Article

Not peer-reviewed version

Do Thermostatic Radiator Valves Waste Energy in UK Heat Pump Retrofits?

Damon Hart-Davis , Lirong Liu , Matthew Leach *

Posted Date: 21 December 2023

doi: 10.20944/preprints202312.1608.v1

Keywords: TRV; zoning; heat pump; decarbonising; domestic; space heating; energy efficiency; retrofit; controls

Article

Do Thermostatic Radiator Valves Waste Energy in UK Heat Pump Retrofits?

Damon Hart-Davis, Lirong Liu and Matthew Leach *

Centre for Environment and Sustainability (CES), University of Surrey, UK
* Correspondence: m.leach@surrey.ac.uk

Abstract: Domestic heating systems in the UK and across northern Europe are responsible for a substantial fraction of their countries' carbon footprints. In the UK the vast majority of home space heating is via natural gas boilers with 'wet' hydronic radiator systems. Most of those use TRVs (Thermostatic Radiator Valves) to avoid overheating, improve comfort and save energy. To meet Net Zero targets 20 million such UK gas systems may be retrofitted with heat pumps. Heat pump system designers and installers are cautious about retaining TRVs in such retrofitted systems in part because of worries that TRV temperature setbacks that lower heat demand may actually raise heat pump electricity demand in a "bad setback effect", thus wasting energy. This paper presents a new view of heat pump control and provides the first exploration of this issue, modelling one such industry claim, and finds that though real it should not apply to typical UK retrofits with weather compensation. The energy efficiency benefits of TRVs for older and partly-occupied homes, and to keep bedrooms cooler, remain valid. Comfort-seeking householders and installers should know that setting 'stiff' temperature regulation may invoke the bad setback effect and cost dearly in energy and carbon footprint.

Keywords: TRV; zoning; heat pump; decarbonising; domestic; space heating; energy efficiency; retrofit; controls

---

1. Introduction

UK residential heating, responsible for 10 to 20% of the UK's carbon footprint [1], must decarbonise as part of Net Zero goals to tackle climate change. Circa 20 million gas-fired radiator systems in UK dwellings standing now that will still be in use in 2050 are likely to be replaced with heat pump systems [1–8]. 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 [9,10]. 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 [11,12], 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. Smart TRVs that respond dynamically to occupation and other factors can further enhance micro-zoning gains [13].

It is reported that only "low-quality" formal evidence for energy savings from TRV (and other zoning) exists, though it *is* evident that domestic heating controls are hard to use effectively [14]. Explicit literature on interactions of TRVs (or similar micro-zoning and static or dynamic temperature setbacks) with heat pumps is relatively thin [15–17], and in any case will likely not be reaching heating professionals designing and implementing gas to heat-pump retrofits. Such information should be dissemimated explicitly though 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 [18,19].

This work aims to fill the understanding gap, and indicates that a common worry deterring installers from using TRVs in heat pump retrofits is likely unfounded for most households. Additional energy, money and carbon savings can be had by using them together.

 doi:10.20944/preprints202312.1608.v1

1.1. TRV history

Thermostatic radiator valves were invented by Mads Clausen of Danfoss (in 1943 [20], 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 (eg primarily depending on external temperature for weather compensation [21]) 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.

1.2. Heating control schemes in Europe

EU ErP (Energy related Products) defines eight control classes (811/2013) per Table 1 [22,23].

Table 1. EU ErP temperature controls classes.

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.

These control schemes can be, and are, applied to heat-pump heat generators.

Research [24] 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" (eg 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.

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" (eg 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, ie 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 [25]. Other controls and schemes exist.

1.3. 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 Sweden and Finland over 40% and Estonia over 30% [26,27], 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 run-time with external temperatures only a little above 0°C and at high relative humidity, requiring significant defrost energy expenditure, occur elsewhere in Europe too [28].

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 [29] (supported by [6,30]), with weather compensation [21,31–33] relatively common for newer installations, as already happens for combustion boilers.

1.4. 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 [7,34–36] (though much of that continental housing is also quite old [33]). 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, eg abundant North Sea gas, UK homes are markedly less energy efficient than those of neighbouring countries too. Approximately 80% of those existing homes have gas-fired wet (ie hydronic, with radiators) central heating [4,37]. 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.

