user agency. It would also be useful to establish which temperature control regimes are in place in current and newly installed domestic space-heat heat-pump systems across northern Europe, and establish which are favoured by regulators and why if not weather compensation. All such work should involve input from practitioners.

2.5 Conclusions

UK heat-pump system installers are unsure if heat pumps and TRVs (and zoning more generally) interact badly, and if TRVs in fact ultimately waste electricity. This work shows, though varying temperature against a decade of external regional temperatures, building archetype, and, critically, the temperature control regime, that this specific industry worry should not in practice be an issue for dwellings with a typical weather compensation control regime, and further that micro-zoning such systems with TRVs will save energy. Thus, TRVs could be deployed in a retrofitted system, for comfort including maintaining bedrooms cooler than living spaces (Bruce-Konuah et al. 2018), and delivering low-cost multiplicative energy and carbon savings. A typical UK home, partly occupied as the modelled homes, may save approximately 500 kWh electricity per year, and thus over GBP100, based on Ofgem's current price cap, though this figure is for space heating without off times such as overnight. Occupants demanding tight ("stiff") temperature control may benefit from a different control setup, avoiding using TRVs for setback. It may still be best to leave some TRVs in place, but turned up to clamp only serious overheating from unexpected or occasional heat gains. Industry guidance and occupant training should maximise the climate benefit of gas boiler retrofits to heat pumps in the UK's existing thermally poor housing stock, while delivering comfort and agency.

Chapter 3

Future Work

This chapter relays my current view of the next stages of the research to deliver on the research objectives, extending Hart-Davis et al. (2024) as reproduced in Chapter 2.

All research will be as far as possible ‘open’, including open sourcing data and code/models created. (Some topics that have been considered for this research are briefly outlined in Appendix A.)

3.1 Control Schemes

3.1.1 Overview

- CS1: In Situ: extend domestic TRV / heat-pump / temperature-regulation interaction investigation (Hart-Davis et al. 2024) to high-fidelity models (eg HEM (UK DESNZ (Department for Energy Security and Net Zero) 2023*b*)) and/or physical housing stock such as Salford Energy House(s) (Marshall et al. 2017). Possible BEAMA project. Investigate the effect that increased short-cycling from zoning has on CoP?

- CS2: Europe in Practice: investigate and catalogue domestic heat-pump temperature regulation schemes in use and as recommended/regulated across northern Europe, possibly with a view to optimising regulation/advice for installers and occupiers. This will be in part in tandem with CS1 to inform exactly what to model and test.

- CS3 (optional): TRV Improvements: investigate possible changes to TRV behaviours with heat pumps to improve overall system efficiency, eg ‘all open’ command to reduce need for a buffer tank.

3.1.2 Methodology

The content of the CS1 workstream will require negotiation with the likely collaborators, so details will change from the projections here. CS1 will require advanced modelling, based on work already done. CS1 will if possible make use of and set-up of chargeable physical facilities, probably in more than one configuration and more than one iteration. The aim would include verifying the claims of Hart-Davis et al. (2024) re zoning continuing to save energy after retrofit from gas to heat pump providing that weather compensation is the main control strategy. The effect of small amounts of loop-closing "room influence" or similar could be verified on temperature deviation from set points (including sag) and on CoP/efficiency. The effect of other control strategies such as load compensation could be verified. In all cases this can be done first in a known-high-fidelity model, then, if possible, in a physical dwelling in controlled conditions. Slightly more generally, BEAMA (a trade association for energy infrastructure companies in the United Kingdom) and other parties may want a wider exploration of the interaction between TRVs and a domestic heat pump. One aspect to consider is the effect of cycling on CoP/SCoP, and the effect that zoning with TRVs has on overall efficiency, eg especially in shoulder seasons and other marginal conditions. I have used the Energy House at least twice before, so have some idea of the limitations and difficulties of such a test.

The CS2 workstream is desktop research, including a further check of the academic literature, but mainly a search of trade and regulatory documents. This may form a separate paper, else its findings may be folded into the CS1 paper.

The CS3 workstream will likely involve industry discussions and modelling work, possibly based on the CS1 high-fidelity model and the OpenTRV open-source codebase. This is marked as optional as time and other resources may not permit. It is a matter of live interest because it would both speak to improved efficiency of retrofit systems though zoning, and reduced space requirements for small houses by allowing a smaller buffer tank or none at all for ASHP systems in particular. The OpenTRV element would be minor: the key aim is to evaluate the feasibilty and efficacy of extended TRV/zoning smarts to better work with heat pumps.

3.2 Understanding First

3.2.1 Overview

- Heat-pump retrofits — must fabric improvements happen first or at all (eg (UK DLUHC (Department for Levelling Up Housing and Communities) et al. 2024)), and if not, how should outcomes be optimised (eg (Eyre et al. 2023, Wollard & Sissons 2024))? What are barriers to increasing wider modulation range to reduce cycling in shoulder months, and if insulation is upgraded post hoc? A recent DESNZ policy document (UK DESNZ (Department for Energy Security and Net Zero) 2023*a*) states that 90% of British homes have sufficient insulation and electrical capacity for a heat pump.

3.2.2 Methodology

This research stand will be primed with a literature and regulation and industry practice review, at least for the UK, and likely northern Europe more generally. What are the pros and cons reported for fabric-first and understanding-first type approaches, at least. This work is currently focussed on individual dwellings, though there are potentially interesting group upgrades of adjoining dwellings with identical or similar construction such as flats and terraced housing.

The next step will extending the review to issues and trends that would support or hinder an understanding-first approach, such as modulation ratios of available domestic heat pumps, regulatory restrictions such as EPCs currently still penalising heat pumps, EPCs and possibly HEM not allowing for a range / volatility of usage patterns, the level of resistance of dwelling external appearance changes (NIMBYism), green intervention cost loadings on gas vs electricity unit prices, pricing structure of heat pumps in the market, (eg avoiding a step up in unit size with a first round of fabric improvements), designer and installer skills and misunderstandings.

