



UK Government

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK



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Executive Summary

This report focusses on the suitability of reversible air-to-air heat pumps (RAAHPs) for providing heating and hot water for various domestic dwelling archetypes in the UK. RAAHPs are a particular type of air source heat pump that can provide domestic space heating, space cooling, and (in some cases) hot water, as well as dehumidification and air filtration. However, currently RAAHPs are infrequently used in domestic settings in the UK, and so there is limited data on their performance and suitability.

To understand and assess suitability, the Energy Systems Catapult has carried out detailed modelling of the performance of domestic dwellings with various heating systems, including RAAHPs, using its proprietary domestic building physics-based simulation toolkit, Home Energy Dynamics (HED). The Department for Energy Security and Net Zero (DESNZ) selected 39 scenarios to be simulated in HED, covering various dwelling archetypes, heating systems, weather files, and heating and occupancy profiles.

The project answered six research questions relating to energy requirements of different systems, operating costs (only, not capex), performance in extreme warm or cold weather, requirements for supplementary systems, and suitability in a dwelling built to the Future Homes Standard (FHS) as proposed at the consultation stage¹.

The project found that RAAHPs operating together with supplementary resistive electric heaters (used in bathrooms etc) provided space heating (i.e. not considering heating water) at a greater combined efficiency for three out of five archetype dwellings, when compared to other types of systems (air-to-water heat pump, combi gas boiler, and electric panel heater). For RAAHPs operating together with supplementary resistive electric heaters, the ratio of useful space heating provided to energy use varied from around 2.5:1 to around 4:1², whereas air-to-water heat pumps typically achieved between 3:1 and 3.5:1, and combi-condensing gas boilers around 0.9:1. It should be noted, however, that the uncertainty associated with the efficiency figures presented for RAAHP systems in this report is higher than that for alternative systems, due to the RAAHP models being constructed from a relatively limited dataset.

RAAHPs also provide a useful additional benefit to households: space cooling to alleviate high temperatures. With the RAAHP system providing cooling, during the summer the maximum living room temperature exceeded 25°C for no more than 15% of the cooling season. In dwellings fitted with a RAAHP, this cooling functionality is built into the system and represents a capital expenditure saving relative to a counterfactual case where cooling would need to be provided by an additional system.

While the performance of RAAHPs for space heating was very positive, given the efficiencies achieved and that desired room temperatures were generally met, the systems did not

¹ The final FHS specification was issued after the start of this project and is now available here: <https://www.gov.uk/government/consultations/the-future-homes-and-buildings-standards-2023-consultation> .

² This finding was derived from the project and refers to the ratio of heat provided by the RAAHP and electricity consumption. The model of the RAAHP was based upon a manufacturer's publicly available data.

generally provide hot water (because the maximum available – and therefore modelled – tank size in the UK at the outset of the project was 120 litres, too small for many households). Instead, in the majority of cases a RAAHP was used for space heating and cooling, but hot water was provided by a less efficient immersion heated tank. Because of this limitation, the project found that the full picture of energy requirements and operating costs on a fixed price tariff for dwellings with RAAHPs in combination with other technologies were often higher than for other types of systems (because the supplementary systems are less efficient), even when comparing against counterfactual cases with cooling included to give a like-for-like comparison.

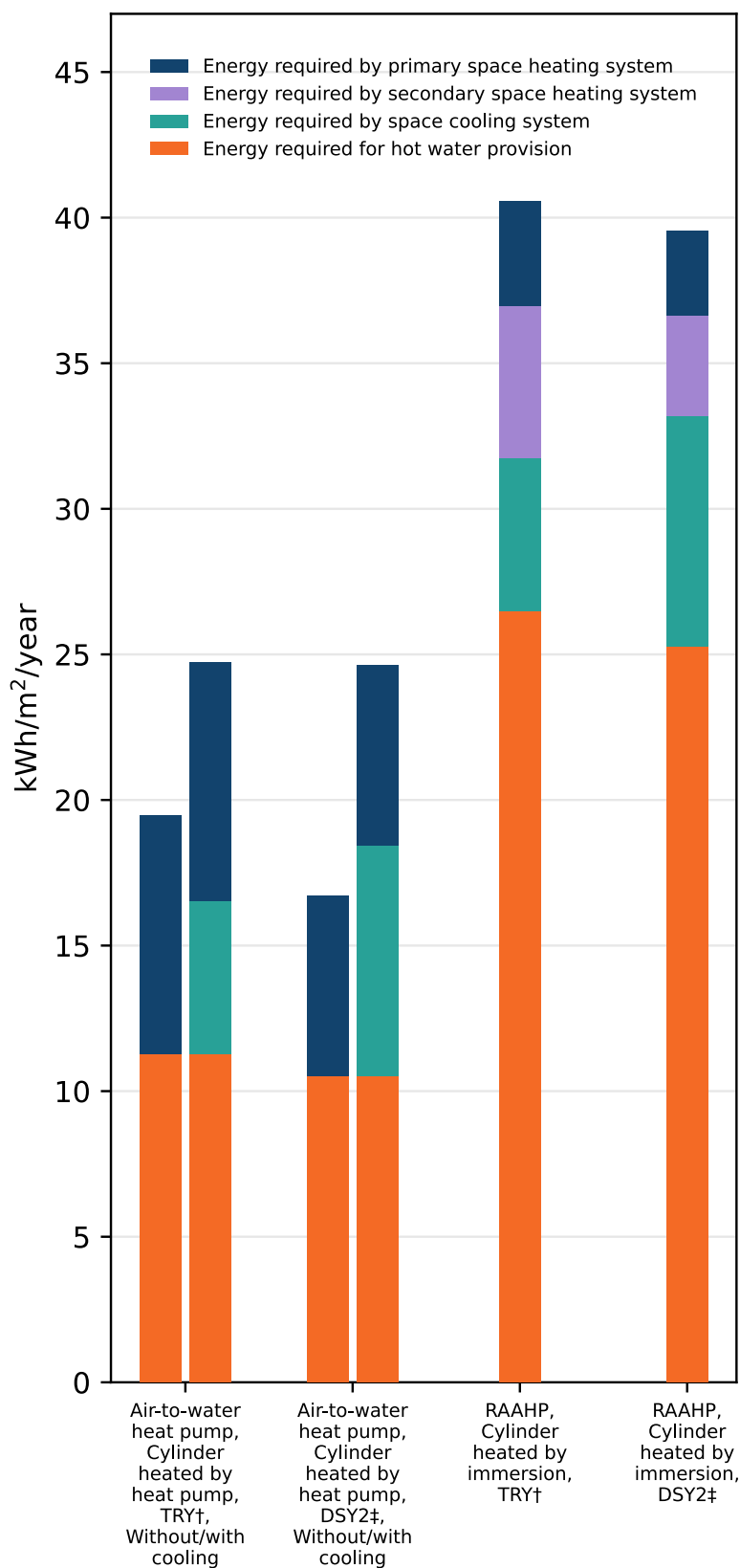
However, in the case of the flat archetype (a post-2002 studio), where use of a RAAHP with an integrated 120 litre hot water tank was possible, this system required a lower annual cost than any of the alternatives, including a gas boiler. The planned release onto the market of RAAHP systems linked to larger capacity 230 litre³ hot water tanks therefore offers the prospect of operating-cost-competitive RAAHP systems being available for a larger range of dwellings.

To help illustrate and aid comparisons across scenarios, Figure 1 to Figure 3 show annual energy demand by end use (e.g., space heating, space cooling, hot water), normalised by m² of floor area, for all 39 simulations. There are instances where the demand is similar across technologies (e.g., the air-to-water heat pump scenario and RAAHP scenario for both the 1919-1944 detached and pre-1919 mid-terraced dwellings), but also where the RAAHP scenarios require more energy because of the need for supplementary systems. Because of the efficiencies of different parts of the system relative to each other (e.g., when a RAAHP is providing space heating and paired with an immersion heater providing hot water), in some cases the largest annual demand is attributed to hot water rather than space heating.

It should be noted that a RAAHP system always requires less energy than a direct electric heating system (see Figure 2). Also, if the RAAHP can provide hot water, rather than relying on an immersion heater, then the overall system efficiency is significantly improved.

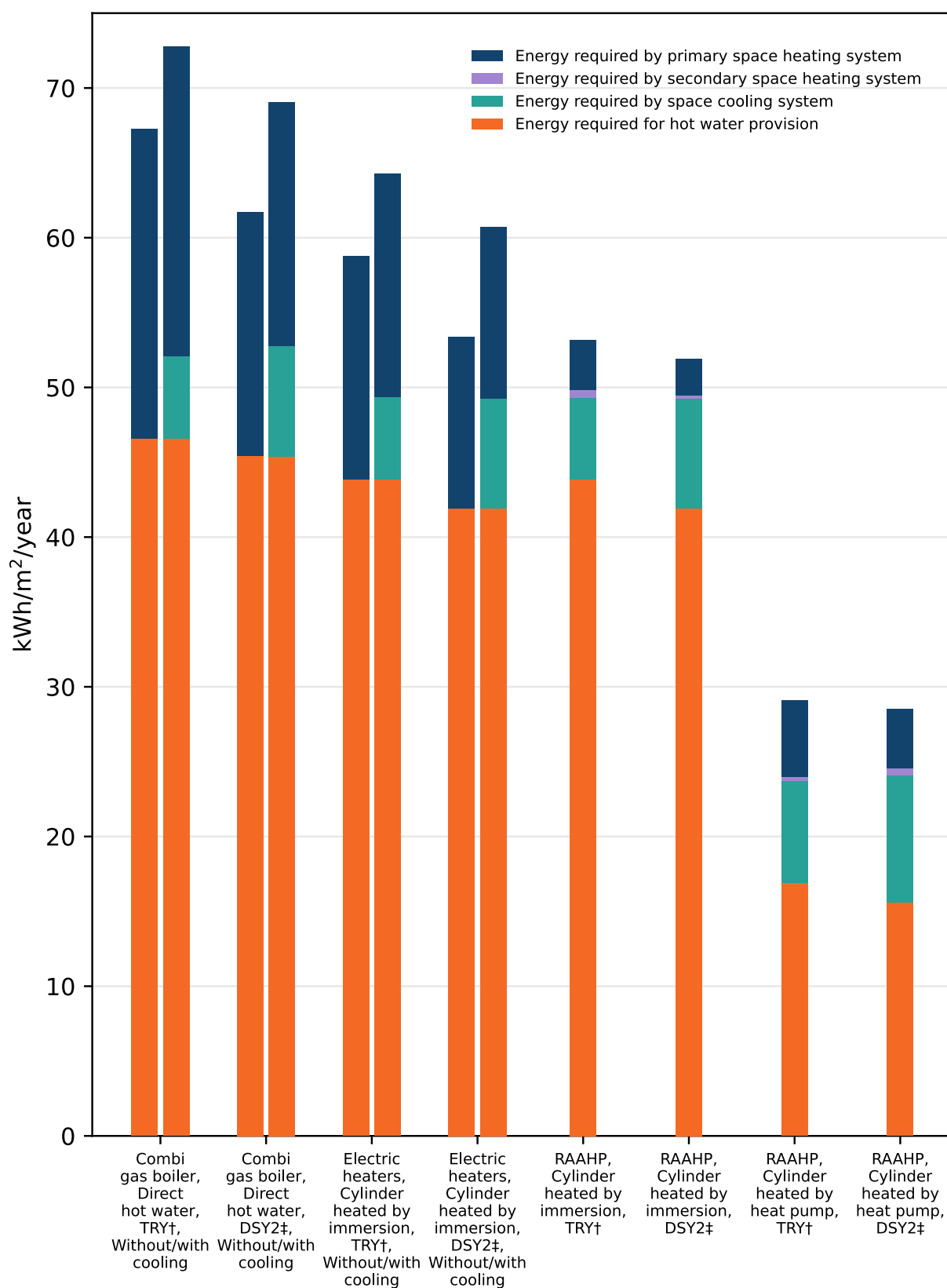
³ https://www.daikin-ce.com/en_us/press-releases/2025/new-solution-for-cooling-heating-hot-water-daikin-multi.html

Figure 1: Post-2026 detached dwelling (built to proposed FHS) annual energy demand (space heating, cooling, and hot water only) by end use per m² of floor area



†TRY: 'Test reference year' weather file. (Typical weather year.)
 ‡DSY2: 'Design summer year 2' weather file. (Year containing intense heat events.)