1.5. TRV and heat-pump interaction concerns

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," [38] (extracted 2023-06).
>
> Nicola Terry also 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," [39] (extracted 2023-08).

It is important not to lose TRVs' additional low-cost decarbonisation and comfort value when retrofitting heat pumps, simply though uncertainty about possible interactions.

1.6. Contribution of the work

This work explores whether the 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

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

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. Methods

The model developed is intended to provide the simplest plausible investigation of TRV and heat pump interactions, to help guide installers. The model is used first to replicate the basic scenario at the heart of negative claims about TRVs, and is then extended to explore the sensitivity to building construction, archetype and geographic location within the UK.

Table 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 supplied heat-pump 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^2K)
$flowC$	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)
IDA	internal door area of a single door (m^2)
$IDAabHL$	initial model internal door heat loss per A room (W/m^2K)
$IDAabHLW$	initial model internal door heat loss per A room (W)
IDU	internal door U-value (W/m^2K)
$IDWAabHLW$	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)

Table 2. *Cont.*

Parameter	Meaning
$IFAabHLW$	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 set-back room layout
$tempA$	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)

2.1. Initial model and claim verification

The main claim of the Heat Geek article [38] re TRVs, heat demand and electricity demand, here described as the "bad setback effect", was transposed as simply as possible into a single-class (`HGTRVHPMModel`) Java model in [40] with all computations nominally at compile time. The results are verified with JUnit unit tests (`TestHGTRVHPModel`); there is approximately 90% code coverage.

 doi:10.20944/preprints202312.1608.v1

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.

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

- The whole system is in equilibrium, ie all temperatures are steady.
- Four equal-size square rooms in a square grid.
- Room arrangement is treated as a horizontal (eg bungalow) plan layout for this work, see Figure 1.
- 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 [11] (IDU).
- The radiators 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 set-back temperature good for sleeping and less-occupied rooms ($t_{IntSetback}$), 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 set-back 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.

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.

A	B
B	A

Figure 1. '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.

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

$$HLDT = t_{Int} - t_{ExT} \tag{1}$$

$$HLpK = HLW/HLDT. \tag{2}$$

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 ($t_{IntMeanWhenSetback}$)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

$$t_{IntMeanWhenSetback} = (t_{Int} + t_{IntSetback})/2 \tag{3}$$
$$HLsbW = HLpK.(t_{IntMeanWhenSetback} - t_{Ext}) \tag{4}$$
$$HLfall = (HLW - HLsbW)/HLW). \tag{5}$$

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

$$IWA = IWL.IWH \tag{6}$$
$$IWAab = 2.IWA \tag{7}$$
$$IWAabmd = IWAab - IDA \tag{8}$$

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

$$IWAabHL = IWAabmd.IWU \tag{9}$$
$$IWAabHLW = IWAabHL.(t_{Int} - t_{IntSetback}) \tag{10}$$
$$IDAabHL = IDA.IDAabHL \tag{11}$$
$$IDAabHLW = IDAabHL.(t_{Int} - t_{IntSetback}) \tag{12}$$
$$IDWAabHLW = IWAabHLW + IDAabHLW \tag{13}$$

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

$$radWAsb = radW + IDWAabHLW \tag{14}$$
$$radWBsb = (HLsbW - 2.radWAsb)/2 \tag{15}$$

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 ($radAMWsb$).

$$radWAmultsb = radWAsb/radW \tag{16}$$
$$radAdTmultsb = radWAmultsb^{MWATP2Dexp} \tag{17}$$
$$radAdTsb = radMWATdT.radAdTmultsb \tag{18}$$
$$radAMWsb = t_{Int} + radAdTsb \tag{19}$$

 doi:10.20944/preprints202312.1608.v1

The radiators in this model are specified as mean water-to-air temperature DT25, ie 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 ($HPinWsb$).

$$HPinWnsb = HLW/CoPLt \tag{20}$$

$$HPinWsb = HLsbW/CoPLt \tag{21}$$

If with B rooms set back and heat demand *down*, electricity demand goes *up*, this would be the "bad setback" effect claimed by the original article.