It is likely that it would be useful to model various outcomes in terms of decarbonisation progress and overall efficiency with varying degrees of understanding-first or fabric-first and varying degrees of technology and regulatory support. This model would be open sourced.

3.3 User Agency

3.3.1 Overview

- Improving agency and understanding for users of heat pumps to end up with cheaper more comfortable homes — controls that work and a mandated uniform common subset? This may involve DSR (Demand Side Response) with heat-pumps as ESA (Energy Smart Appliances) (UK DESNZ (Department for Energy Security and Net Zero) 2024*b*), and novel UI/UX including visualisation and sonification and psychoacoustically-driven audio salience encoding (Johnston 1988, Stevens 2013, Zong et al. 2024). Almost certainly requires collaboration across fields.

3.3.2 Methodology

This is currently the least developed and certain of the research elements, and so I will spend some effort in parallel with other strands to try to grasp and nail down better the topic before starting in earnest, such as by continuing with my own home data sonification. I have some experience designing user interfaces and user journeys, from trading applications in finance through to small physical heating controls. I have already thought about alternative ways of driving understanding, including when as editor of a supercomputing trade journal decades ago literally seeing how important visualisation was to make sense of output.

The key items to be explored, in parallel, are:

- Can we improve user (and installer) interaction with heat pump systems with sound in parallel with visual and physical/tactile controls?
- How can we improve understanding and agency around heat pump such as improving 'folk physics', on top of the complications of demand response?

Both of these could be desktop-only research. However, there is ample time to consider and prepare for real-world testing with end users across an entire heating season or two.

The proposed initial outline method is a subset of:

- As a background slow-burn task before the main work package start, work on sonification of real-world data to try to convey with sound and optional co-derived visuals some aspects of random access and information delivery speed typically associated with visuals alone.
- Discover what does and does not work to increase saliency of the workings of a typical domestic heat pump system and how to use it well with a range of users, eg tenancy types and ages and educational attainments and in different building archetypes, both from the literature and possibly with interviews, focus groups and in lab settings. This should include successes and failures to date with both "low and slow" heating systems (cf fast-response gas), and with retail static and dynamic ToU (Time-of-Use) tariffs and demand response electricity supply arrangements; ideally any learnings already evident from the intersection of the two, and other confounding factors.
- Attempt to identify new multi-modal interface styles including audio as a first-class participant that improves salience and accessibility for users overall. This would require first a review of the literature on UIs (especially multimodal), and on psychoacoustics, and may involve some lab testing of information conveyed and perceived, ideally by representative residents that in practice manage their homes' heating systems.
- Establish the likely utility of mandating some common elements of user interaction and controls (ie UI) across all heat pumps products of a particular class regardless of manufacturer, eg for the EU and/or UK markets. This would require estimating the possible net value of, and likely manufacturer and installer support for and resistance to, such mandates. This implies a mixture of literature review and interviews with civil servants (at least UK and EU) and politicians and manufacturers and designers/installers (of systems sold in the UK and EU).
- Investigate feasibility of other non-informational aspects of agency, real or perceived, that might improve acceptance of heat pump retrofits, such as developing product lines that can be substantially safely maintained by end users directly, not requiring inconvenient and/or expensive yearly technician visits, in stark contrast to gas boilers for example.

- Extension of Hart-Davis (2023*a*) with new data set being collected for 2024, maybe with "qualitative study of why people do it, and what are the factors that might get them to think differently?" to probe one aspect of salience and agency already missed; possible collaboration.

Involvement of the public is slow and expensive to do well. and carries extra ethics and data-handling responsibilities. It also likely requires external funding and project management resources. Where possible existing studies will be drawn on to maximise the outputs given time and resource constraints.

3.4 Plan

This outlines timing and dependencies, data handling, and risks.

3.4.1 Data

It is not evident at this stage if any of the research will require handling sensitive commercial or personal data. In any case, University research data management policy rules and general good practice will be followed. I have been a Data Protection Officer and have long experience of handling personal and commercial data, eg in previous heating system trials and as a school governor.

Normal non-sensitive research data, including documents such as this, will in general be kept in my version controlled repositories, with regular copies to University-managed file systems, dated, thus minimising risk of significant data loss, and allowing tracking and auditability against a timeline where needed.

(Note that the data in Hart-Davis (2023*a*) and its extension in 2024 is completely anonymous for example, should this become part of the PhD.)

3.4.2 Timeline

- 2024-05: paper published (Hart-Davis et al. 2024)
- 2024-07: confirmation report submission
- 2024-09: confirmation viva
- 2024-09: (subject to confirmation) start "Control Schemes"
- 2025-01: (subject to confirmation) start "Understanding First"
- 2028-06: start: "User Agency"
- 2030-01: writing up
- 2030-09: PhD thesis submission