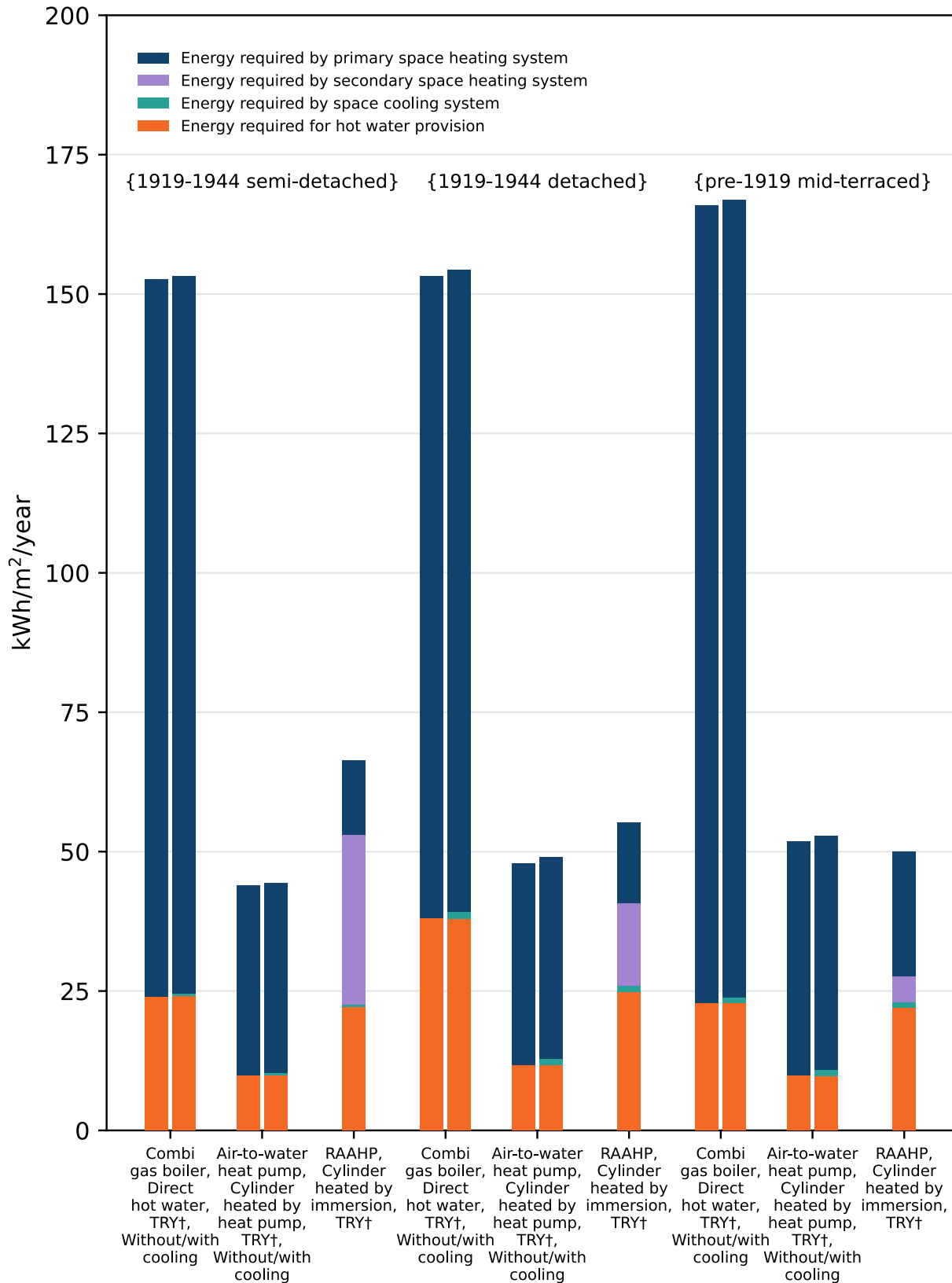
Figure 2: Post-2002 studio flat annual energy demand by end use per m² of floor area



†TRY: 'Test reference year' weather file. (Typical weather year.)

‡DSY2: 'Design summer year 2' weather file. (Year containing intense heat events.)

Figure 3: Annual energy demand by end use per m² of floor area for three dwelling archetypes



†TRY: 'Test reference year' weather file. (Typical weather year.)

Typically, the RAAHP was able to meet occupancy requirements for space heating and cooling. In hotter weather that might occur more frequently in a warmer future climate, the useful cooling demand was significant, at ~25kWh/day in an 81m² dwelling.

For the dwelling built to the proposed Future Homes Standard (FHS), the air-to-water heat pump scenarios used less energy and were cheaper to run across the course of the year, even with cooling included to give a like-for-like summer comparison with the air-to-air heat pump scenarios. However, for the mid-terrace archetype, the RAAHP system used less energy than the alternative air-to-water heat pump system. In the case of the post-2002 flat archetype, the air-to-air heat pump system with combined hot water tank give the lowest energy consumption and annual cost of any alternative system, including a gas boiler.

Introduction

This report focusses on the suitability of reversible air-to-air heat pumps (RAAHPs) for providing heating and hot water for various domestic dwelling archetypes in the UK. RAAHPs are a particular type of air source heat pump (ASHP) that can provide space heating, space cooling, and hot water, as well as dehumidification and air filtration. The carbon intensity of the UK's electricity generation is decreasing, with a target for clean power by 2030. Therefore, electrically powered heating systems such as RAAHPs offer a net zero-compatible solution in place of existing fossil fuelled heating systems.

This report builds upon a previous literature review of RAAHPs⁴. The scope of the literature review included analysis of the current deployment, international usage, barriers to uptake, installer capacity, and potential for scaling up. The findings of the literature review indicated that RAAHPs offer unique advantages such as cooling, dehumidification, and air filtration, but face challenges like limited incentives and regulatory barriers. The review also revealed that these systems are more common in some European countries but remain niche in the UK. Furthermore, it was noted that there are vastly more qualified installers for air-to-air systems than for air-to-water; however, the literature on their costs and efficiency is limited and often contradictory.

The review emphasised the need for further studies to assess the suitability of RAAHPs for different housing archetypes. RAAHPs are different to air-to-water heat pumps and gas boiler systems as they work with air blower units in rooms to provide space heating (and cooling), rather than heating water and pumping it around a dwelling via pipes and radiators. The way in which these systems are used to provide comfort is therefore also likely to be different, and raises questions within the UK context, for example, around running costs for householders or demand placed on the electricity grid.

The additional function of providing space cooling is likely to be attractive to householders, but also increases their annual energy demand, and is likely to have energy system implications in summer. Furthermore, the installation process for a RAAHP is also considerably different to other heating systems, with units fitted to the exterior of the building connected by ducting to one or more internal blower units.

To understand some of these implications and assess suitability, the Energy Systems Catapult (the "Catapult") has carried out detailed modelling of the performance of domestic dwellings with various heating systems including RAAHPs. The research questions of the study were:

- How much energy does a RAAHP require to provide space heating and hot water?
- Using a fixed price tariff, what is the cost to run a RAAHP?
- Are there scenarios where the RAAHP struggles to meet occupancy requirements (e.g., on particularly cold days in winter)?

⁴ <https://www.gov.uk/government/publications/air-to-air-heat-pumps-literature-review>

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- If the RAAHP does not provide space heating for all rooms, or does not provide hot water, what are the running costs and energy requirements of these supplementary systems?
- Are other uses of RAAHPs (i.e., cooling in summer), materially beneficial to householders? How frequently might they be used, how much will they cost to run and what are the energy requirements for also providing cooling?
- What is the suitability of RAAHPs for a dwelling built to a Future Homes Standard (FHS)?

Method

Using the Catapult's proprietary domestic building physics-based simulation toolkit⁵, Home Energy Dynamics (HED), several scenarios were specified to assess the suitability of RAAHPs in a range of typical UK dwelling archetypes. This section covers:

- An overview of HED;
- Details of the simulation choices, and model inputs.

Home Energy Dynamics (HED)

HED is the Catapult's proprietary building physics simulation toolkit. Briefly, HED:

- considers all the aspects that typical building simulation tools do, such as details of a building's fabric and heating system, size and geometry, orientation, and location/weather data.
- differs from other building simulation tools by taking a 'first principles' approach, dynamically simulating every component and the interactions between them.
- is also able to consider detailed occupancy and heating profiles, allowing the temperatures in each room at different times of day to be set, and including incidental gains⁶ from occupants being in the buildings and using appliances, as well as solar gains.
- is built in the Modelica language and uses a Dymola user interface.
- has been used to model buildings where detailed monitoring data exists, and during analysis the difference between HED's predicted energy performance and actual energy performance was found to be 1-2%.
- was built as part of the Smart Systems and Heat (SSH) project commissioned by the Energy Technologies Institute (ETI).

The Catapult has built up a library of models of dwelling archetypes from undertaking real world surveys – these models can be used in simulations to represent proportions of the housing stock. As well as models of dwelling archetypes, the Catapult has developed a library of occupancy and heating profiles from analysing data from households in its Living Lab⁷, and a library of technologies working with manufacturers and using publicly available data.

A single simulation is a combination of facets from these libraries. For example, a pre-1919 mid-terrace house with two occupants who like their home heated 7-9am and 4-11pm and have an air source heat pump (ASHP). Simulations also require detailed weather data and use

⁵ <https://es.catapult.org.uk/tools-and-labs/our-homes-net-zero-toolkit/home-energy-dynamics/>

⁶ 'Incidental gains' is heat from people inside the dwelling, and is approximately 90W/person

⁷ <https://www.livinglab.energy/home>

either a 'test reference year' (TRY) that represents 'typical' weather data, or atypical hot weather ('design summer year' (DSY2⁸)).

To deliver this project, the Catapult added models of RAAHPs to its library of technologies. Publicly available data from original equipment manufacturers (OEMs) on the characteristics, components and processes of RAAHPs were used to inform these models. Two system types were developed for use in this project:

- A single-split system, consisting of a single external unit rated at 2.5kW, and a single internal unit;
- A multi-split system, consisting of a single external unit rated at 10.4kW, and capable of being connected to five internal units.

Dwellings can be modelled with a single split, a multi-split, or a combination of both. The multi-split can be connected to between two and five units; this includes being connected to a hot water tank. The appendices describe the systems used in each model.

The outputs available from the model are exhaustive and cover several types of detailed analyses. Analyses that are typically of interest include assessments of single days (e.g., on a cold winter day, the amount of energy used to heat the dwelling; how long it takes for the living room to reach the desired setpoint, etc.) monthly or annual analyses (e.g., how much energy is required to heat a dwelling, how much it costs).

⁸ All weather file locations are Birmingham and are either *test reference year* (TRY) or *design summer year* (DSY). 'Current' refers to averages from recent decades. DSY2 refers to a summer with a short intense hot spell.

Simulation Choices

DESNZ worked with the Catapult to select 39 combinations from the HED libraries (see Table 1). Each counterfactual model (i.e. each model with space heating not provided by an air-to-air heat pump) was specified both with and without a cooling system identical to that of the corresponding air-to-air heat pump model. This enabled a like-for-like comparison to be made between the counterfactual cases and the air-to-air cases.

Table 1: Summary of simulation choices

Dwelling built form	Age band	Size (m ²) ⁹ / Bedrooms	Occupants	Heating profile	Space heating	Hot water provision	Solar PV	Weather file ¹⁰	Cooling ¹¹
Detached (Potential Future Homes Standard ¹²)	Post-2026	81m ² / 3	Family of 4	7am-11pm	Air-to-water heat pump	Cylinder hot water tank heated by heat pump	No	TRY	No
									Yes
								DSY2	No
									Yes
							Yes	TRY	No
									Yes
								DSY2	No
									Yes
					Air-to-air heat pump	Cylinder heated by immersion heater	No	TRY	Yes
								DSY2	Yes

⁹ Size refers only to the heated space, and excludes porches, garages, and other unheated spaces.

¹⁰ All weather file locations are Birmingham and are either *test reference year* (TRY) or *design summer year* with a short intense hot spell (DSY2).

¹¹ Cooling was added to each counterfactual model (i.e., each model with space heating not provided by an air-to-air heat pump) in a post-processing step, using the results from the corresponding air-to-air model.

¹² At the start of this project the Future Homes Standard was still to be published, so this model was built within the bounds of the proposed specifications in the Government consultation from 2023. Hence it is referred to as 'potential' or 'proposed' throughout this report. Full details are in Appendix A.

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Dwelling built form	Age band	Size (m ²) ⁹ / Bedrooms	Occupants	Heating profile	Space heating	Hot water provision	Solar PV	Weather file ¹⁰	Cooling ¹¹
							Yes	TRY	Yes
								DSY2	Yes
Studio flat	post-2002	29m ² / 1	Couple	7am-11pm	Combi gas boiler	Direct from combi gas boiler	No	TRY	No
									Yes
								DSY2	No
									Yes
					Electric panel heaters	Cylinder heated by immersion heater	No	TRY	No
									Yes
								DSY2	No
									Yes
Semi-detached	1919-1944	98m ² / 3	Family of 4	7am-11pm	Air-to-air heat pump	Cylinder heated by immersion heater	No	TRY	Yes
								DSY2	Yes
						Cylinder heated by immersion heater	No	TRY	Yes
						Cylinder heated by heat pump	No	DSY2	Yes
					Combi gas boiler	Direct from combi gas boiler	No	TRY	No
									Yes
Semi-detached	1919-1944	98m ² / 3	Family of 4	7am-11pm	Air-to-water heat pump	Cylinder heated by heat pump	No	TRY	No
									Yes
Semi-detached	1919-1944	98m ² / 3	Family of 4	7am-11pm	Air-to-air heat pump	Cylinder heated by immersion heater	No	TRY	Yes
Detached		85m ² / 4	Family of 4		Combi gas boiler		No	TRY	No

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Dwelling built form	Age band	Size (m ²) ⁹ / Bedrooms	Occupants	Heating profile	Space heating	Hot water provision	Solar PV	Weather file ¹⁰	Cooling ¹¹
	1919-1944			7am-11pm		Direct from combi gas boiler			Yes
					Air-to-water heat pump	Cylinder heated by heat pump	No	TRY	No
									Yes
					Air-to-air heat pump	Cylinder heated by immersion heater	No	TRY	Yes
Mid-terrace	Pre-1919	61m ² / 2	Family of 3	7am-11pm	Combi gas boiler	Direct from combi gas boiler	No	TRY	No
									Yes
					Air-to-water heat pump	Cylinder heated by heat pump	No	TRY	No
									Yes
					Air-to-air heat pump	Cylinder heated by immersion heater	No	TRY	Yes

Further details of each of the dwelling archetypes can be found in Appendix A – Dwelling archetype details. These details include aspects such as thermal efficiency of fabric elements, power output of heating systems, and so on.

Other simulation inputs

The aforementioned choices are inputs that shape the simulations in HED. The following sections provide a description of how some of these are developed and used in the simulations. Further, there are some inputs that have not been noted to date, and these are described here.