2.2. Extended model

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

- 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 run-time, unlike the initial model implementation.

2.2.1. Fixes

To allow doors per internal wall ($dpIW$) to be adjusted, from the original half to a more plausible one, one equation (8) is reimplemented in the extended models:

$$IWAabmd = IWAab - (2.dpIW.IDA) \tag{22}$$

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 5K from flow to return, and thus with the mean 2.5K 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:

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

$$tempDeltaK = CoPHt - CoPLt \tag{23}$$
$$CoPDelta = CoPH - CoPL \tag{24}$$
$$CoP = CoPL + ((flowC - CoPLt).(CoPDelta/tempDeltaK) \tag{25}$$

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

2.2.2. Layout

The initial model maximises internal heat flow/loss with the ABAB layout. With the same 50% of rooms set back an 'AABB' layout (see Figure 2) minimises internal heat flow by minimising the number of shared surfaces between A and B rooms.

A	A
B	B

Figure 2. 'AABB' layout of rooms minimising internal heat flows compared to the 'ABAB' layout shown in Figure 1.

Switching between ABAB and AABB layouts tests sensitivity to the juxtaposition of setback (eg 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 adustment of Equation 13, internal wall heat loss per A room to B room(s).

$$IDWAabHLW = (IWAabHLW + (2.dpIW.IDAabHLW)).\begin{cases} 1 & \text{if } roomsAlternatingABAB \\ 0.5 & \text{otherwise} \end{cases} \tag{26}$$

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

2.2.3. 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.

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 ie 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 indentical storey.

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

$$detachedExternalArea = TERA + 2.TEWA, \tag{27}$$

ie 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,

$$HHLnsb = (t_{Int} - t_{ExtVar}).(TERA + nStories.TEWA).EWRU. \tag{28}$$

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 set-back 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 simplifiying 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:

$$IFAabHL = (AFA.IFU) \tag{29}$$

$$IFAabHLW = (t_{Int} - t_{IntSetback}).IFAabHL \tag{30}$$

$$DIWAabHLW = \begin{cases} 0 & \text{if nStories=1 or is AABB} \\ IFAabHLW & \text{otherwise} \end{cases} \tag{31}$$

$$DIFWAabHLW = DIWAabHLW + DIFAabHLW, \tag{32}$$

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

2.2.4. 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 [41].

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-set-back and set-back 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 optimisaton (and opportunity for introducing errors) was avoided as the model run-time is barely noticeable.

2.2.5. Simulation of 'soft' temperature regulation

To simulate 'soft' temperature regulation in A rooms, ie 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-set-back 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.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

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 ($tempA$), eg floor losses

$$IFAabHLW = (tempA - t_{IntSetback}).IFAabHL, \tag{33}$$

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

$$VradAdTsb = DradAMWnsb - tempA \tag{34}$$
$$VradAdTmultsb = VradAdTsb/DradAdTsb \tag{35}$$
$$VradWAmultsb = VradAdTmultsb.VradAdTmultsb^{1/MWATP2Dexp} \tag{36}$$
$$VradWAsb = VradWAmultsb.DradWnsb \tag{37}$$

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.

2.3. 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 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 3. Input parameters and select calculated values across all scenarios.

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

2.3.1. Initial model

The Table 4 parameter values apply only to the initial model, prior to any fixes and extensions.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

Table 4. Input parameters and select calculated values for the initial model only.

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

2.3.2. 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 5.

Table 5. Input parameters and select calculated values for fixes.

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

2.3.3. AABB layout

This flag allows rearranging the set back (B) rooms to minimise internal heat flows. See Table 6.

Table 6. Input parameters and select calculated values for varying set-back room layout.

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

2.3.4. 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 7.

Table 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, eg by hour for weather

2.3.5. 2-storey detatched

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 8.

Table 8. Input parameters and select calculated values across scenarios.

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

The initial model example home is being treated here as a bungalow, ie four rooms on one level. At approximately 64m^2 heated floor area it would be in a moderately-common size category as can be seen in Table 11, though Table 10 indicates that bungalows themselves make up a small part of the housing stock.

Table 9. English 2020 dwelling stock profile: age. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey [42].