- 2030-12: PhD viva

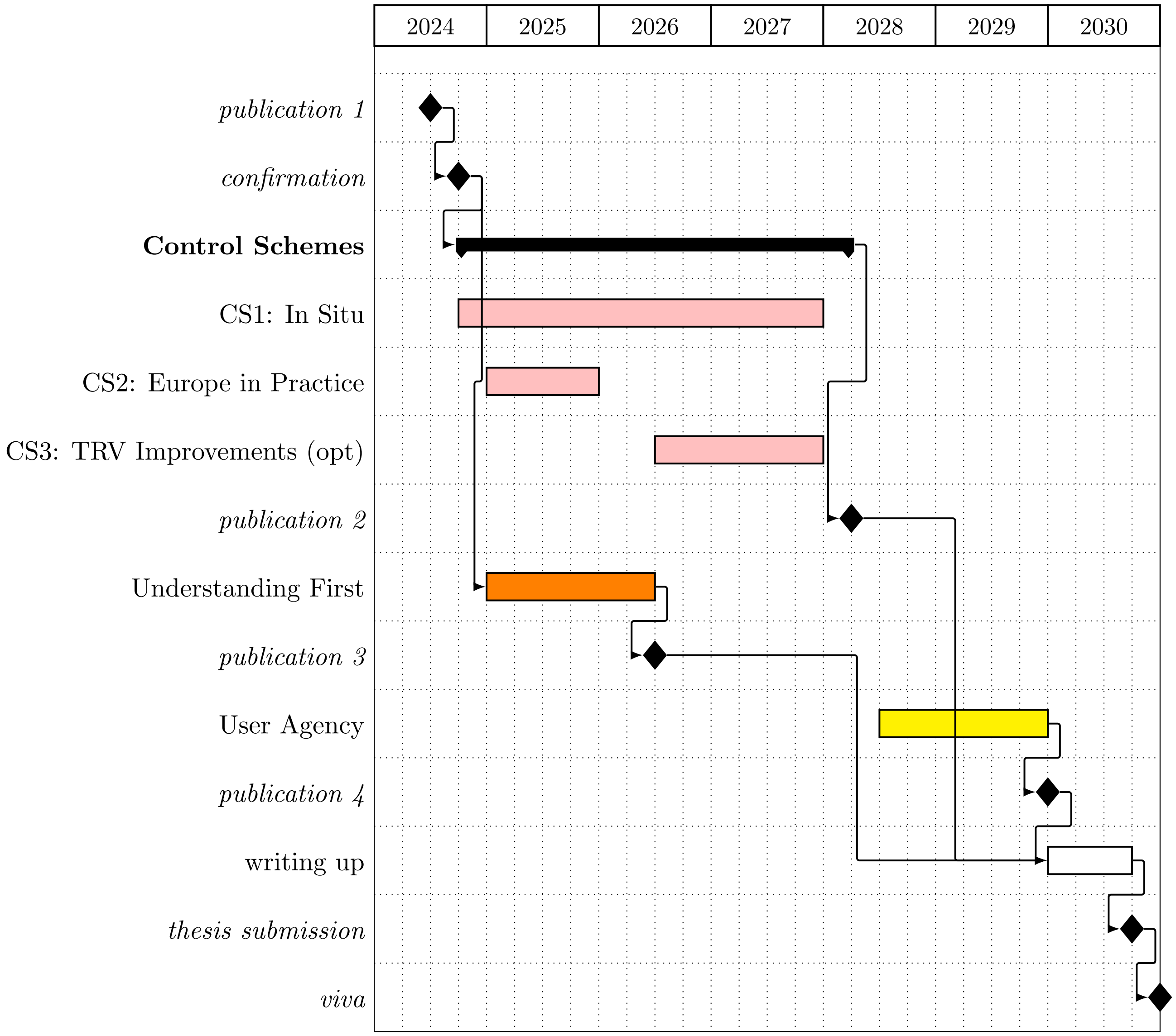


Figure 3.1: Time plan: Gantt chart of key timings and dependencies.

3.4.3 Risks

Table 3.1: Risk register of key issues; levels and mitigations.

H/M/L	Project	Description	Mitigation
L	Control Schemes: In Situ	Not being lead author; controlling direction of the work?	Have Salford professor as collaborating co-supervisor; formally, or informally.
M	Multiple	Starting multiple work strands around 2024Q4, in order to in particular minimise project risk on In Situ strand.	Careful time management and tracking; push back Understanding First segment if needed.
M	Control Schemes: In Situ	Need to clearly demonstrate my own contribution within collaboration, especially when using Salford's model.	Transparency, extension of model; early negotiation of research plan and questions.
M	Control Schemes: In Situ and TRV Improvements	This depends on collaboration (possibly commercial and academic), potential use of busy Salford facilities and thus wall-clock delays, and which may require funding to be raised.	Starting early; reasonable academic and industry contacts; familiarity with Salford Energy House facilities; potential pivot to models away from fully physical.
M	Multiple	Shifts in policy landscape changing decarbonisation priorities, eg from changes in UK and EU governments, and/or dramatic salient UK/EU climate impacts changing public mood.	Ability to pivot and adjust research plans.
H	User Agency: UX/UI and sonification work	Areas around UI design, salience, etc, are not my strengths, and the sonification component may be a blind alley.	Putting this project last while thinking about it slowly already; active cross-discipline collaboration from musicians to sociologists?

Chapter 4

Bibliography

Ambrose, A., Davies, K., Shaw, B., Shahzad, S., Jiglau, G., Vornicu, A., Sinea, A., Lobont, D., Palm, J., von Platten, J., Krishna, R., Pelsmakers, S., Kilpelainen, S., Castano-Rosa, R. & Aho, H. (2023), *Looking back to move forwards: A social and cultural history of home heating (JUSTHEAT)*.
URL: *https://ukerc.ac.uk/news/how-were-past-heating-transitions-experienced/*

Andersen, V. (2017), 'Danfoss'.
URL: *https://denstoredanske.lex.dk/Danfoss*

ASHRAE & ANSI (2023), 'Standard 55-2023 - thermal environmental conditions for human occupancy (ANSI approved)'.

Bagarella, G., Lazzarin, R. & Noro, M. (2016), 'Sizing strategy of on–off and modulating heat pump systems based on annual energy analysis', *International Journal of Refrigeration* **65**, 183–193.
URL: *https://www.sciencedirect.com/science/article/pii/S0140700716000475*

Beizaee, A., Allinson, D., Lomas, K. J., Foda, E. & Loveday, D. L. (2015), 'Measuring the potential of zonal space heating controls to reduce energy use in UK homes: The case of un-furbished 1930s dwellings', *Energy and Buildings* **92**, 29–44.
URL: *https://www.sciencedirect.com/science/article/pii/S037877881500047X*

Bennett, G., Watson, S., Wilson, G. & Oreszczyn, T. (2021), 'Domestic heating with compact combination hybrids (gas boiler and heat pump): A simple English stock model of different heating system scenarios', *Building Services Engineering Research and Technology* **43**(2), 143–159.
URL: *https://journals.sagepub.com/doi/full/10.1177/01436244211040449*

Berry, O., Kiley, D., King, K., Marsden, A., Regan, A., Woollard, M., Jacob, M., Jenkinson, R., Garcia, D. L., Yu, L., Schein, A. & Steele, P. (2023), 'Automating heat pump flexibility: results from a pilot'.