Occupants

The number of people that live in the dwelling and which rooms they are in at different times of the day are HED inputs. The data for these is based upon expectations of usage, as no publicly available representative data is available. They are based upon relatively typical usage of rooms, such as bedrooms being occupied overnight, bathrooms being occupied first thing in the morning and last thing at night, kitchens and dining rooms being occupied at mealtimes, and living rooms being occupied during the day and evenings. Data on occupancy is included so that latent heat gains¹³ are included in heat demand calculations in HED. These data are kept consistent across each simulation per dwelling and therefore do not have a material impact when making comparisons between heating systems. Further details are in Appendix B – Appliance use details.

Heating and Hot Water Profiles

The temperatures to which occupants heat each room at different times of the day are HED inputs. These data are based on insights from the Catapult's Living Lab and publicly available data from documents such as SAP 10.2¹⁴.

In all simulations, the heating is on seven days a week during the day from 7am until 11pm. In spaces such as living and dining rooms, the setpoint is 21°C with a 1°C setback¹⁵. In other rooms such as bedrooms and bathrooms, this is 18°C with a 1°C setback. In each dwelling model with a wet radiator network (i.e. one using pumped hot water), a single thermostat is used to determine whether heat is needed or not, and this is typically placed in the living room (as above). The radiators on the heating system are 'balanced' so that rooms heat to their desired setpoints at approximately the same rate, preventing rooms being either too warm or too cold. When the thermostat is below the desired setpoint, the heating system starts and runs until the setpoint is met. The setback temperature allows the room to cool before the heating starts again. The heating season commences on 1st October and runs until 31st May; if room temperatures drop below setpoints outside of these months, the heating system does not start.

In the RAAHP scenarios, bathrooms and toilets are not heated by the RAAHP but instead by an electrically powered towel rail. RAAHP systems have been chosen not to be installed in

¹³ Latent heat gains include heat given off from human bodies and appliances.

¹⁴ BRE (2025) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*, available from <https://bregroup.com/expertise/energy/sap/sap10>

¹⁵ A 'setback' temperature is a lower boundary that internal temperatures can drop to before the heating starts again, and is used to represent thermostat hysteresis.

such spaces¹⁶. In the scenarios with a RAAHP, outputs include the energy required by these supplementary or 'secondary' heating systems to be able to quantify the total space heating demand for the whole dwelling and make comparisons with gas boiler and air-to-water heat pump scenarios.

Likewise, the cooling season runs from 1st June to 31st August. If room temperatures exceed a setpoint, cooling systems start and reduce the room temperature below a setpoint. This setpoint is taken from SAP 10.2, and is set to 24°C¹⁷, though it has a +/-1°C hysteresis, meaning cooling does not commence until temperatures reach 25°C, and stops at 23°C. This setpoint is active for 24 hours a day, seven days a week across all rooms in the house and is controlled by each individual air blower unit.

A profile of hot water demand is included in HED simulations and based upon the number of occupants. The hot water is supplied in the mornings, when the bathrooms are occupied for showering, and at mealtimes for washing up. When hot water tanks are required, a weekly pasteurisation cycle (to reduce Legionella risk¹⁸) is included for safety reasons.

Counterfactual models

Each counterfactual model (i.e., each model with space heating not provided by an air-to-air heat pump) was specified both with and without a cooling system identical to that of the corresponding air-to-air heat pump model. This enables a like-for-like comparison to be made between the counterfactual cases and the air-to-air cases.

Appliances

A schedule of appliance use is included in HED simulations. Publicly available data on appliance rating profiles are used alongside studies of appliance use to develop these schedules. Appliance use is included in HED simulations as latent heat gains reduce heat demand. As with occupancy profiles, these are kept consistent across simulations to prevent them having a material impact on simulation outputs.

Tariff data

HED can use tariff data to control the behaviour of technologies and systems in the house, however this was not within the scope of the project. As such, the most recent (1st April to 30th June 2026) Ofgem Price Cap¹⁹ tariff rates were used in the post-processing of simulations to calculate energy costs; these prices are 24.67p/kWh for electricity, and 5.74p/kWh for gas. Associated daily standing charges of 57.21p/day for electricity, and 29.09p/day for gas have

¹⁶ There are several reasons for this; OEMs do not recommend that their units are installed in bathrooms, regulations and zoning will prevent installations in many bathrooms, units may struggle and/or degrade in humid conditions that they are not designed for, and can blow humid air into neighbouring rooms.

¹⁷ CIBSE recommends a higher setpoint of 26°C, that would mean cooling demand is lower than when using the setpoint in SAP.

¹⁸ The risk of Legionnaire's disease (<https://www.hse.gov.uk/legionnaires/what-is.htm>) is reduced if hot water tanks are heated to 60°C once a week. Legionnaire's bacteria grow in water stored at 20-45°C.

¹⁹ <https://www.ofgem.gov.uk/energy-price-cap>. Rates are for households that pay by Direct Debit and include VAT at 5%.

also been used, with the assumption that archetypes that do not use natural gas for heating do not have a gas supply, and therefore do not pay the associated standing charge.

This project assumed a flat rate tariff (rather than a time-varying tariff). Different assumptions on tariff would not impact total energy demand, but could influence timing of energy demand and impact overall bills. This may affect different technologies and properties differently, as some systems may be more able to take advantage of pre-heating at off-peak times to reduce bills.

Results

Simulation outputs from HED are numerical and are either time-series values (e.g., room temperature) or cumulative values (e.g., electricity used per year). Both are used in the assessment of suitability of heating and cooling systems.

For each dwelling, a table of cumulative annual outputs is provided alongside qualitative information to describe scenario details. Each table provides several outputs, with a description of each output provided in Table 2.

Several outputs have an asterisk (*) in their description to denote that these outputs are only provided where applicable (e.g., HED only provides solar PV outputs when the dwelling has PV).

Table 2: Description of cumulative annual outputs

Type	Label	Description
Scenario identifier	Heating / Cooling source	The system that is primarily used in the dwelling to provide space heating, and space cooling* where applicable.
	Hot water provision	The system that is primarily used in the dwelling to provide hot water.
	Weather file	Weather file used in the scenario
	Cooling	Space cooling used in this scenario during the summer months (June, July, August).
Outputs that express amount of energy bought from the grid, generated, or sold to the grid	Total gas from grid (kWh)	The total number of kWh of gas imported from the grid*.
	Total electricity from grid (kWh)	The total number of kWh of electricity imported from the grid.
	Total solar PV exported to grid (kWh)	The total number of kWh of electricity generated by solar PV panels and exported to the grid*.
	Total solar PV used by household (kWh)	The total number of kWh of electricity generated by solar PV panels used by the household*.
	Total solar PV generation (kWh)	The total number of kWh of electricity generated by solar PV panels, regardless of end-use*.
	Total electricity use (kWh)	The total number of kWh of electricity used by the household, regardless of source.
Outputs that express energy demand	Total energy required for provision of space heating, space cooling, and hot water (kWh)	The total number of kWh of energy required to provide space heating, space cooling, and hot water. This is the energy that is required to go into heating / cooling sources.

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Type	Label	Description
	Total energy required by primary space heating system (kWh)	The total number of kWh of energy required by primary space heating system. This is the energy that is required to go into the heating source.
	Total energy required by secondary space heating system (kWh)	The total number of kWh of energy required by secondary space heating system*. This is the energy that is required to go into the heating source.
	Total energy required by space cooling system (kWh)	The total number of kWh of energy required by space cooling system*. This is the energy that is required to go into the cooling source.
	Total energy required for hot water provision (kWh)	The total number of kWh of energy required to provide hot water. This is the energy that is required to go into the heating source.
Outputs that express useful energy demand	Total useful demand (kWh)	The total number of kWh of useful space heating, useful space cooling, and useful heat for hot water, provided to the household. This is the total provided by the heating / cooling sources.
	Primary space heating useful heat demand (kWh)	The total number of kWh of useful space heating provided to the household by the primary heat source. This is the total provided by the heat source.
	Secondary space heating useful heat demand (kWh)	The total number of kWh of useful space heating provided to the household by the secondary heat source*. This is the total provided by the heat source.
	Useful space cooling demand (kWh)	The total number of kWh of useful space cooling provided to the household by the primary cooling source*. This is the total provided by the cooling source.
	Hot water useful heat demand (kWh)	The total number of kWh of useful heat for hot water provided to the household by the primary heat source. This is the total provided by the heat source.
Converting outputs to energy cost	Energy bill (£)	The total energy bill for the year, including gas use, electricity use, and electricity export. Daily standing charges have been included, with the assumption that archetypes that do not use natural gas for heating do not have a gas supply and therefore do not pay the daily standing charge for gas. The rates used follow the most recent (1 st April to 30 th June 2026) Ofgem price cap, and are: Electricity from grid: 24.67p/kWh, Gas from grid: 5.74p/kWh, Electricity standing charge: 57.21p/day, Gas standing charge: 29.09p/day. Electricity exported to grid: 12p/kWh

Also provided are time-series outputs from some simulations in the Discussion section. These show visual comparisons and illustrations of room temperatures for a week in particularly cold weather or a week in particularly warm weather.

Notes on simulation outputs

When making comparisons across scenarios, it is important to recognise the many inputs to HED and that these each affect the outputs. For example, the hot water demand across multiple scenarios in the same dwelling is ostensibly the same – the same number of people live in the dwelling and require the same amount of hot water – regardless of the systems that are used to provide it. However, the total energy demand and useful heat across a calendar year may vary, due to the way in which the hot water is created and stored before use, and whether a pasteurisation cycle is required. The same is true for space heating, whereby weather compensation affects flow temperatures, warm-up times and thermostat control strategies vary, and the way that heat is provided to spaces varies across scenarios. These differences cause variations in the annual figures that may give the impression of errors in simulations. All models have gone through rigorous quality assurance during setup and running, to ensure that simulation inputs are set correctly and therefore that simulations outputs are accurate.

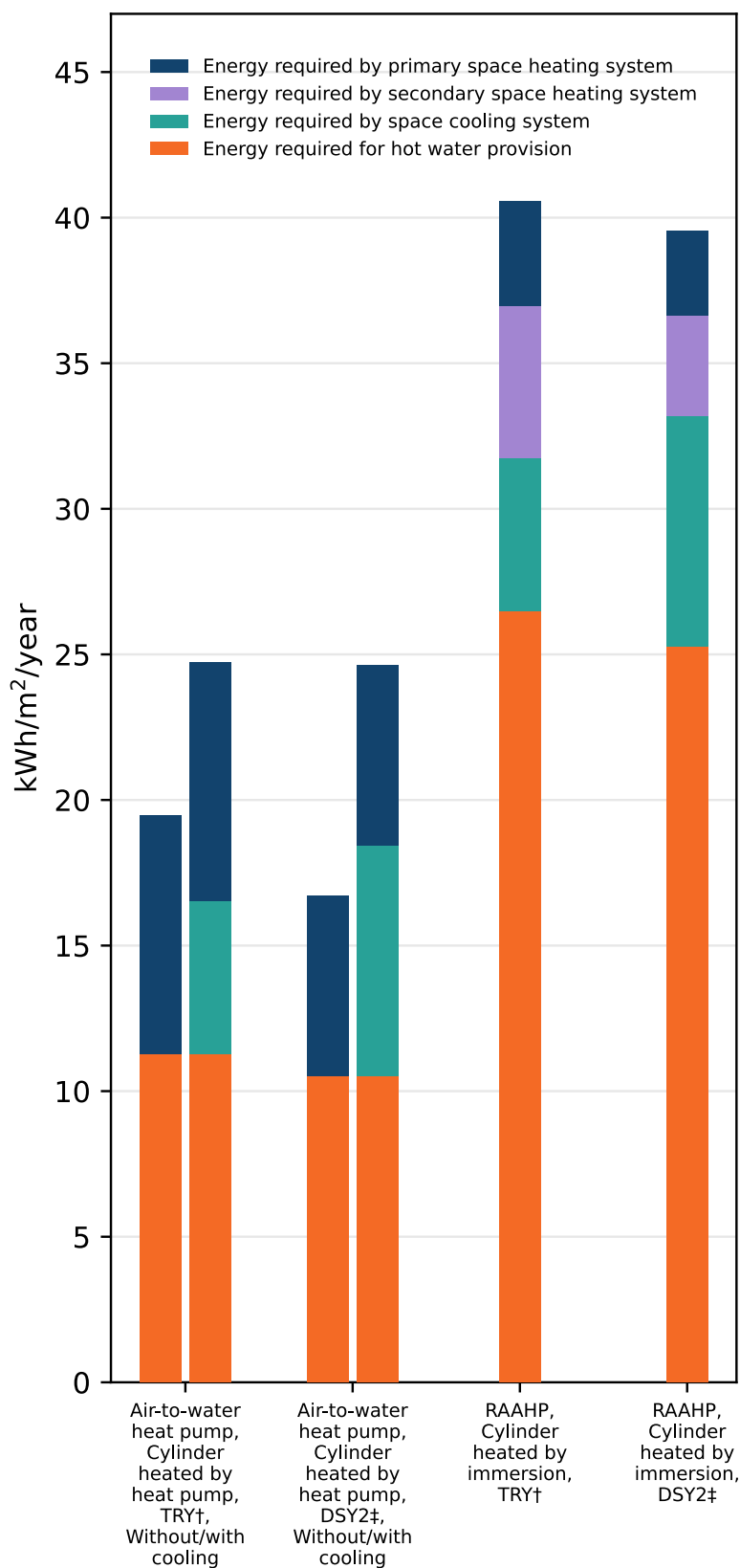
Post-2026 3-bed detached

This dwelling is built to the proposed Future Homes Standard (FHS) and has solar PV in half the scenarios. PV makes a significant impact to the annual energy bill, approximately halving it in scenarios with air-to-water heat pumps, and reducing it by ~40% in scenarios with RAAHPs. Focussing on the heating system, two facets significantly affect energy bills. Firstly, the RAAHP scenarios rely on ~100% efficient systems for secondary heating and hot water, making them expensive compared to an air-to-water heat pump scenario that does not require secondary systems and where efficiency is higher (i.e., 200-400%) and costs are lower. Secondly, the ability of air-to-air systems to provide space cooling incurs annual energy costs of ~£105 (TRY) to ~£160 (DSY2). Table 3 provides several numerical outputs from the HED simulations, some of which are used to illustrate annual demand in Figure 4.