Dwelling age range	000s
pre-1919	4,684
1919–44	3,450
1945–64	4,106
1965–80	4,604
1981–90	1,745
post-1990	4,946

Table 10. English 2020 dwelling stock profile: archetype. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey [42].

Dwelling type	000s
all terrace	6,417
semi-detached	5,810
detached	4,137
bungalow	1,753
converted flat	1,028
purpose built flat, low rise	3,764
purpose built flat, high rise	625

Table 11. English 2020 dwelling stock profile: usable floor area m^2. From the 2020 English stock profile, table DA1101 (SST1.1), English Housing Survey [42].

Usable floor area m^2	000s
less than 50	2,340
50–69	5,113
70–89	6,390
90–109	3,579
110 or more	6,111

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 10, and at 128m^2 is the second most common size category by Table 11.

 doi:10.20944/preprints202312.1608.v1

To capture some of this shape effect as simply as possible, the initial model non-setback 2kW 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 [43], that would imply a late 1970s build or thereabouts. Another reasonably common slice of the English stock according to Table 9.

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 then 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 ($2W/m^2K$). 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.

2.3.6. 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 12.

Table 12. Input parameters and select calculated values for soft temperature regulation.

Parameter	Value
$tempStepK$	0.01K

2.4. Model runtime

All code and temperature data used for this paper is available open source at [40].

The model run time to compute and output all the numbers discussed in this paper is trivial: for the main calculations a few seconds on a 2020 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.

3. Results

3.1. Testing the original bad setback effect claim

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 [38].

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 769W with no B-room setbacks, and with setbacks 815W. With the updated parameters those became 812W and 895W. A 6% rise in heat-pump demand with B rooms set back became 10% with the adjustments.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 December 2023 doi:10.20944/preprints202312.1608.v1

3.2. 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 895W to 824W, ie 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 [11] into rooms that are set back. (It is good practice to ensure doors are closed into such rooms to reduce moisture flow along with heat.)

3.3. External air temperature

See Table 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, ie 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 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%

3.4. Alternative building archetype

Taking the original bungalow with fixes applied, the heat demand was 812W. For the detached house, though twice the heated floor area, demand was 1131W, 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.

3.5. 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 [41], years 2010 to 2019 inclusive (avoiding the somewhat abnormal 2020), across 7 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 14.

Table 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 detached	-11.7%	3.1% 11.5%	-4.5% -4.6%
Manchester (EGCC)	bungalow detached	-11.8%	3.1% 11.5%	-4.5% -4.6%
Cardiff (EGFF)	bungalow detached	-12.5%	2.1% 10.4%	-5.4% -5.5%
London (EGLL)	bungalow detached	-12.3%	2.5% 10.8%	-5.1% -5.2%
Newcastle (EGNT)	bungalow detached	-11.4%	3.6% 12.0%	-4.1% -4.2%
Glasgow (EGPF)	bungalow detached	-11.5%	3.5% 11.9%	-4.2% -4.3%
Edinburgh (EGPH)	bungalow detached	-11.4%	3.6% 12.0%	-4.1% -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.

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.

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.

3.6. 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 [24].

A more common scheme in heat pump installations is to use weather compensation to set the radiator flow temperature based on the outside temperature [21]. (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.

 doi:10.20944/preprints202312.1608.v1

Similar behaviour was observed in a Chinese apartment block [44]. 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 1.5K. For the detached house version, approximately 1.9K.

These sags were smaller with a less extreme zoning pattern such as AABB (approximately 1.0K / approximately 1.1K).

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 15.

Table 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 14.

Location (Weather Station)	Archetype	Home heat demand delta	ABAB heat-pump demand delta	AABB heat-pump demand delta
Belfast (EGAA)	bungalow detached	-17.5%	-17.1% -18.6%	-15.2% -15.6%
Manchester (EGCC)	bungalow detached	-17.6%	-17.1% -18.7%	-15.2% -15.6%
Cardiff (EGFF)	bungalow detached	-18.7%	-18.3% -20.0%	-16.3% -16.7%
London (EGLL)	bungalow detached	-18.3%	-17.9% -19.5%	-15.9% -16.3%
Newcastle (EGNT)	bungalow detached	-17.0%	-16.5% -18.1%	-14.7% -15.1%
Glasgow (EGPF)	bungalow detached	-17.2%	-16.6% -18.2%	-14.8% -15.2%
Edinburgh (EGPH)	bungalow detached	-17.0%	-16.5% -18.1%	-14.7% -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 [45]. Steady deviations such as in [44] also seem to be tolerated. Thus a temperature sag such as seen above in A rooms with soft regulation may be entirely acceptable to householders.