URL: *https://www.centrefornetzero.org/work/automating-heat-pump-flexibility-results-from-a-pilot/*

BizEE Software (n.d.), 'Degree days calculated accurately for locations worldwide'.
URL: *https://www.degreedays.net/*

Black, M. H., McGarry, S., Churchill, L., D'Arcy, E., Dalgleish, J., Nash, I., Jones, A., Tse, T. Y., Gibson, J., Bölte, S. & Girdler, S. (2022), 'Considerations of the built environment for autistic individuals: A review of the literature', *Autism* **26**(8), 1904–1915.
URL: *https://journals.sagepub.com/doi/full/10.1177/13623613221102753*

Boait, P. J., Fan, D. & Stafford, A. (2011), 'Performance and control of domestic ground-source heat pumps in retrofit installations', *Energy and Buildings* **43**(8), 1968–1976.
URL: *https://www.sciencedirect.com/science/article/pii/S037877881100154X*

Bruce-Konuah, A., Jones, R. V., Fuertes, A., Messi, L. & Giretti, A. (2018), 'The role of thermostatic radiator valves for the control of space heating in UK social-rented households', *Energy and Buildings* **173**, 206–220.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778818307035*

CBE (2020), 'CBE thermal comfort tool'.
URL: *https://comfort.cbe.berkeley.edu/*

Chapman, A. (2023), 'Why not to zone heat pumps or boilers!'.
URL: *http://web.archive.org/web/20230630205017/https://www.heatgeek.com/why-not-to-zone-heat-pumps-or-boilers/*

Cockroft, J., Cowie, A., Samuel, A. & Strachan, P. (2017), 'Potential energy savings achievable by zoned control of individual rooms in UK housing compared to standard central heating controls', *Energy and Buildings* **136**, 1–11.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778816315808*

Coupé, C., Oh, Y. M., Dediu, D. & Pellegrino, F. (2019), 'Different languages, similar encoding efficiency: Comparable information rates across the human communicative niche', *Science Advances* **5**(9).
URL: *https://www.science.org/doi/10.1126/sciadv.aaw2594*

Cretu, C., Kerle, I., Sarsentis, D. & Sissons, A. (2022), 'How to scale a highly skilled heat pump industry'.
URL: *https://www.nesta.org.uk/report/how-to-scale-a-highly-skilled-heat-pump-industry/*

Davies, J. (2016), 'Building regulations and U-values: How have they changed?'.
URL: *https://great-home.co.uk/building-regulations-u-values-how-have-they-changed/*

Delta, L. (2023), 'Vaillant installer survey report: Aspiring to a green future'.
URL: *http://web.archive.org/web/20230515223307/https://www.vaillant.co.uk/for-installers/training/installer-survey/*

Domestic Building Services Panel (2020), 'Domestic heating design guide'.
URL: *https://www.cibse.org/knowledge-research/knowledge-portal/domestic-heating-design-guide-2021*

Dongellini, M. & Morini, G. L. (2019), 'On-off cycling losses of reversible air-to-water heat pump systems as a function of the unit power modulation capacity', *Energy Conversion and Management* **196**, 966–978.
URL: *https://www.sciencedirect.com/science/article/pii/S0196890419306934*

Donkin, A. & Marmot, M. (2024), 'Left out in the cold: The hidden impact of cold homes'.
URL: *https://www.instituteofhealthequity.org/resources-reports/left-out-in-the-cold-the-hidden-impact-of-cold-homes*

Ecotricity Limited (2024), 'Our domestic electricity and gas tariffs: May 2024'.
URL: *https://www.ecotricity.co.uk/support/our-energy-tariffs*

Emerson Climate Technologies Inc. (2014), 'Understanding compressor modulation in air conditioning applications'.
URL: *https://climate.emerson.com/documents/understanding-compressor-modulation-en-us-3844210.pdf*

European Union (n.d.*a*), 'Commission communication in the framework of the implementation of commission regulation (eu) no 814/2013'.

European Union (n.d.*b*), 'Commission delegated regulation (eu) no 811/2013 of 18 february 2013 supplementing directive 2010/30/eu of the european parliament and of the council'.

Eyre, N., Fawcett, T., Topouzi, M., Killip, G., Oreszczyn, T., Jenkinson, K. & Rosenow, J. (2023), 'Fabric first: is it still the right approach?', *Buildings and Cities* **4**(1), 965–972.
URL: *https://journal-buildingscities.org/articles/10.5334/bc.388*

Fabbri, M., Kockat, J., Jankovic, I. & Sibileau, H. (2023), 'How to stay warm and save energy – insulation opportunities in European homes'.
URL: *https://www.bpie.eu/publication/how-to-stay-warm-and-save-energy-insulation-opportunities-in-european-homes/*

Fabrizio, E., Ferrara, M. & Monetti, V. (2017), Chapter 10 - smart heating systems for cost-effective retrofitting, *in* F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco & J. Kurnitski, eds, 'Cost-Effective Energy Efficient Building Retrofitting', Woodhead Publishing, pp. 279–304.
URL: *https://www.sciencedirect.com/science/article/pii/B9780081011287000101*