Table 3: Post-2026 3-bed detached HED outputs

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Air-to-water heat pump	Heat pump via cylinder	TRY	No	-	5880	0	0	0	5880	1577	665	0	0	913	4221	2199	0	0	2022	1659
			Yes	-	6307	0	0	0	6307	2004	665	0	426	913	6061	2199	0	1841	2022	1765
		DSY2	No	-	5657	0	0	0	5657	1354	502	0	0	852	3646	1727	0	0	1919	1604
			Yes	-	6297	0	0	0	6297	1994	502	0	640	852	6039	1727	0	2393	1919	1762
		TRY	No	-	4554	3984	1326	5310	5880	1577	665	0	0	913	4221	2199	0	0	2022	854
			Yes	-	4729	3732	1579	5310	6307	2005	665	0	427	913	6068	2199	0	1848	2022	928
		DSY2	No	-	4367	3879	1290	5169	5657	1354	502	0	0	852	3646	1727	0	0	1919	821
			Yes	-	4661	3532	1636	5169	6298	1995	501	0	641	852	6045	1727	0	2399	1919	935
Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	-	7588	0	0	0	7588	3286	293	422	426	2145	5697	1411	422	1841	2023	2081
		DSY2	Yes	-	7506	0	0	0	7506	3204	236	280	640	2048	5725	1132	280	2393	1920	2061
		TRY	Yes	-	5939	3680	1644	5325	7583	3281	293	422	427	2140	5700	1413	422	1842	2023	1232
		DSY2	Yes	-	5828	3510	1671	5181	7499	3197	236	280	640	2041	5726	1134	280	2394	1920	1225

Figure 4: Post-2026 detached dwelling (built to proposed Future Homes Standard) annual energy demand by end use per m² of floor area



†TRY: 'Test reference year' weather file. (Typical weather year.)
 ‡DSY2: 'Design summer year 2' weather file. (Year containing intense heat events.)

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK Post-2002 studio flat

This dwelling is quite different to the others. Firstly, the heating system consists of just two spaces and has a small heat loss envelope, and secondly, the studio flat has scenarios where hot water is provided by the RAAHP. Compared to the counterfactual cases with cooling included, the scenario with the RAAHP providing hot water is approximately 5% cheaper than the gas boiler scenario over the course of the year, and 20% cheaper than other scenarios. Table 4 provides several numerical outputs from the HED simulations, some of which are used to illustrate annual demand in Figure 5.

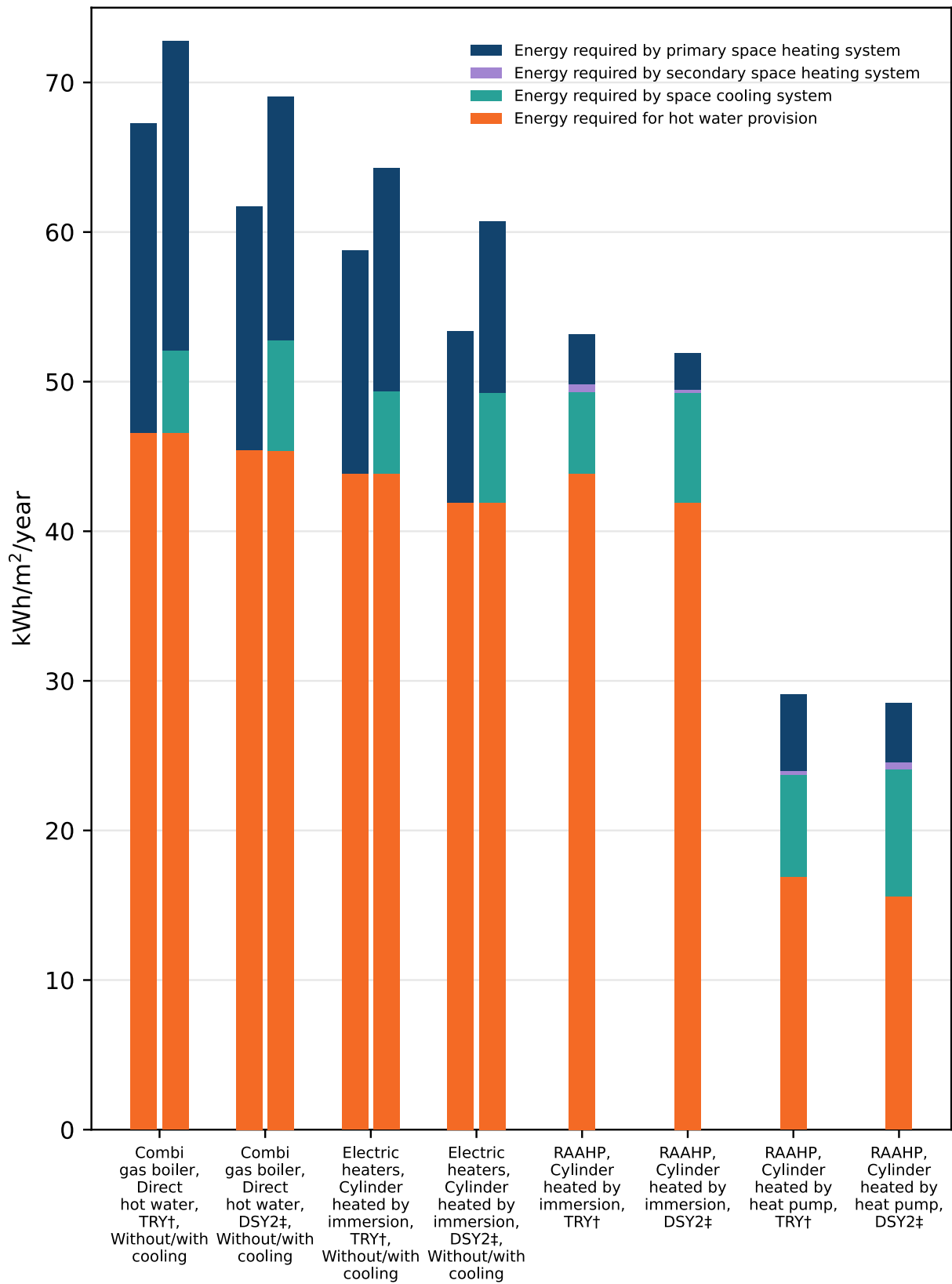
Table 4: Post-2002 studio flat HED outputs

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Combi gas boiler	Direct	TRY	No	1887	2495	-	-	-	2495	1951	600	-	-	1351	1728	647	-	-	1081	1039
			Yes	1887	2654	-	-	-	2654	2110	600	-	159	1351	2463	647	-	735	1081	1078
		DSY2	No	1728	2493	-	-	-	2493	1790	473	-	-	1317	1586	550	-	-	1036	1029
			Yes	1728	2706	-	-	-	2706	2003	473	-	213	1317	2577	550	-	992	1036	1082
Electric heater	Cylinder w/immersion	TRY	No	-	4136	-	-	-	4136	1705	433	-	-	1273	1659	433	-	-	1226	1229
			Yes	-	4295	-	-	-	4295	1864	433	-	159	1273	2394	433	-	735	1226	1268
		DSY2	No	-	3978	-	-	-	3978	1548	333	-	-	1215	1496	333	-	-	1164	1190
			Yes	-	4191	-	-	-	4191	1761	333	-	213	1215	2488	333	-	992	1164	1243

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	-	3972	-	-	-	3972	1542	97	14	159	1272	2322	347	14	735	1226	1189
		DSY2	Yes	-	3936	-	-	-	3936	1506	70	7	213	1216	2418	255	7	992	1164	1180
	Heat pump via cylinder	TRY	Yes	-	3274	-	-	-	3274	843	148	8	197	491	2410	356	8	818	1229	1016
		DSY2	Yes	-	3258	-	-	-	3258	828	115	14	248	452	2505	278	14	1047	1166	1013

Figure 5: Post-2002 studio flat annual energy demand by end use per m² of floor area



†TRY: 'Test reference year' weather file. (Typical weather year.)
‡DSY2: 'Design summer year 2' weather file. (Year containing intense heat events.)

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK 1919-1944 3-bed semi-detached

This dwelling is simulated almost ‘as built’; without cavity wall insulation, uninsulated solid floors, little loft insulation, and upgrades made to doors and windows that were installed decades ago. Gas use in the ‘base case’ is high, and the base case scenario is approximately 3% cheaper than the air-to-water heat pump scenario across the course of the year. Comparing against the counterfactual cases with cooling included, the air-to-air heat pump scenario is ~25% more expensive than the gas boiler and air-to-water heat pump scenarios, again due to a lower rate of efficiency for secondary space heating and hot water provision. Table 5 provides several numerical outputs from the HED simulations, some of which are used to illustrate annual demand in Figure 6.

Table 5: 1919-1944 3-bed semi-detached HED outputs

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Combi gas boiler	Direct	TRY	No	14796	4472	-	-	-	4472	14965	12609	-	-	2356	13814	11841	-	-	1973	2267
		TRY	Yes	14796	4526	-	-	-	4526	15019	12609	-	54	2356	14082	11841	-	268	1973	2281
Air-to-water heat pump	Heat pump via cylinder	TRY	No	-	8602	-	-	-	8602	4300	3336	-	-	964	11991	9989	-	-	2002	2331
		TRY	Yes	-	8656	-	-	-	8656	4354	3336	-	54	964	12259	9989	-	268	2002	2344
Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	-	10809	-	-	-	10809	6507	1312	2976	54	2166	12334	7084	2976	268	2007	2875

1919-1944 4-bed detached

This dwelling has had ‘basic retrofit’ measures, such as cavity wall insulation and loft insulation, but has uninsulated solid and suspended floors, and doors and windows that were installed decades ago. Comparing the cases with cooling included, the gas boiler base case is approximately 10% cheaper than the air-to-air heat pump scenario, with the air-to-water heat pump scenario being approximately 5% cheaper than the air-to-air scenario. Table 6 provides several numerical outputs from the HED simulations, some of which are used to illustrate annual demand in Figure 6.

Table 6: 1919-1944 4-bed detached HED outputs

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Combi gas boiler	Direct	TRY	No	12890	4431	-	-	-	4431	13019	9788	-	-	3231	10802	8788	-	-	2014	2148
		TRY	Yes	12890	4530	-	-	-	4530	13118	9788	-	99	3231	11262	8788	-	459	2014	2172
Air-to-water	Heat pump via cylinder	TRY	No	-	8372	-	-	-	8372	4070	3070	-	-	1001	10855	8865	-	-	1990	2274

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
heat pump		TRY	Yes	-	8472	-	-	-	8472	4170	3070	-	99	1001	11315	8865	-	459	1990	2299
Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	-	9000	-	-	-	9000	4697	1226	1260	99	2112	10050	6326	1260	459	2004	2429

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK Pre-1919 2-bed mid-terrace

Like other scenarios, this dwelling is simulated almost ‘as built’, with uninsulated solid walls, little loft insulation, uninsulated solid and suspended floors, and upgrades made to doors and windows that were installed decades ago. Comparing the cases with cooling included, the gas boiler base case is comparable (less than 5% variation) in cost to the heat pump scenarios. The RAAHP scenario has, proportionately, a small demand for secondary heating, which coupled with the more efficient primary space heating, make it comparable in terms of annual energy bill to the air-to-water heat pump scenario. Table 7 provides several numerical outputs from the HED simulations, some of which are used to illustrate annual demand in Figure 6. Note that Figure 6 shows the electrical energy consumed for cooling to be particularly low for each of the three archetypes. This stands in contrast to the higher cooling energy consumption for the Future Homes Standard dwelling of Figure 4 and the flat of Figure 5, but is consistent with the three archetypes of Figure 6 being associated with higher rates of heat loss and the RAAHP simulations not including passive cooling measures.