4. Discussion

Unexpectedly the Heat Geek claim was shown 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 heat pump and TRVs who did not find the original article and initial model to reflect their reality, would depend on the detail of 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 [46], 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, eg 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-set-back 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 for defrost cycles.

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, ie the hourly modelling treats each hour independently and in equilibrium.

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 models (such as in EnergyPlus, or EWASP [47]), 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.

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 indicates that such interaction should not in practice be an issue for dwellings with a typical weather compensation control regime. Thus TRVs could be deployed in a retrofitted system, for comfort including maintaining bedrooms cooler than living spaces [10], and delivering low-cost multiplicative energy and carbon savings.

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 climate benefit of gas boiler retrofits to heat pumps in the UK's existing thermally poor housing stock, while delivering comfort and agency.

Author Contributions: Conceptualization, D.HD; methodology, D.HD; software, D.HD; investigation, D.HD; resources, D.HD; data curation, D.HD; writing—original draft preparation, D.HD; writing—review and editing, M.L and L.L; supervision, M.L and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The project code (Apache 2.0 licence) and data is available at https://github.com/DamonHD/TRVmodel [40], specifically V1.0.0 for this paper at https://github.com/DamonHD/TRVmodel/releases/tag/V1.0.0 and via doi:10.15126/900901 also. Within it is embedded UK weather temperature data from https://www.degreedays.net/ [41].

Acknowledgments: Many thanks to Adam Chapman and Nicola Terry for providing clear worked examples of this potential bad setback effect. Also thanks to the many people who helped informally review this analysis, in its various versions. Thanks to Nathan Gambling for explaining why TRVs were invented. Thank you to https://www.degreedays.net/ for the comprehensive UK weather data. Thanks to Deniz Erbilgin and Chay Strawbridge for reviewing the model code.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASHP	Air-source heat pump
CoP	Coefficient of performance
CSV	Comma separated values
DHW	Domestic hot water
HDD	Heating degree day
TPI	Time Proportional and Integral
TRV	Thermostatic radiator valve

References

1. Stark, C.; Thompson, M. Net Zero Technical report. Technical report, UK Committee on Climate Change, 2019.
2. The Second National Infrastructure Assessment. https://nic.org.uk/studies-reports/national-infrastructure-assessment/second-nia/, accessed on 2023-10-18.
3. LCP Delta. Electrification of Heat: Home Surveys and Install Report. Technical report, Energy Systems Catapult, UK, 2022.
4. English Housing Survey: Energy Report 2020-21. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1091144/Energy_Report_2020_revised.pdf, accessed on 2023-01-20.
5. Open consultation: Improving boiler standards and efficiency. https://www.gov.uk/government/consultations/improving-boiler-standards-and-efficiency, accessed on 2023-02-15.
6. Reguis, A.; Vand, B.; Currie, J. Challenges for the Transition to Low-Temperature Heat in the UK: A Review. *Energies* **2021**, *14*. doi:10.3390/en14217181.
7. Piddington, J.; Nicol, S.; Garrett, H.; Custard, M. The Housing Stock of The United Kingdom. https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf, accessed on 2022-11-30.
8. Hart-Davis, D. UK Homes Wet Heating Retrofits Needed for Net Zero. https://www.earth.org.uk/UK-homes-needing-retrofit.html, accessed on 2023-03-21.
9. Conservation of fuel and power: Approved Document L. https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l, accessed on 2023-05-18.