Fitton, R. P. (2017), The thermal energy performance of domestic dwellings in the UK, PhD thesis, University of Salford.
URL: *https://salford-repository.worktribe.com/output/1396756/the-thermal-energy-performance-of-domestic-dwellings-in-the-uk*

Fitton, R., Swan, W., Hughes, T., Benjaber, M. & Todd, S. (2016), 'Assessing the performance of domestic heating controls in a whole house test facility', *Building Services Engineering Research and Technology* **37**(5), 539–554.
URL: *https://journals.sagepub.com/doi/10.1177/0143624416634070*

Foulds, R. (2004), 'Biomechanical and perceptual constraints on the bandwidth requirements of sign language', *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **12**(1), 65–72.
URL: *https://ieeexplore.ieee.org/abstract/document/1273524*

Future Energy Scenarios: Bridging the Gap to Net Zero (2023).
URL: *https://www.nationalgrideso.com/future-energy/future-energy-scenarios/bridging-the-gap-to-net-zero*

Great British Energy founding statement (2024).

Harris, B. & Walker, A. (2023), 'Research briefing: Heat pumps'.
URL: *https://post.parliament.uk/research-briefings/post-pn-0699/*

Hart-Davis, D. (2023*a*), 'EOU UK central heating on/off date micro-survey result 2017 to 2023'.
URL: *https://datadryad.org/stash/dataset/doi:10.5061/dryad.wstqjq2t6*

Hart-Davis, D. (2023*b*), 'TRVmodel: TRV energy modelling in home heating'.
URL: *https://github.com/DamonHD/TRVmodel*

Hart-Davis, D. (2023*c*), 'UK homes wet heating retrofits needed for Net Zero'.
URL: *https://www.earth.org.uk/UK-homes-needing-retrofit.html*

Hart-Davis, D., Erbilgin, D., Bard, A. D. & Hill, M. J. (2022), 'Radiator thermostatic control'.
URL: *https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2594749*

Hart-Davis, D., Liu, L. & Leach, M. (2023), Do thermostatic radiator valves waste energy in uk heat pump retrofits? (preprint).
URL: *https://www.preprints.org/manuscript/202312.1608/v1*

Hart-Davis, D., Liu, L. & Leach, M. (2024), ‘To zone or not to zone when upgrading a wet heating system from gas to heat pump for maximum climate impact: A UK view’, *Sustainability* **16**(11).
URL: *https://www.mdpi.com/2071-1050/16/11/4710*

Henretty, N. (2020), ‘Energy efficiency of housing in England and Wales’.
URL: *https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/energyefficiencyofhousingineng*
09-23

Hoggett, R., Ward, J. & Mitchell, C. (2011), ‘Heat in homes: customer choice on fuel and technologies’.

Huchtemann, K. & Müller, D. (2013), ‘Simulation study on supply temperature optimization in domestic heat pump systems’, *Building and Environment* **59**, 327–335.
URL: *https://www.sciencedirect.com/science/article/pii/S0360132312002405*

Ji, Y., Lee, A. & Swan, W. (2019), ‘Building dynamic thermal model calibration using the energy house facility at salford’, *Energy and Buildings* **191**, 224–234.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778818337885*

Jindal, S., King, K., Marsden, A. & Gabriel, M. (2022), ‘Money saving boiler challenge: Supporting evidence october 2022’.
URL: *https://www.nesta.org.uk/report/money-saving-boiler-challenge-supporting-evidence-october-2022/*

Johnson, R., Royapoor, M. & Mayfield, M. (2021), ‘A multi-zone, fast solving, rapidly reconfigurable building and electrified heating system model for generation of control dependent heat pump power demand profiles’, *Applied Energy* **304**, 117663.
URL: *https://www.sciencedirect.com/science/article/pii/S0306261921010266*

Johnston, J. D. (1988), ‘Transform coding of audio signals using perceptual noise criteria’, *IEEE Journal on selected areas in communications* **6**(2), 314–323.
URL: *https://ieeexplore.ieee.org/abstract/document/608*

Kelly, N. & Cockroft, J. (2011), ‘Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data’, *Energy and Buildings* **43**(1), 239–245.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778810003385*

LCP Delta (2022), Electrification of heat: Home surveys and install report, Technical report, UK Energy Systems Catapult.
URL: *https://es.catapult.org.uk/report/electrification-of-heat-home-surveys-and-install-report/*

Lomas, K., Allinson, D., Watson, S., Beizaee, A., Haines, V. & Li, M. (2022), ‘Energy savings from domestic zonal heating controls: Robust evidence from a controlled field trial’, *Energy and Buildings*

254, 111572.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778821008562*

Lomas, K. J., Oliveira, S., Warren, P., Haines, V., Chatterton, T., Beizaee, A., Prestwood, E. & Gething, B. (2018), ‘Do domestic heating controls save energy? A review of the evidence’, *Renewable and Sustainable Energy Reviews* **93**, 52–75.
URL: *https://www.sciencedirect.com/science/article/pii/S1364032118303381*

Maivel, M. & Kurnitski, J. (2015), ‘Heating system return temperature effect on heat pump performance’, *Energy and Buildings* **94**, 71–79.
URL: *https://www.sciencedirect.com/science/article/pii/S037877881500153X*

Makasis, N., Gu, X., Kreitmair, M. J., Narsilio, G. A. & Choudhary, R. (2023), ‘Geothermal pavements: A city-scale investigation on providing sustainable heating for the city of cardiff, UK’, *Renewable Energy* **218**, 119248.
URL: *https://www.sciencedirect.com/science/article/pii/S0960148123011631*

Marshall, A., Fitton, R., Swan, W., Farmer, D., Johnston, D., Benjaber, M. & Ji, Y. (2017), ‘Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance’, *Energy and Buildings* **150**, 307–317.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778817305200*

Marshall, E., Steinberger, J. K., Dupont, V. & Foxon, T. J. (2016), ‘Combining energy efficiency measure approaches and occupancy patterns in building modelling in the uk residential context’, *Energy and Buildings* **111**, 98–108.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778815304060*