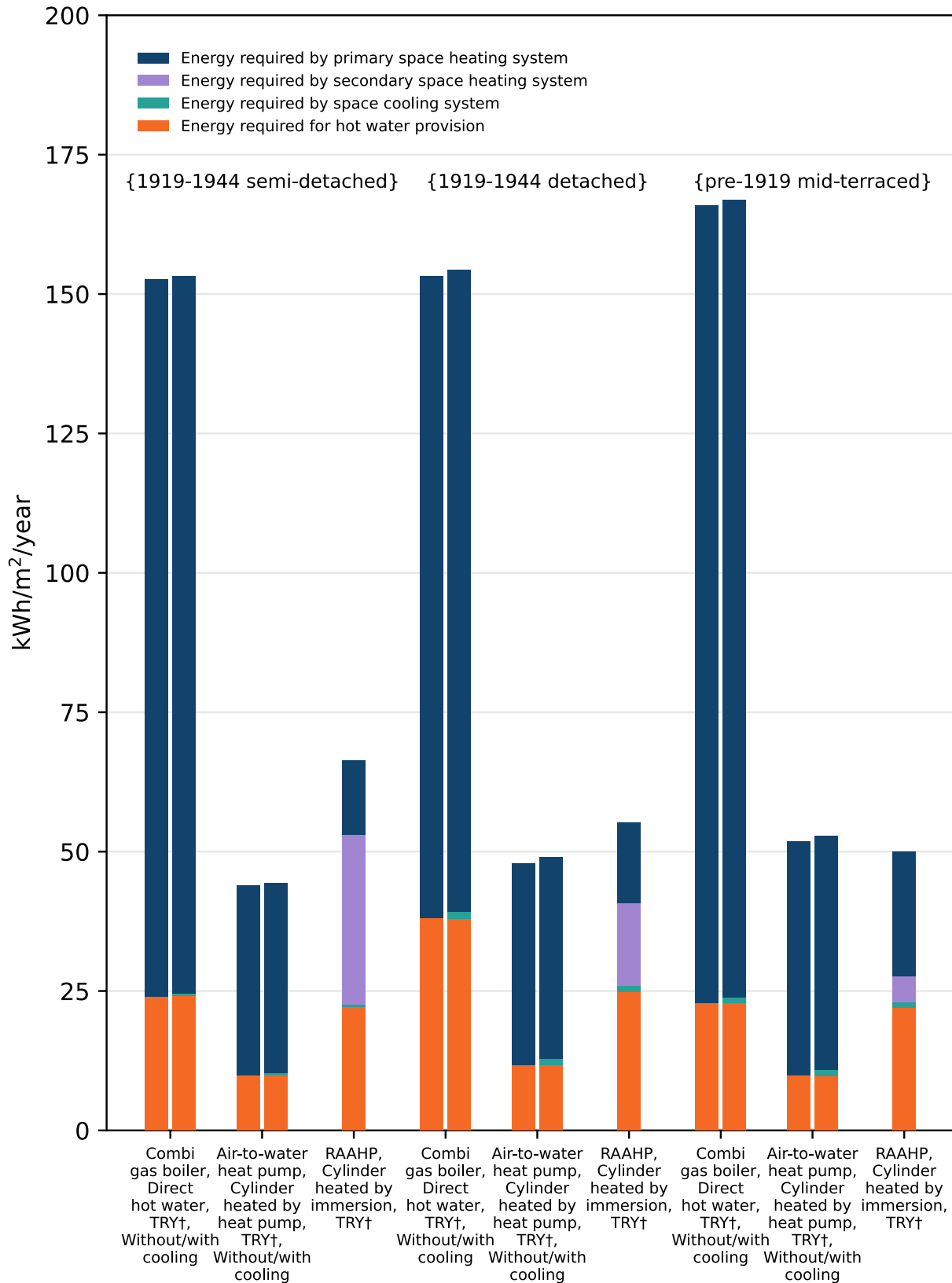
Table 7: Pre-1919 2-bed mid-terrace HED outputs

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Combi gas boiler	Direct	TRY	No	9925	2639	-	-	-	2639	10117	8723	-	-	1394	8759	7623	-	-	1136	1536
		TRY	Yes	9925	2702	-	-	-	2702	10179	8723	-	63	1394	8979	7623	-	220	1136	1551

Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK

Heat source	Hot water provision	Weather file	Cooling	Total gas from grid	Total electricity from grid (kWh)	Total solar PV exported to grid (kWh)	Total solar PV used by household (kWh)	Total solar PV generation (kWh)	Total electricity use (kWh)	Total energy required for provision of space heating, space cooling, and hot water (kWh)	Total energy required by primary space heating system (kWh)	Total energy required by secondary space heating system (kWh)	Total energy required by space cooling system (kWh)	Total energy required for hot water provision (kWh)	Total useful demand (kWh)	Primary space heating useful heat demand (kWh)	Secondary space heating useful heat demand (kWh)	Useful space cooling demand (kWh)	Hot water useful heat demand (kWh)	Energy bill (£)
Air-to-water heat pump	Heat pump via cylinder	TRY	No	-	5606	-	-	-	5606	3159	2560	-	-	599	9142	7918	-	-	1224	1592
		TRY	Yes	-	5669	-	-	-	5669	3222	2560	-	63	599	9362	7918	-	220	1224	1607
Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	-	5499	-	-	-	5499	3053	1360	287	63	1343	8116	6385	287	220	1224	1566

Figure 6: Annual energy demand by end use per m² of floor area for three dwelling archetypes



†TRY: 'Test reference year' weather file. (Typical weather year.)

Discussion

A discussion of the results follows, structured per the project's six research questions.

How much energy does a RAAHP require to provide space heating and hot water?

The Results section provides detailed energy requirements of the RAAHP systems when providing heating and hot water, and how this varies per dwelling archetype, and when the system is coupled with provision of hot water.

In summary across the dwelling archetypes, the energy requirements for space heating with a RAAHP are lower than when compared to an air-to-water heat pump scenario, and significantly lower than when compared to a gas boiler scenario. However, the RAAHP only provides space heating to part of the dwellings, excluding bathrooms, and so a fairer comparison is the total space heating requirement including secondary heating systems.

When the total space heating requirement is considered, the air-to-water heat pump scenarios sometimes use a lower amount of energy than the RAAHP scenarios, the net result being a function of the relative efficiencies of RAAHPs and air-to-water heat pumps and the proportion of (less efficient) secondary heating used in a given RAAHP scenario. In all cases, the RAAHP scenarios consume significantly less energy than the gas boiler scenarios.

For hot water provision, comparisons between heating systems are again complex, with gas boilers providing hot water directly to end users, air-to-water heat pumps heating a tank, and RAAHPs either heating a tank, or relying on an immersion heater to heat a tank. For the studio flat, the RAAHP provides hot water (via a tank), and consequently it requires the least amount of energy when compared to other scenarios for that dwelling type. For other dwelling scenarios using a RAAHP, hot water is provided by an immersion heated tank and therefore use more energy when compared to air-to-water heat pump-powered hot water provision.

Using a fixed price tariff, what is the cost to run a RAAHP?

The Results section provides a detailed account of energy costs, how they vary per dwelling archetype, and comparison with other systems such as gas boilers and air-to-water heat pumps. The most recent Ofgem Price Cap tariff unit rates and standing charges were used.

In summary, across the dwelling archetypes, the total annual energy cost for an archetype fitted with a RAAHP system that uses an immersion heater for hot water is higher when compared to the same dwelling using the most economical alternative system (varying from ~£15/yr to £600/yr more). This can be explained by the differential between electricity and gas

costs²⁰, and RAAHP systems relying on supplementary systems that are less efficient (i.e., electric radiators in bathrooms, immersion heaters for hot water).

If gas boilers are excluded from the comparison, leaving electrically powered systems only, a different picture emerges. The total annual energy cost for an archetype fitted with a RAAHP that uses an immersion heater for hot water is greater in three of the archetype dwellings (by between £130 and £530) but smaller (by around £40 and £80 respectively) in the two smaller archetypes, the flat and the terraced house. This stems from the flat and the terraced house using a smaller proportion of less efficient secondary heating than the other three archetypes.

For the flat fitted with a RAAHP connected to a small hot water tank (which is more efficient than using an immersion heater for hot water) the annual energy cost is smaller at around £60 less than the most economical alternative (the gas boiler case). Relative to the case with a RAAHP and an immersion heated hot water tank and the case with electric panel heaters and an immersion heated hot water tank, the RAAHP with connected hot water tank costs ~ £170 and ~ £250 less per year, respectively.

This project assumed a flat rate tariff (rather than a time-varying tariff). Different assumptions on tariff would not impact total energy demand, but could influence timing of energy demand and impact overall bills. This may affect different technologies and properties differently, as some systems may be more able to take advantage of pre-heating at off-peak times to reduce bills.

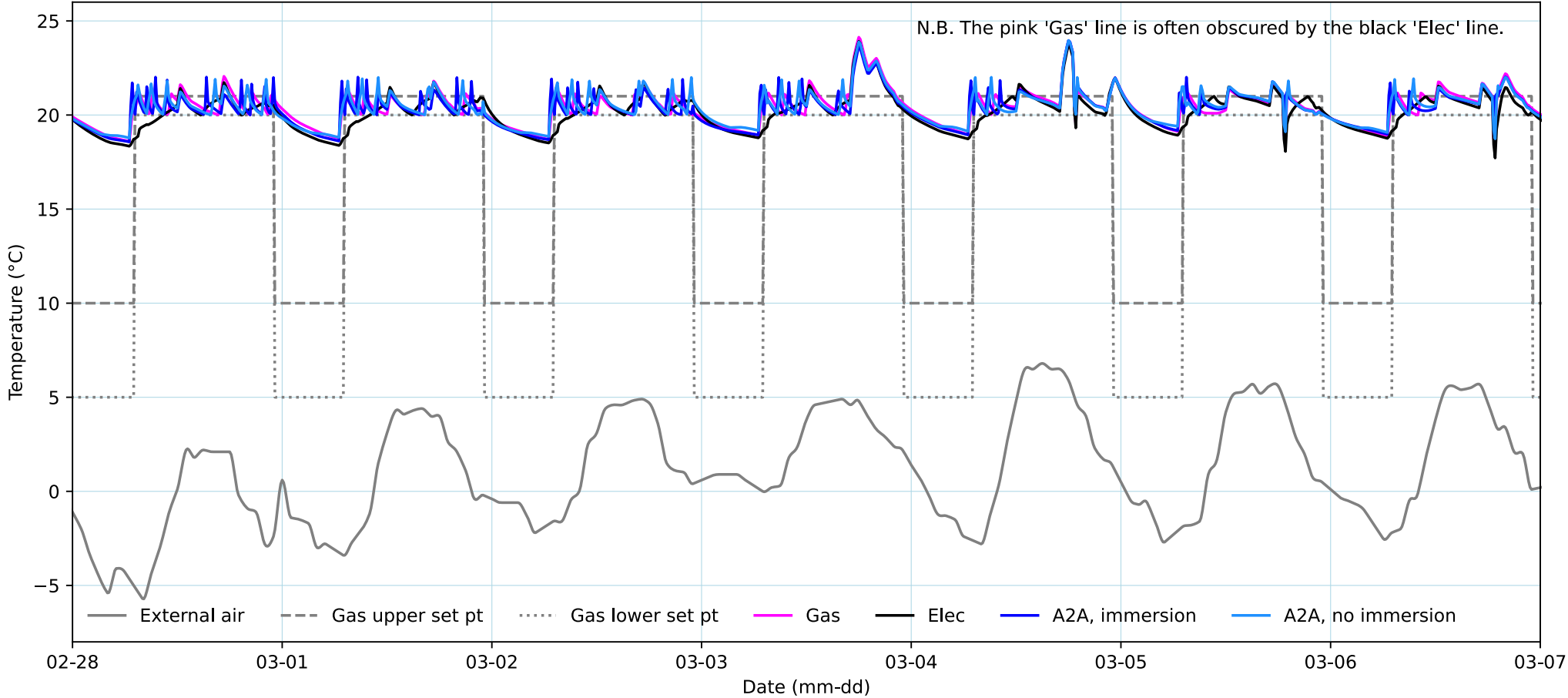
Are there scenarios where the RAAHP struggles to meet occupancy requirements (i.e., on particularly cold days in winter)?

The following plots show the temperatures in the living room for two of the five dwellings during a cold week in winter (a plot for the FHS dwelling is included against a later research question).

For the studio flat, Figure 7 shows each of the heating systems (gas boiler, electric heaters, RAAHP) heating the living space to meet the setpoints. The gas boiler and RAAHP perform very similarly, whereas the electric heaters take longer to meet desired temperatures.

²⁰ The electricity costs used in the analysis are nearly four and a half times the gas costs; this differential is known as the 'spark gap' and is due to marginal wholesale prices, taxes and levies placed on electricity costs that are significantly higher than those placed on gas costs.

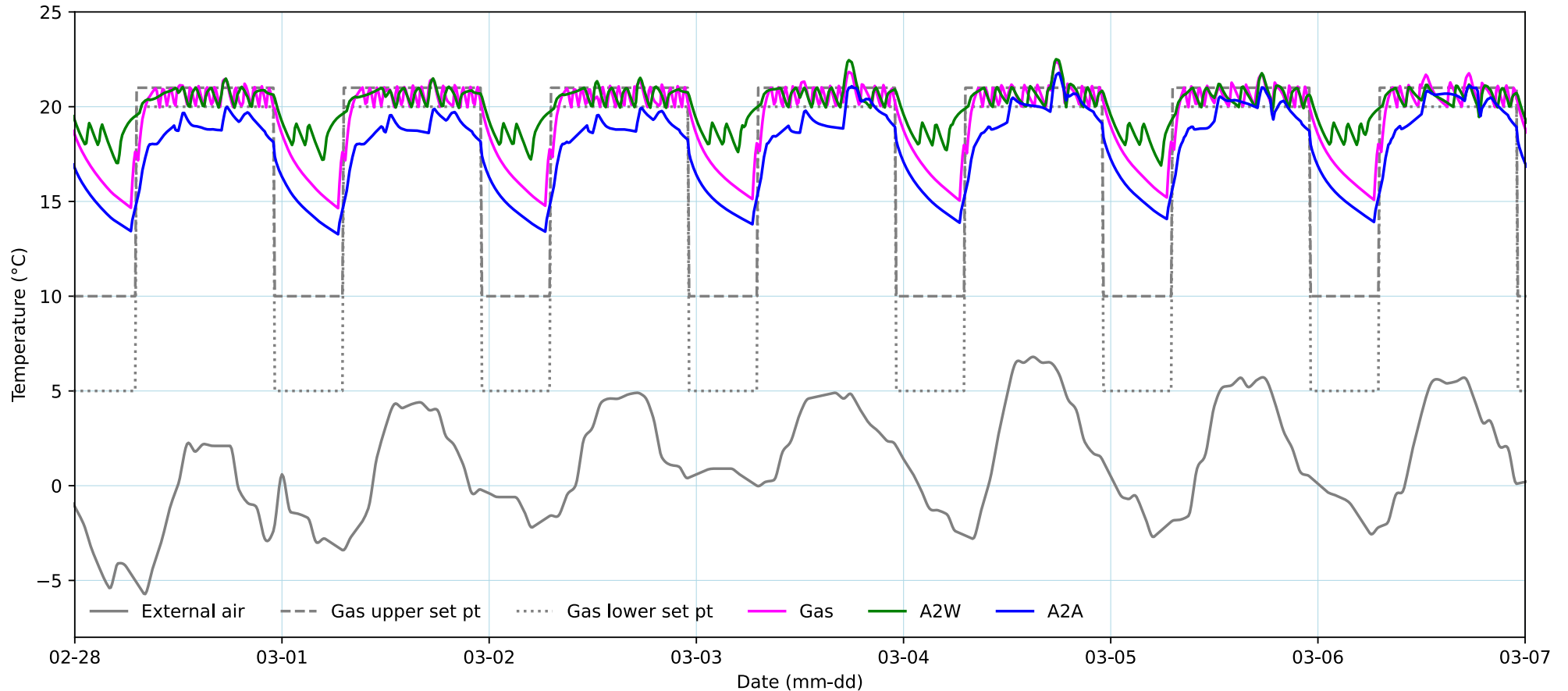
Figure 7: The studio flat dwelling during a cold week in winter (TRY)



Understanding the suitability of reversible air-to-air heat pumps for domestic use in the UK

Figure 8 shows the 1919-1944 4-bed detached dwelling during a cold week in winter. In the plot, the room temperatures with the RAAHP are often below the setpoint, and far more frequently than for the same dwelling heated by the gas boiler or air-to-water heat pump. This suggests that the RAAHP is struggling to meet occupancy requirements on particularly cold days²¹.