10. Bruce-Konuah, A.; Jones, R.V.; Fuertes, A.; Messi, L.; Giretti, A. The role of thermostatic radiator valves for the control of space heating in UK social-rented households. *Energy and buildings* **2018**, *173*, 206–220. doi:10.1016/j.enbuild.2018.05.023.
11. Cockroft, J.; Cowie, A.; Samuel, A.; Strachan, P. Potential energy savings achievable by zoned control of individual rooms in UK housing compared to standard central heating controls. *Energy and Buildings* **2017**, *136*, 1–11. doi:10.1016/j.enbuild.2016.11.036.
12. Domestic Building Services Panel. Domestic Heating Design Guide. https://www.cibse.org/knowledge-research/knowledge-portal/domestic-heating-design-guide-2021, accessed on 2023-05-31.
13. Hart-Davis, D.; Erbilgin, D.; Bard, A.D.; Hill, M.J. Radiator thermostatic control. GB2594749, 08, 2022.
14. Lomas, K.J.; Oliveira, S.; Warren, P.; Haines, V.; Chatterton, T.; Beizaee, A.; Prestwood, E.; Gething, B. Do domestic heating controls save energy? A review of the evidence. *Renewable and Sustainable Energy Reviews* **2018**, *93*, 52–75. doi:10.1016/j.rser.2018.05.002.
15. Xu, B.; Jiang, P.; Chen, Z.; Li, Q.; Wang, X.; Yan, Y. An integrated simulation of intermittent heating of multi-zone buildings by heat-pump heating systems with different terminal types. *Applied Thermal Engineering* **2023**, *235*, 121427. doi:10.1016/j.applthermaleng.2023.121427.
16. Johnson, R.; Royapoor, M.; Mayfield, M. 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* **2021**, *304*, 117663. doi:10.1016/j.apenergy.2021.117663.
17. Terry, N.; Galvin, R. How do heat demand and energy consumption change when households transition from gas boilers to heat pumps in the UK. *Energy and Buildings* **2023**, p. 113183. doi:10.1016/j.enbuild.2023.113183.
18. Open consultation: The Future Homes and Buildings Standards: 2023 consultation. https://www.gov.uk/government/consultations/the-future-homes-and-buildings-standards-2023-consultation/the-future-homes-and-buildings-standards-2023-consultation, accessed on 2023-12-17.
19. Open consultation: Home Energy Model: Future Homes Standard assessment. https://www.gov.uk/government/consultations/home-energy-model-future-homes-standard-assessment, accessed on 2023-12-17.
20. Andersen, V. Danfoss. https://denstoredanske.lex.dk/Danfoss, accessed on 2023-10-30.
21. Huchtemann, K.; Müller, D. Simulation study on supply temperature optimization in domestic heat pump systems. *Building and Environment* **2013**, *59*, 327–335. doi:10.1016/j.buildenv.2012.08.030.
22. Commission Delegated Regulation (EU) No 811/2013 of 18 February 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02013R0811-20170307, accessed on 2023-12-17.
23. Commission communication in the framework of the implementation of Commission Regulation (EU) No 814/2013. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014XC0703%2801%29, accessed on 2023-12-17.
24. Pout, C. Evidence Gathering - Compensation and TPI Heating Controls. https://www.gov.uk/government/publications/heating-controls-compensation-and-time-proportional-and-integral-tpi-controls, accessed on 2023-10-04.
25. Hart-Davis, D. EOU UK central heating on/off date micro-survey result 2017 to 2023. https://datadryad.org/stash/dataset/doi:10.5061/dryad.wstqjq2t6, accessed on 2023-11-12. doi:10.5061/dryad.wstqjq2t6.
26. Monschauer, Y.; Wetzel, D. The Future of Heat Pumps. https://www.iea.org/reports/the-future-of-heat-pumps, accessed on 2023-11-02.
27. Rosenow, J.; Gibb, D.; Nowak, T.; Lowes, T. Heating up the global heat pump market. *Nature Energy* **2022**, *7*, 901–904. doi:10.1038/s41560-022-01104-8.
28. Vocale, P.; Morini, G.L.; Spiga, M. Influence of outdoor air conditions on the air source heat pumps performance. *Energy Procedia* **2014**, *45*, 653–662. doi:10.1016/j.egypro.2014.01.070.
29. Kelly, N.; Cockroft, J. Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data. *Energy and Buildings* **2011**, *43*, 239–245. doi:10.1016/j.enbuild.2010.09.018.
30. Fabrizio, E.; Ferrara, M.; Monetti, V. Chapter 10 - Smart Heating Systems for Cost-Effective Retrofitting. In *Cost-Effective Energy Efficient Building Retrofitting*; Pacheco-Torgal, F.; Granqvist, C.G.;

Jelle, B.P.; Vanoli, G.P.; Bianco, N.; Kurnitski, J., Eds.; Woodhead Publishing, 2017; pp. 279–304. doi:10.1016/B978-0-08-101128-7.00010-1.