MCS (UK Microgeneration Certification Scheme) (2020), ‘Domestic heat pumps – a best practice guide’.
URL: *https://mcscertified.com/standards-tools-library/*

MCS (UK Microgeneration Certification Scheme) (2021), ‘The heat pump standard (installation)’.
URL: *https://mcscertified.com/standards-tools-library/*

Miller, R. & Sarshar, M. (2020), ‘Scaling up retrofit 2050: Why a nationwide programme to upgrade the existing housing stock is the only way for the uk to achieve its carbon saving goals’.
URL: *https://www.theiet.org/media/8758/retrofit.pdf*

Milligan, A. (2023), ‘Decision for typical domestic consumption values 2023’.
URL: *https://www.ofgem.gov.uk/decision/decision-typical-domestic-consumption-values-2023*

Monschauer, Y. & Wetzel, D. (2022), 'The future of heat pumps'.
URL: *https://www.iea.org/reports/the-future-of-heat-pumps*

Najjar, M. K., Figueiredo, K., Hammad, A. W., Tam, V. W., Evangelista, A. C. J. & Haddad, A. (2019), 'A framework to estimate heat energy loss in building operation', *Journal of Cleaner Production* **235**, 789–800.
URL: *https://www.sciencedirect.com/science/article/pii/S0959652619323650*

Neubert, D., Glück, C., Schnitzius, J., Marko, A., Wapler, J., Bongs, C. & Felsmann, C. (2022), 'Analysis of the operation characteristics of a hybrid heat pump in an existing multifamily house based on field test data and simulation', *Energies* **15**(15), 5611.

Office of Gas and Electricity Markets (Ofgem), UK (2024), 'Ofgem lays the groundwork for consumer friendly flexible energy use'.
URL: *https://www.ofgem.gov.uk/press-release/ofgem-lays-groundwork-consumer-friendly-flexible-energy-use*

Office of Gas and Electricity Markets (Ofgem), UK (n.d.), 'Energy price cap'.
URL: *https://www.ofgem.gov.uk/energy-price-cap*

Oikonomou, E. (2022), Understanding the drivers affecting the in-situ performance of domestic heat pumps in the UK, PhD thesis.
URL: *https://discovery.ucl.ac.uk/id/eprint/10150776/*

Oquab, M., Stock, P., Haziza, D., Xu, T., Zhang, P., Celebi, O., Hasson, Y., Labatut, P., Bose-Kolanu, B., Peyronel, T. & Couprie, C. (2021), Low bandwidth video-chat compression using deep generative models, *in* 'Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) Workshops', pp. 2388–2397.

Palmer, J. & Terry, N. (2021), 'Cost optimal domestic electrification (code)'.
URL: *https://www.gov.uk/government/publications/cost-optimal-domestic-electrification-code*

Piddington, J., Nicol, S., Garrett, H. & Custard, M. (2020), 'The housing stock of the United Kingdom'.

Pout, C. (2017), 'Evidence gathering - compensation and TPI heating controls'.
URL: *https://www.gov.uk/government/publications/heating-controls-compensation-and-time-proportional-and-integral-tpi-controls*

Preston, I. (2023), 'From retrofit to resilience: Cse's response to the government heating our homes consultation'.

URL: *https://www.cse.org.uk/news/from-retrofit-to-resilience-cses-response-to-the-government-heating-our-homes-consultation/*

Reguis, A., Vand, B. & Currie, J. (2021), 'Challenges for the transition to low-temperature heat in the UK: A review', *Energies* **14**(21).
URL: *https://www.mdpi.com/1996-1073/14/21/7181*

Rosenow, J., Gibb, D., Nowak, T. & Lowes, T. (2022), 'Heating up the global heat pump market', *Nature Energy* **7**, 901–904.
URL: *https://www.nature.com/articles/s41560-022-01104-8*

Schuetz, P., Melillo, A., Businger, F., Durrer, R., Frehner, S., Gwerder, D. & Worlitschek, J. (2020), 'Automated modelling of residential buildings and heating systems based on smart grid monitoring data', *Energy and Buildings* **229**, 110453.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778820318119*

Sørensen, S. V. (2023), 'The world's largest untapped energy source: Excess heat'.
URL: *https://www.whyenergyefficiency.com/solutions/allsolutions/the-worlds-largest-untapped-energy-source-excess-heat*

Staffell, I., Brett, D., Brandon, N. & Hawkes, A. (2012), 'A review of domestic heat pumps', *Energy & Environmental Science* **5**(11).
URL: *https://pubs.rsc.org/en/content/articlehtml/2012/ee/c2ee22653g*

Stark, C. & Thompson, M. (2019), Net Zero technical report, Technical report, UK Committee on Climate Change.
URL: *https://www.theccc.org.uk/publication/net-zero-technical-report/*

Stevens, M. (2013), *Sensory Ecology, Behaviour, and Evolution*, OUP Oxford.

Sustainability, Imagination and Aesthetics (2024), Sustainability, Creativity and Communication research group, University of Surrey, Guildford GU2 7XH, UK.
URL: *https://www.ias.surrey.ac.uk/event/sustainability-imagination-and-aesthetics/*

Tartarini, F., Schiavon, S., Cheung, T. & Hoyt, T. (2020), 'CBE thermal comfort tool: Online tool for thermal comfort calculations and visualizations', *SoftwareX* **12**, 100563.
URL: *https://www.sciencedirect.com/science/article/pii/S2352711020302454*

Terry, N. (2021), 'Turning down the radiators in unused rooms'.
URL: *http://web.archive.org/web/20220811232617/https://energy-surprises.blogspot.com/2021/09/turning-down-radiators-in-unused-rooms.html*