Figure 8: The 1919-1944 4-bed detached dwelling during a cold week in winter (TRY)



²¹ The 1919-1944 4-bed detached dwelling was the only archetype where the RAAHP system was not always able to heat the living room to within the target temperature range during the coldest week.

If the RAAHP does not provide space heating for all rooms, or does not provide hot water, what are the running costs and energy requirements of these supplementary systems?

For all the scenarios with a RAAHP, supplementary systems were required. This is due to RAAHP units not being installed in bathrooms and toilets¹⁶, and in some scenarios, the RAAHP not providing hot water.

The running costs for the supplementary systems are high when compared to a scenario with an air-to-water heat pump system that does not require them. Electric radiators and immersion heaters are, at best, 100% efficient, significantly less than air-to-water heat pump systems that have efficiencies of ~200-400%.

To help understand and compare the energy requirements and running costs, Table 8 provides a summary of specific outputs across all scenarios. The supplementary heating energy requirements and costs cover both secondary heating systems and hot water provision, and in all instances, these outweigh the energy requirements and costs of the RAAHP systems. The only exception is the studio flat, where the RAAHP provides hot water as well as space heating. Although there is secondary heating in the bathroom of the studio flat, it is seldom required due to the heat from the open plan studio room generally being sufficient to heat the bathroom.

Table 8: Energy requirements and costs for supplementary systems

Dwelling Archetype	Heat source	Hot water provision	Weather file	Cooling	Total energy required for space heating, space cooling, and HW (kWh)	Energy bill (£)	RAAHP energy requirements for heating (kWh)	Supplementary energy requirements (kWh)	RAAHP energy costs for heating (£)	Supplementary energy costs (£)	Total space heating, cooling and hot water costs (£)
Potential Future Homes Standard	Air-to-water heat pump	Heat pump via cylinder	TRY	No	1577	1659	-	-	-	-	389
				Yes	2004	1765	-	-	-	-	494
			DSY2	No	1354	1604	-	-	-	-	334
				Yes	1994	1762	-	-	-	-	492
			TRY	No	1577	854	-	-	-	-	389
				Yes	2005	928	-	-	-	-	495
			DSY2	No	1354	821	-	-	-	-	334
				Yes	1995	935	-	-	-	-	492
	Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	3286	2081	293	2567	72	633	811
			DSY2	Yes	3204	2061	236	2328	58	574	790
			TRY	Yes	3286	1234	293	2567	72	633	811
			DSY2	Yes	3204	1227	236	2327	58	574	790
Post-2002 studio flat	Combi gas boiler	Direct	TRY	No	1951	1039	-	-	-	-	230
				Yes	2110	1078	-	-	-	-	270
			DSY2	No	1790	1029	-	-	-	-	221
				Yes	2003	1082	-	-	-	-	273
	Electric heaters	Cylinder w/immersion	TRY	No	1705	1229	-	-	-	-	421
				Yes	1864	1268	-	-	-	-	460
			DSY2	No	1548	1190	-	-	-	-	382
				Yes	1761	1243	-	-	-	-	434
	Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	1542	1189	97	1286	24	317	380
			DSY2	Yes	1506	1180	70	1222	17	302	371
		Heat pump via cylinder	TRY	Yes	843	1016	639	8	158	2	208
			DSY2	Yes	828	1013	567	14	140	3	204
1919-1944 3-bed semi-detached	Combi gas boiler	Direct	TRY	No	14965	2267	-	-	-	-	997
				Yes	15019	2281	-	-	-	-	1011
	Air-to-water heat pump	Heat pump via cylinder	TRY	No	4300	2331	-	-	-	-	1061
				Yes	4354	2344	-	-	-	-	1074
	Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	6507	2875	1312	5141	324	1268	1605
				Yes	6507	2875	1312	5141	324	1268	1605
1919-1944 4-bed detached	Combi gas boiler	Direct	TRY	No	13019	2148	-	-	-	-	878
				Yes	13118	2172	-	-	-	-	902

Dwelling Archetype	Heat source	Hot water provision	Weather file	Cooling	Total energy required for space heating, space cooling, and HW (kWh)	Energy bill (£)	RAAHP energy requirements for heating (kWh)	Supplementary energy requirements (kWh)	RAAHP energy costs for heating (£)	Supplementary energy costs (£)	Total space heating, cooling and hot water costs (£)
bed detached	Air-to-water heat pump	Heat pump via cylinder	TRY	No	4070	2274	-	-	-	-	1004
				Yes	4170	2299	-	-	-	-	1029
	Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	4697	2429	1226	3372	302	832	1159
Pre-1919 2-bed mid-terrace	Combi gas boiler	Direct	TRY	No	10117	1536	-	-	-	-	723
				Yes	10179	1551	-	-	-	-	739
	Air-to-water heat pump	Heat pump via cylinder	TRY	No	3159	1592	-	-	-	-	779
				Yes	3222	1607	-	-	-	-	795
	Air-to-air heat pump	Cylinder w/immersion	TRY	Yes	3053	1566	1360	1629	336	402	753

Are other uses of RAAHP (i.e., cooling in summer) materially beneficial to householders? How frequently might they be used, how much will they cost to run and what are the energy requirements for also providing cooling?

In all scenarios that have a RAAHP, including counterfactuals using the RAAHP for cooling only, the cooling season is set to run from 1st June to 31st August, and if the room temperature exceeds the setpoint of 24°C at any point 24 hours a day, the RAAHP provides cooling.

The extent of the use of cooling varied across the dwelling archetypes. Table 9 summarises the cooling energy requirements and costs across scenarios with a RAAHP. In some instances, the cooling demand on the grid is minimal (<1kWh/day), but in other scenarios – particularly the newer, better insulated dwellings and DSY2 weather file scenarios – the useful cooling demand is much more significant, at close to ~25kWh/day and costing more than £10/week. However, the RAAHP simulations do not currently include householders using passive cooling measures, such as closing blinds or installing shutters, that could reduce this. Further, in the case of the Future Homes Standard dwelling, the simulation does not account for compliance with Part O of the Building Regulations, which came into force in 2022 and requires that new dwellings are built to mitigate the risk of overheating – including prioritising consideration of passive measures, alongside active cooling such as RAAHPs. The priority in the first phase of this project has been to model the performance of RAAHPs across different conditions and archetypes, and compared to other heating systems, rather than archetype performance more broadly. Hence, the comparison here is between the uncooled FHS archetype and cooling using the RAAHP, without considering passive measures as an intermediate step. This was done to enable the cooling performance of the RAAHP system to

be assessed in an extreme case. However, further work will follow that will include modelling of passive measures.

For existing homes, in practice it has been found²² that better insulated homes do not overheat more, with passive cooling likely playing an important role.

Table 9: Simulation outputs across all scenarios with cooling provided by RAAHP

Dwelling Archetype	Heat source	Hot water provision	Weather file	Total energy required by space cooling system (kWh)	Useful space cooling demand (kWh)	Cooling costs (£)
Potential Future Homes Standard	Air-to-air heat pump	Cylinder w/immersion	TRY	426	1841	105
			DSY2	640	2393	158
			TRY	427	1842	105
			DSY2	640	2394	158
Post-2002 studio flat	Air-to-air heat pump	Cylinder w/immersion	TRY	159	735	39
			DSY2	213	992	53
		Heat pump via cylinder	TRY	197	818	48
			DSY2	248	1047	61
1919-1944 3-bed semi-detached	Air-to-air heat pump	Cylinder w/immersion	TRY	54	268	13
1919-1944 4-bed detached	Air-to-air heat pump	Cylinder w/immersion	TRY	99	459	24
Pre-1919 2-bed mid-terrace	Air-to-air heat pump	Cylinder w/immersion	TRY	63	220	16

To further understand the benefits that cooling provides, the proportion of time that the living room in each dwelling exceeds 25°C²³ during the summer and the associated maximum temperatures are shown in Table 10. Simulation outputs in HED are every 600 seconds; to calculate the proportion of time that the living room exceeds 25°C, the total number of temperature datapoints during the cooling season (June, July and August) is compared with a count of how many are above 25°C. With the RAAHPs acting to provide cooling during the summer months, the living room temperature in each archetype is above 25°C for 1% or less of the time in the case of the flat and the older house archetypes. In the case of the dwelling built to the proposed Future Homes Standard, the proportion of time above the 25°C threshold is larger, suggesting that the RAAHP system may be undersized for this archetype. It should also be noted that the RAAHP simulations do not include passive cooling measures to mitigate

²² See <https://www.gov.uk/government/publications/energy-follow-up-survey-efus-overheating-in-homes>

²³ A threshold temperature of 25°C is used as this is the upper set point temperature of the air-to-air units modelled in this study. This temperature of 25°C also corresponds to the upper temperature limit presented in CIBSE Guide A, Table 1.5 for living rooms in air-conditioned dwellings.

higher temperatures, such as shutters or blinds, or (in the case of the Future Homes Standard dwelling), follow the real-world Part O process – as explained [above](#).

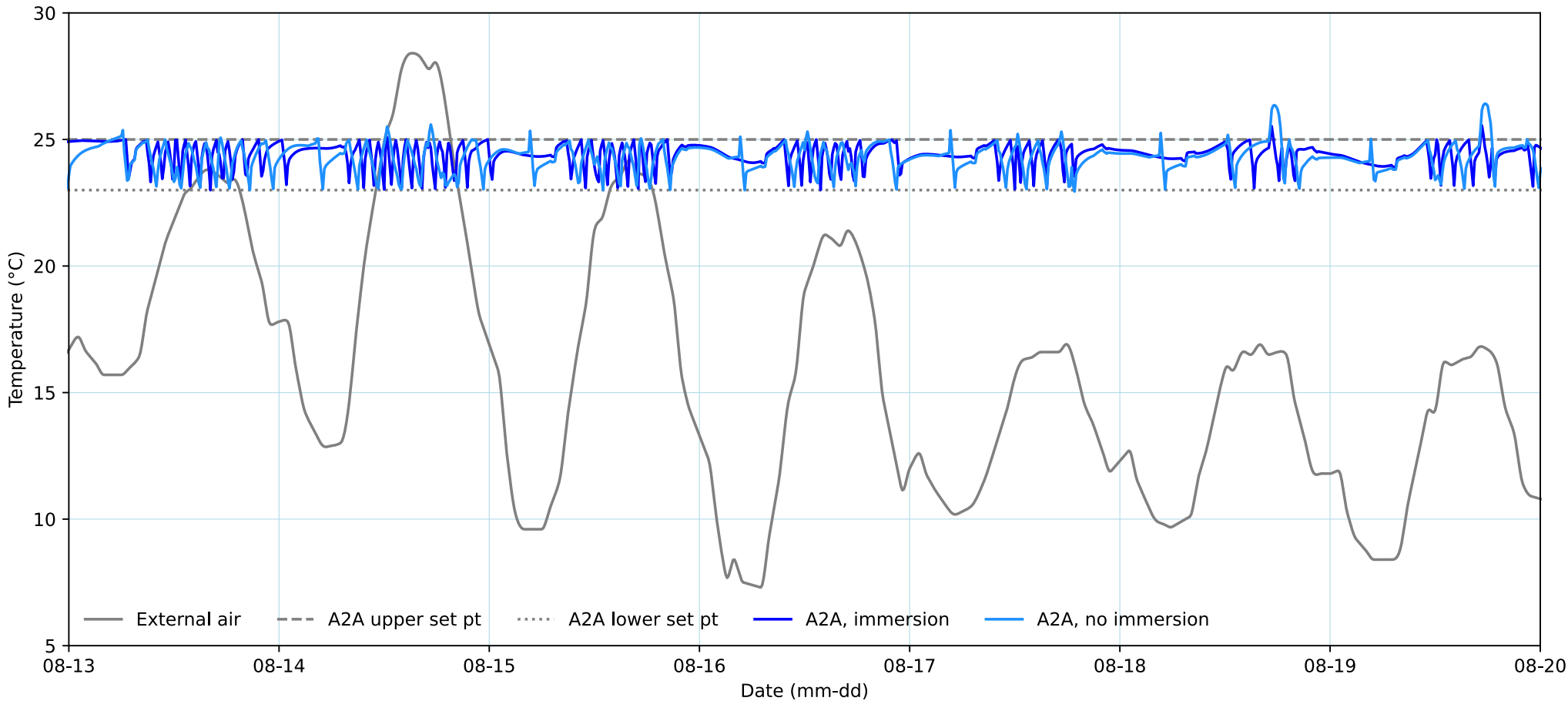
Table 10: Summer cooling performance of air-to-air heat pumps

Dwelling Details	Weather file	Proportion of time Living Room is above 25°C	Maximum Living Room Temperature
Detached (Potential Future Homes Standard) post-2026	TRY	8%	26.8
	DSY	15%	33.4
Studio flat post-2002	TRY	1%	25.8
	DSY	1%	26.1
Semi-detached 1919-1944	TRY	0%	25
Detached 1919-1944	TRY	1%	26.1
Mid-terrace pre-1919	TRY	0%	25.7

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Figure 9 shows the temperatures during a warm week in summer for the studio flat. In both cases, the cooling provided by the RAAHPs keeps the room temperature below 25°C for the majority of the time, including on the second day when the external air temperature exceeds 28°C.