31. Boait, P.J.; Fan, D.; Stafford, A. Performance and control of domestic ground-source heat pumps in retrofit installations. *Energy and Buildings* **2011**, *43*, 1968–1976. doi:10.1016/j.enbuild.2011.04.003.
32. Neubert, D.; Glück, C.; Schnitzius, J.; Marko, A.; Wapler, J.; Bongs, C.; Felsmann, C. Analysis of the Operation Characteristics of a Hybrid Heat Pump in an Existing Multifamily House Based on Field Test Data and Simulation. *Energies* **2022**, *15*, 5611. doi:10.3390/en15155611.
33. 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. *The heat pump wave: opportunities and challenges.*; Number JRC134045, Publications Office of the European Union, 2023. doi:10.2760/27877.
34. Miller, R.; Sarshar, M. 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. https://www.theiet.org/media/8758/retrofit.pdf, accessed on 2023-01-04.
35. Fabbri, M.; Kockat, J.; Jankovic, I.; Sibileau, H. How to stay warm and save energy – insulation opportunities in European homes. https://www.bpie.eu/publication/how-to-stay-warm-and-save-energy-insulation-opportunities-in-european-homes/, accessed on 2023-01-19.
36. Housing supply: net additional dwellings, England: 2021 to 2022. https://www.gov.uk/government/statistics/housing-supply-net-additional-dwellings-england-2021-to-2022/housing-supply-net-additional-dwellings-england-2021-to-2022, accessed on 2023-01-30.
37. Henretty, N. Energy efficiency of housing in England and Wales. https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/energyefficiencyofhousinginenglandandwales/2020-09-23, accessed on 2023-11-21.
38. Chapman, A. Why NOT to ZONE Heat Pumps or Boilers! http://web.archive.org/web/20230630205017/https://www.heatgeek.com/why-not-to-zone-heat-pumps-or-boilers/, accessed on 2023-06-30.
39. Terry, N. Turning down the radiators in unused rooms. http://web.archive.org/web/20220811232617/https://energy-surprises.blogspot.com/2021/09/turning-down-radiators-in-unused-rooms.html, accessed on 2022-08-11.
40. Hart-Davis, D. TRVmodel: TRV energy modelling in home heating. https://github.com/DamonHD/TRVmodel, accessed on 2023-11-12. doi:10.15126/900901.
41. Degree Days Calculated Accurately for Locations Worldwide. https://www.degreedays.net/, accessed on 2023-08-08.
42. English Housing Survey data on stock profile (UK DCLG statistical data set). https://www.gov.uk/government/statistical-data-sets/stock-profile, accessed on 2023-11-14.
43. Davies, J. Building Regulations And U-values: How have they changed? https://great-home.co.uk/building-regulations-u-values-how-have-they-changed/, accessed on 2023-09-20.
44. Xu, B.; Chen, Z.; Wang, X.; Jiang, P. 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* **2023**, *29*, 96–105. doi:10.1080/23744731.2022.2138689.
45. 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. Automating heat pump flexibility: results from a pilot. https://www.centrefornetzero.org/work/automating-heat-pump-flexibility-results-from-a-pilot/, accessed on 2023-09-18.
46. Vu, L.; Soraperra, I.; Leib, M.; van der Weele, J.; Shalvi, S. Ignorance by choice: A meta-analytic review of the underlying motives of willful ignorance and its consequences. *Psychological Bulletin* **2023**, *149*, 611–635. doi:10.1037/bul0000398.
47. Johnson, R.; Royapoor, M.; Mayfield, M. 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* **2021**, *304*, 117663. doi:10.1016/j.apenergy.2021.117663.