Terry, N. & Galvin, R. (2023), 'How do heat demand and energy consumption change when households transition from gas boilers to heat pumps in the UK', *Energy and Buildings* p. 113183.
URL: *https://www.sciencedirect.com/science/article/pii/S0378778823004139*

Toleikyte, A., Roca Reina, J. C., Volt, J., Carlsson, J., Lyons, L., Gasparella, A., Koolen, D., De Felice, M., Tarvydas, D., Czako, V., Koukoufikis, G., Kuokkanen, A. & Letout, S. (2023), *The heat pump wave: opportunities and challenges.*, Publications Office of the European Union.
URL: *https://op.europa.eu/en/publication-detail/-/publication/94cf1914-10b1-11ee-b12e-01aa75ed71a1/language-en*

UK BEIS (2022), 'Open consultation: Improving boiler standards and efficiency'.
URL: *https://www.gov.uk/government/consultations/improving-boiler-standards-and-efficiency*

UK BEIS & UK DESNZ (Department for Energy Security and Net Zero) (2022), 'Smart meter enabled thermal efficiency ratings (smeter) technologies project: technical evaluation'.
URL: *https://www.gov.uk/government/publications/smart-meter-enabled-thermal-efficiency-ratings-smeter-technologies-project-technical-evaluation*

UK DCLG (Department for Communities and Local Government) (n.d.), 'English Housing Survey data on stock profile (UK DCLG statistical data set)'.
URL: *https://www.gov.uk/government/statistical-data-sets/stock-profile*

UK DESNZ (Department for Energy Security and Net Zero) (2023*a*), 'Heat pump net zero investment roadmap'.
URL: *https://www.gov.uk/government/publications/heat-pump-net-zero-investment-roadmap*

UK DESNZ (Department for Energy Security and Net Zero) (2023*b*), 'Open consultation: Home energy model: Future homes standard assessment'.
URL: *https://www.gov.uk/government/consultations/home-energy-model-future-homes-standard-assessment*

UK DESNZ (Department for Energy Security and Net Zero) (2024*a*), 'Domestic hot water use in the uk'.
URL: *https://www.gov.uk/government/publications/domestic-hot-water-use-in-the-uk*

UK DESNZ (Department for Energy Security and Net Zero) (2024*b*), 'Open consultation: Delivering a smart and secure electricity system: implementation'.
URL: *https://www.gov.uk/government/consultations/delivering-a-smart-and-secure-electricity-system-implementation*

UK DLUHC (Department for Levelling Up Housing and Communities) (2014), 'Conservation of fuel and power: Approved document l'.

URL: *https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l*

UK DLUHC (Department for Levelling Up Housing and Communities) (2022*a*), 'English housing survey: Energy report 2020-21'.

UK DLUHC (Department for Levelling Up Housing and Communities) (2022*b*), 'Housing supply: net additional dwellings, England: 2021 to 2022'.
URL: *https://www.gov.uk/government/statistics/housing-supply-net-additional-dwellings-england-2021-to-2022/housing-supply-net-additional-dwellings-england-2021-to-2022*

UK DLUHC (Department for Levelling Up Housing and Communities) (2023), 'Open consultation: The future homes and buildings standards: 2023 consultation'.
URL: *https://www.gov.uk/government/consultations/the-future-homes-and-buildings-standards-2023-consultation/the-future-homes-and-buildings-standards-2023-consultation*

UK DLUHC (Department for Levelling Up Housing and Communities), UK DCMS (Department for Culture Media and Sport) & UK DESNZ (Department for Energy Security and Net Zero) (2024), 'Adapting historic homes for energy efficiency: a review of the barriers'.
URL: *https://www.gov.uk/government/publications/adapting-historic-homes-for-energy-efficiency-a-review-of-the-barriers*

UK Energy Systems Catapult (2021), 'Electrification of heat: All housing types are suitable for heat pumps'.
URL: *https://es.catapult.org.uk/news/electrification-of-heat-trial-finds-heat-pumps-suitable-for-all-housing-types/*

UK Energy Systems Catapult (2023), 'Electrification of heat: Interim heat pump performance data analysis report'.
URL: *https://es.catapult.org.uk/news/heat-pumps-shown-to-be-three-times-more-efficient-than-gas-boilers/*

UK HMRC (His Majesty's Revenue and Customs) (2023), 'Climate change levy: changes to rates from 1 april 2024'.
URL: *https://www.gov.uk/government/publications/climate-change-levy-ccl-rates-from-1-april-2024/climate-change-levy-changes-to-rates-from-1-april-2024*

UK National Infrastructure Commission (2023), 'The second national infrastructure assessment'.
URL: *https://nic.org.uk/studies-reports/national-infrastructure-assessment/second-nia/*

UK NHBC (National House-Building Council) (2023), 'Heat pump design and specification'.
URL: *https://www.nhbc.co.uk/binaries/content/assets/nhbc/tech-zone/nhbc-standards/tech-guidance/8.2/tg-8.2-01-heatpumpdesign.pdf*

Vocale, P., Morini, G. L. & Spiga, M. (2014), 'Influence of outdoor air conditions on the air source heat pumps performance', *Energy Procedia* **45**, 653–662.
URL: *https://www.sciencedirect.com/science/article/pii/S187661021400071X*

Vu, L., Soraperra, I., Leib, M., van der Weele, J. & Shalvi, S. (2023), 'Ignorance by choice: A meta-analytic review of the underlying motives of willful ignorance and its consequences.', *Psychological Bulletin* **149**(9-10), 611–635.
URL: *https://psycnet.apa.org/fulltext/2024-16890-004.html*

Wollard, M. & Sissons, A. (2024), 'Insulation impact: how much do uk houses really need?'.
URL: *https://www.nesta.org.uk/report/insulation-impact-how-much-do-uk-houses-really-need/*

Woollard, M., Alsop, J. & King, K. (2023), 'How to improve boiler standards and efficiency — a consultation response by nesta and the heating hub'.
URL: *https://medium.com/all-you-can-heat/how-to-improve-boiler-standards-and-efficiency-a-consultation-response-by-nesta-and-the-heating-4722895b7384*

Xu, B., Chen, Z., Wang, X. & Jiang, P. (2023), 'Field tests to examine energy saving effects of occupants' thermostatic radiator valves (TRVs) regulating behavior in district heating systems', *Science and Technology for the Built Environment* **29**(1), 96–105.
URL: *https://www.tandfonline.com/doi/full/10.1080/23744731.2022.2138689*

Xu, B., Jiang, P., Chen, Z., Li, Q., Wang, X. & Yan, Y. (2023), 'An integrated simulation of intermittent heating of multi-zone buildings by heat-pump heating systems with different terminal types', *Applied Thermal Engineering* **235**, 121427.