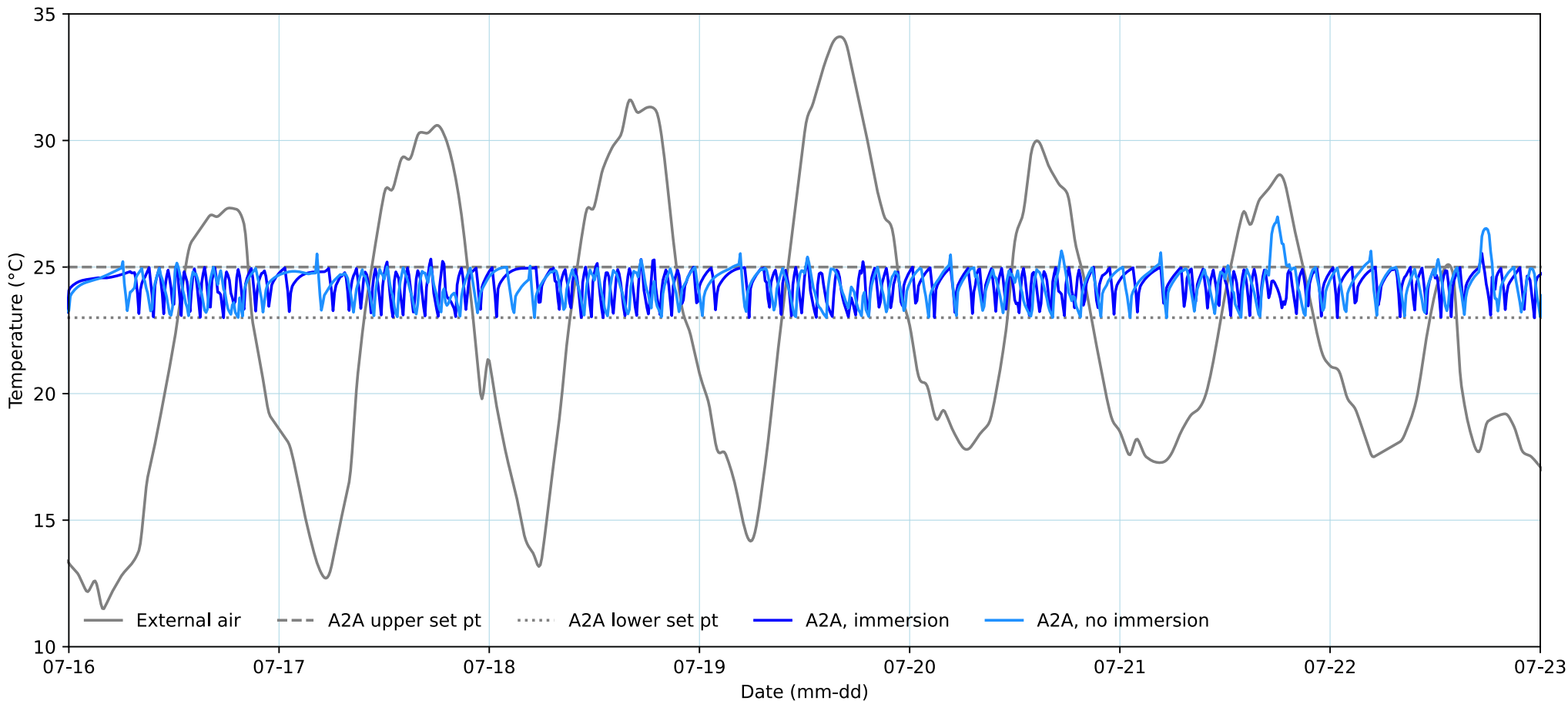
Figure 9: The studio flat dwelling during a warm week in summer (TRY)



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Figure 10 shows the temperatures during a warm week in summer for the studio flat with the DSY2 weather file. In both cases, the cooling provided by the RAAHP keeps the room temperature below 25°C for the majority of the time, including on the fourth day when the external air temperature peaks at around 34°C.

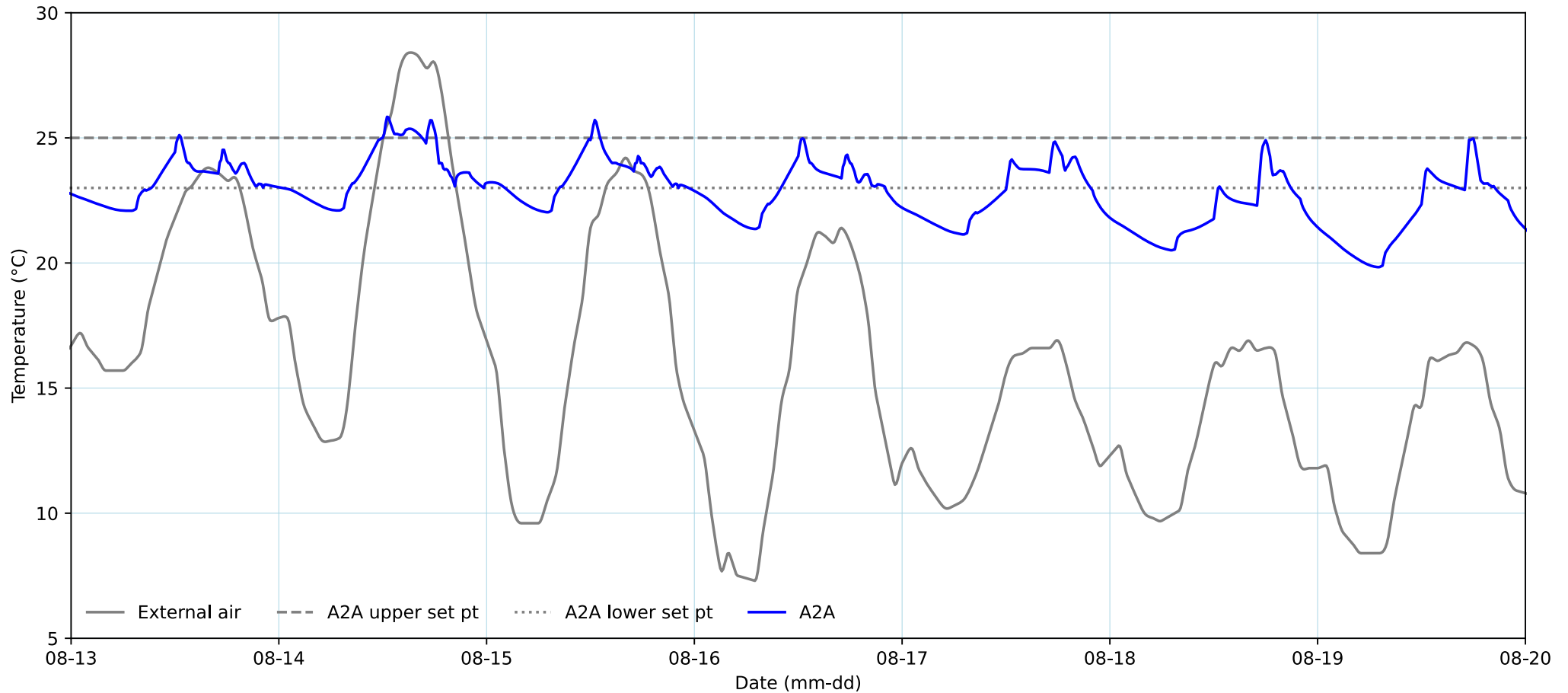
Figure 10: The studio flat dwelling during a warm week in summer (DSY2)



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Figure 11 shows the 1919-1944 4-bed detached dwelling during a warm week in summer. On two of the days, the dwelling exceeds 25°C despite the presence of the RAAHP system. However, the maximum temperature reached is only one degree higher than the 25°C threshold, and below the maximum outdoor temperature of around 28°C.

Figure 11: The 1919-1944 4-bed detached dwelling during a warm week in summer (TRY)



In warm weather, the RAAHP is used daily and provides a material benefit to householders.

Understanding the suitability of RAAHPs for a dwelling built to a Future Homes Standard (FHS)

The Future Homes Standard, as proposed at the consultation stage, sets increased targets for the efficiency of the fabric of dwellings and therefore is likely to use less energy for heating when compared to an existing dwelling. However, per the previous research question, it may have a higher energy requirement due to the desire for and availability of cooling. A RAAHP may therefore offer a suitable solution for a FHS dwelling.

Looking solely at operational cost, the RAAHP scenarios are consistently more expensive than the air-to-water heat pump scenarios with cooling included. There are two factors contributing towards the additional costs. Firstly, in the absence of a large enough integrated hot water tank, the FHS dwelling with a RAAHP has an immersion heated hot water tank, which increases costs owing to the difference in efficiencies. Secondly, the RAAHP does not provide space heating to all rooms, and so supplementary heating systems that are less efficient are required.

The following plots show weeks during the year when the weather is particularly cold or hot. Each plot shows the temperature setpoints that the householders want to be comfortable, and the actual temperatures provided by the systems in the house.

Figure 12 shows temperatures in the living room during a cold week in winter. The air-to-water heat pump generally takes longer to heat the dwelling, and starts an hour before the setpoint, whereas the RAAHP starts when the setpoint does and reaches the setpoint at approximately the same time, despite being cooler overnight due to having a lower setback temperature. Figure 13 shows the living room temperature with cooling being provided by the RAAHP system during a warm summer week. The temperature never exceeds 27°C, and on three days of the week the RAAHP keeps the temperature below 25°C.

Figure 14 shows the same, but with a DSY2 weather file. On six of the seven days, the temperature exceeds the 25°C setpoint, suggesting that the RAAHP system may be undersized for this archetype.

In practice, real homes built to the FHS specification would also comply with Part O of the Building Regulations, including consideration of passive measures. That has not been the case with these simulations, although further work will incorporate this - as explained [above](#).

Figure 12: The FHS dwelling during a cold week in winter (TRY)

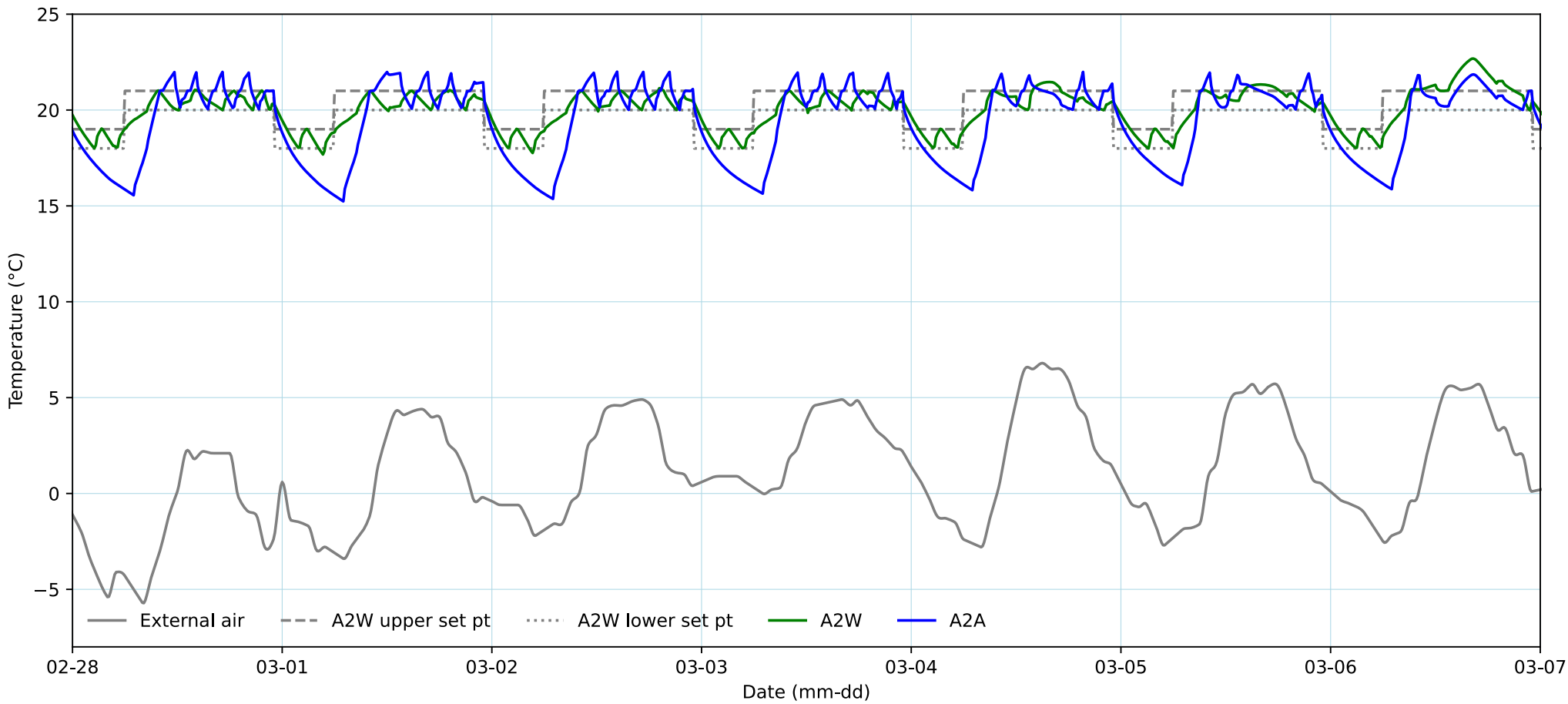


Figure 13: The FHS dwelling during a warm week in summer (TRY)