Zanetti, O. (2024), 'Overcoming barriers for newly trained heat pump installers'.
URL: *https://www.nesta.org.uk/project-updates/overcoming-barriers-for-newly-trained-heat-pump-installers/*

Zong, J., Pedraza Pineros, I., Chen, M. K., Hajas, D. & Satyanarayan, A. (2024), Umwelt: Accessible structured editing of multi-modal data representations, *in* 'Proceedings of the CHI Conference on Human Factors in Computing Systems', CHI '24, ACM.
URL: *https://dl.acm.org/doi/10.1145/3613904.3641996*

Appendix A

Potential Topics

Topics initially considered for this research can be broadly grouped into ‘controls’, ‘transition’ and ‘other’, briefly bulleted here:

Controls

- Extend domestic TRV / heat-pump / temperature-regulation interaction investigation (Hart-Davis et al. 2024) to high-fidelity models (eg HEM (UK DESNZ (Department for Energy Security and Net Zero) 2023*b*)) and/or physical housing stock such as Salford Energy House(s) (Marshall et al. 2017). Possible BEAMA project.

- Investigate and catalogue domestic heat-pump temperature regulation schemes in use and as recommended/regulated across northern Europe, possibly with a view to optimising regulation/advice for installers and occupiers.

- Investigate possible changes to TRV behaviours with heat pumps to improve overall system efficiency, eg ‘all open’ command to reduce need for a buffer tank.

- Improving agency and understanding for users of heat pumps to end up with cheaper more comfortable homes — controls that work and a mandated uniform common subset? This may involve DSR (Demand Side Response) with heat-pumps as ESA (Energy Smart Appliances) (UK DESNZ (Department for Energy Security and Net Zero) 2024*b*), and novel UI/UX including visualisation and sonification and psychoacoustically-driven audio salience encoding (Johnston 1988, Zong et al. 2024, Stevens 2013). Almost certainly requires collaboration across fields.

Transition

- Heat-pump retrofits — must fabric improvements happen first or at all (eg (UK DLUHC (Department for Levelling Up Housing and Communities) et al. 2024)), and if not, how should outcomes be optimised (eg (Eyre et al. 2023, Wollard & Sissons 2024))? What are barriers to increasing wider modulation range to reduce cycling in shoulder months, and if insulation is upgraded post hoc? A recent DESNZ policy document (UK DESNZ (Department for Energy Security and Net Zero) 2023*a*) states that 90% of British homes have sufficient insulation and electrical capacity for a heat pump.

- Thermochromic radiator stickers to help tune condensing boilers and de-risk a move to a heat-pump. Other methods to reduce FUD (Fear, Uncertainty and Dubt) introduced by lobbyists and clickbait-fuelled media, eg Smart Meter Enabled Thermal Efficiency Ratings (SMETER) (UK BEIS & UK DESNZ (Department for Energy Security and Net Zero) 2022).
- Describe and explore my current heat battery cross-vector control algorithm and anticipated future overhaul for heat-pump and continuing grid interaction.
- Allowing for adaption: systems with some cooling capability for the very hottest days, not necessarily comfort cooling.
- 'Just transition' (Ambrose et al. 2023) learning from previous domestic energy transitions, eg some in UK are only now switching away from coal heating, fairness across groups, persuading people who are rich or retired to make a contribution though it may be expensive for them also and not existential. Transition to ICE cars took 10Y, and buildings have become more fossil-fuel centric over last 100Y: how long to unwind?
- Messaging and information for the general public, green groups, local government, education from primary to PhD.
- Art and story-telling as a tool... "Sustainability, Imagination and Aesthetics" : "How should literature, art, film and other creative media respond to the growing environmental crisis? How can they best assist the dual project of mitigating the threats we face and fashioning a more sustainable future?" (*Sustainability, Imagination and Aesthetics* 2024).

Other

- How and when will the long tail of fossil home heat switch away?
- Maximising co-benefit health improvements eg (Donkin & Marmot 2024).
- Collaborations around slightly wider topics related to the above, eg domestic hot water, non-domestic space heating/zoning/sizing/modelling.
- Keeping an open brief for new barriers and opportunities that arise in domestic heat decarbonisation.

Appendix B

Relevant Recent/Current Sustainability Engagement

- Inventor and developer of Radbot domestic heating control (Hart-Davis et al. 2022) and other heating efficiency concepts.
- Official liaison between the Royal Borough of Kingston (including the Climate Action Team) and local environmental groups, as (interim) chair of Kingston Environment Forum (and Transition Town Kingston).
- Helped recreate Kingston Community Energy and have several RBK schools interested in putting solar PV on their roofs this year.
- Co-organiser of Repair Café Kingston, and co-signatory to the new Prime Minister with the Restart Project on prioritising repair and reuse (2024-07-08).
- Mentored in recent Surrey Hackathons, and was a joint winner of the Vice Chancellor's Award for Collaborative Teaching (2023-12). Other teaching support such as helping assess a Kingston University sustainability poster session.
- Participant in industry groups such as Elexon working group issue 109: netting of import/export for domestic customers.