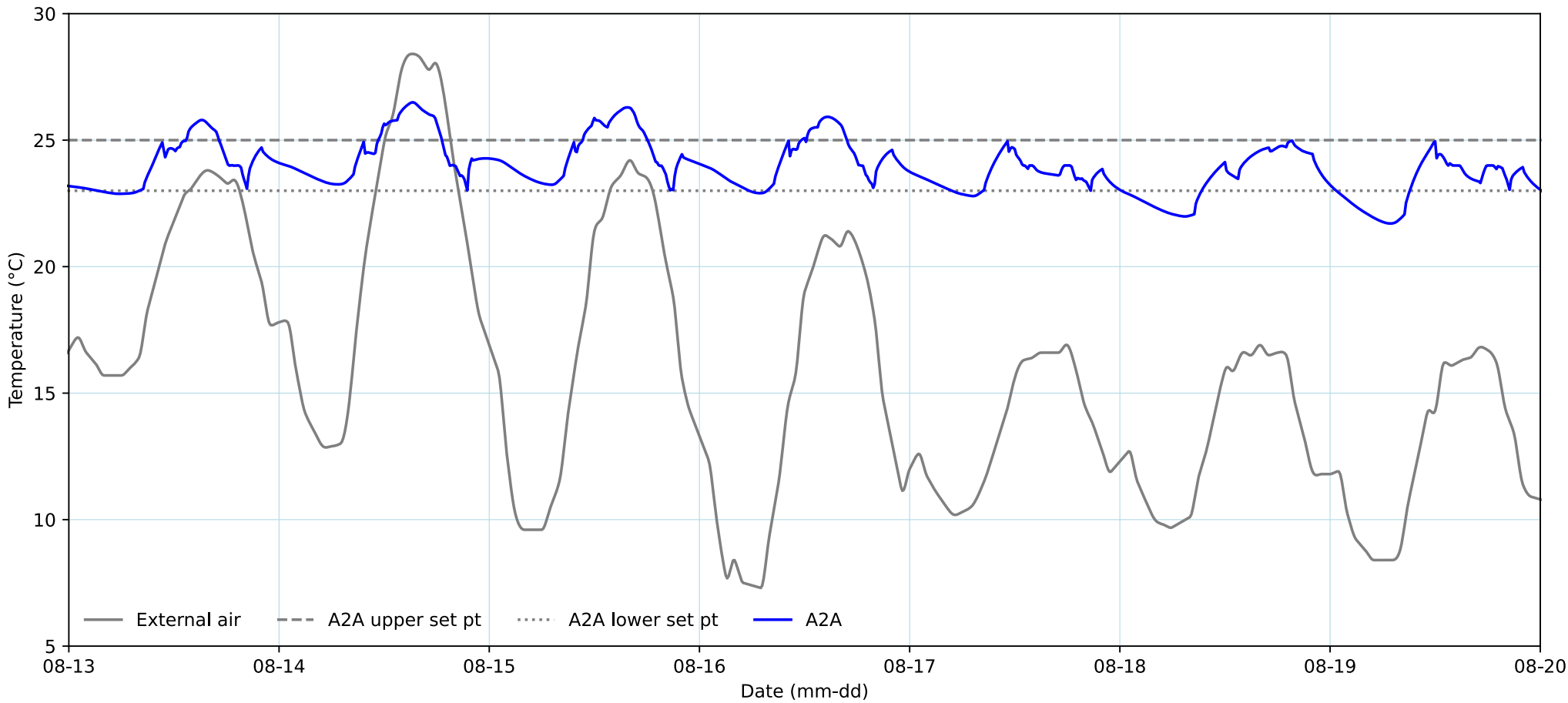
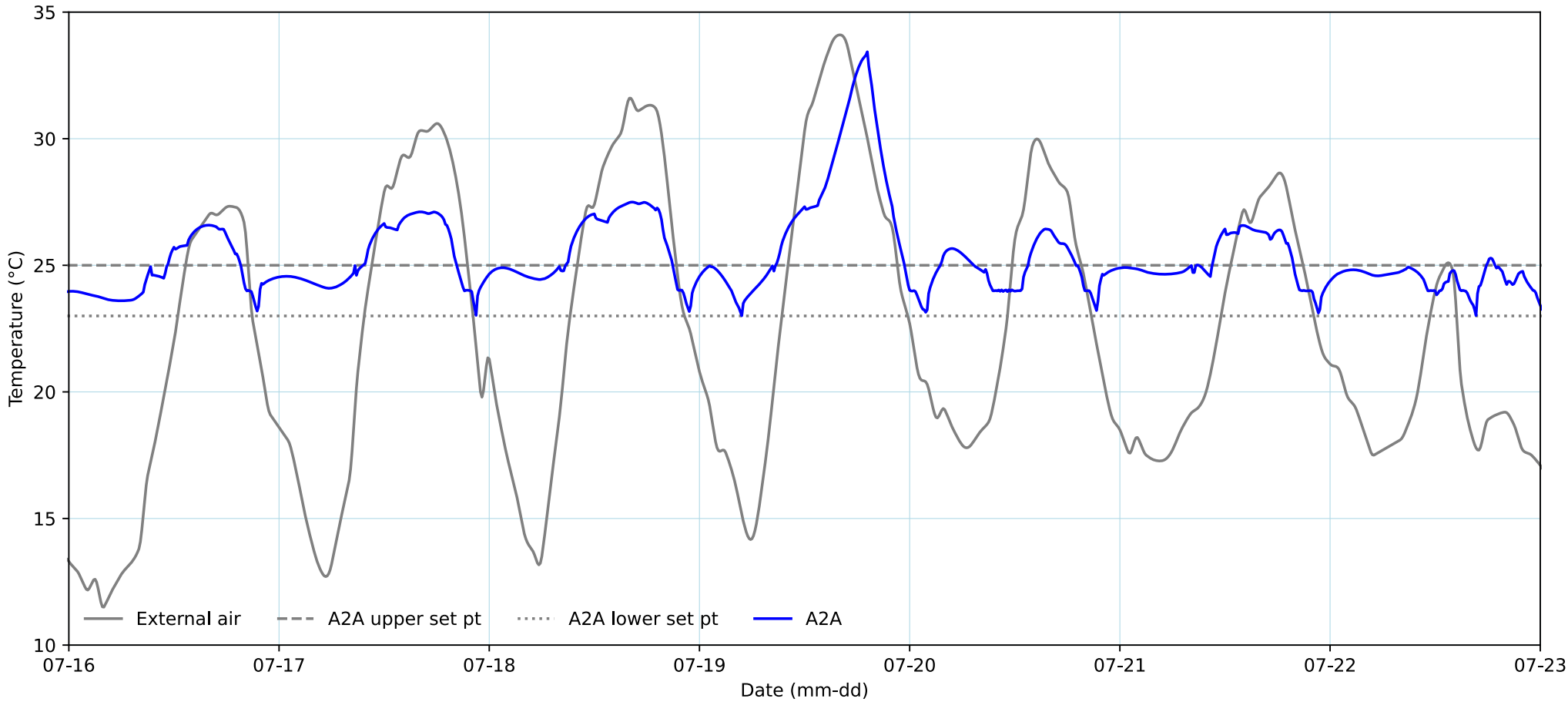


Figure 14: The FHS dwelling during a warm week in summer (DSY2)



Conclusions

This report focussed on the suitability of reversible air-to-air heat pumps (RAAHPs) for providing heating and hot water for various domestic dwelling archetypes in the UK. The project answered six research questions relating to energy requirements of different systems, operating costs, performance in extreme warm or cold weather, requirements for supplementary systems, and suitability in a dwelling built to the proposed Future Homes Standard (FHS).

The project found that RAAHPs operating together with supplementary resistive electric heaters (used in bathrooms etc.) provided space heating at a greater combined efficiency for three out of five archetype dwellings, when compared to other types of system. For RAAHPs operating together with supplementary resistive electric heaters, the ratio of useful space heating provided to energy use²⁴ varied from around 2.5:1 to around 4:1, whereas air-to-water heat pumps typically achieved between 3:1 and 3.5:1, and combi-condensing gas boilers around 0.9:1.

Whilst the performance of RAAHPs for space heating was very positive, the systems did not generally provide hot water (because the maximum available tank size at the outset of the project was 120 litres, too small for some households). Because of this limitation, the project found that the full picture of energy requirements and operating costs for dwellings with RAAHPs in combination with other technologies were often higher than for other types of systems, even with cooling included in the counterfactual cases to give a like-for-like comparison.

However, it should be noted that in the case of the flat archetype, where use of a RAAHP system linked to a small hot water tank was possible, this system provided a lower annual cost than any of the alternative systems, including a gas boiler. Further, in the case of the terraced house archetype, the RAAHP system, even though combined with an immersion heated tank, was found to give a lower annual running cost than the alternative air-to-water heat pump system.

Typically, the RAAHP was able to meet occupancy requirements for space heating and cooling across the set of archetype dwellings considered.

Several considerations are made for follow-on work:

- A trial in which RAAHPs are installed in domestic dwellings should seek to add real-world findings to those modelled for this report. These trials should seek to build the evidence base against the same research questions answered in this report but also consider householders' lived experience with RAAHPs. It remains to be seen whether householders are comfortable with domestic space heating and cooling provided by

²⁴ Note that the uncertainty associated with the efficiency figures presented for RAAHP systems in the present report is higher than that for alternative systems, due to the RAAHP models being constructed from a relatively limited dataset.

blower units, how householders will use the systems (recognising that it may be different to how they use existing systems), and what issues there may be related to their installation and maintenance. The ongoing *Homes for Net Zero* programme has begun to explore this by installing and monitoring RAAHPs in real homes.

- It remains to be seen whether RAAHPs paired with more efficient supplementary systems for space heating and hot water provision make energy demand and operating costs comparable to alternative systems across a wider range of archetypes. Further, since this project was specified, an OEM has published plans to provide hot water tanks up to 230 litres as a combined solution with its RAAHPs,²⁵ making them more suitable for a broader range of households.
- A small number of dwelling archetypes representing a modest proportion of the housing stock were modelled; future studies including additional dwelling archetypes, with different characteristics such as size, built form, and age will build a broader evidence base to assess suitability.
- Analysis of the full system costs, including the capital cost of the systems modelled, their maintenance, disposal and end-of-life replacement, as well as operating costs should be considered.
- For comparison with the electricity consumed by the RAAHP system when providing space cooling, analysis of the electricity consumed by ceiling fans should be considered.
- Analysis of the impact of passive cooling measures, including window opening and shading, should be considered.
- The effect of variable-price tariffs should be considered.
- Some changes could be made to the scenarios already modelled, including:
 - Using a weather file that represents an extremely cold winter,
 - Using the higher CIBSE cooling setpoint of 26°C.
 - Altering occupancy and heating profiles.

²⁵ https://www.daikin-ce.com/en_us/press-releases/2025/new-solution-for-cooling-heating-hot-water-daikin-multi.html

Appendices

Appendix A – Dwelling archetype details

Detached (Potential Future Homes Standard)

The post-2026 three-bedroom detached dwelling is built to the proposed Future Homes Standard. It has the following characteristics:

- Solid floors with 150mm of insulation.
- Cavity walls with 185mm of insulation.
- Pitched roof with 325mm of insulation.
- Double glazing with a U value of 1.2 W/m²K (19.4m², includes patio doors).
- Modern composite doors with a U value of 1.0 W/m²K (1.74m²).
- Air change rate 0.8/hour.
- Air-to-water heat pump (where applicable):
 - 7kW output,
 - Flow temperature of 25-45°C (with weather compensation),
 - 9 radiators,
 - Single thermostat in the living room,
 - 250 litre hot water tank, 50°C setpoint, with once weekly 60°C pasteurisation cycle.
- Air-to-air heat pump (where applicable):
 - Five internal units driven by a multi-split unit,
 - 10.4kW heating capacity, 9.0kW cooling capacity,
 - 250 litre hot water tank with immersion, with once weekly 60°C pasteurisation cycle.
- Secondary heating system for use with air-to-air heat pump (where applicable):
 - 400 W electric radiator in toilet,
 - 500 W electric radiator in bathroom,
 - 500 W electric radiator in shower room.
- Photovoltaic panels (where applicable):
 - 12 panels at 437kWp/panel = 5.24kWp total,
 - South facing roof, 45° pitch.

Studio flat

The post-2002 studio flat dwelling is in a medium-rise building on a mid-floor and in the middle of the block. It has the following characteristics:

- Party floor, party ceiling, and has three party walls.
- Cavity wall with 60mm of insulation.
- Double glazing with a U value of $2.0 \text{ W/m}^2\text{K}$ (8.2m^2).
- Modern composite door with a U value of $1.6 \text{ W/m}^2\text{K}$ (1.68m^2). This door is to a shared heated corridor.
- Air change rate 0.72/hour.
- Gas-fired combi-boiler (where applicable):
 - 14kW output,
 - Flow temperature of 70°C ,
 - 3 radiators,
 - Single thermostat in the living space,
 - Hot water provided direct at 60°C flow temperature.
- Electric radiators (where applicable):
 - 3 x 500W electric radiators,
 - 120 litre hot water tank with immersion, with once weekly 60°C pasteurisation cycle.
- Air-to-air heat pump (where applicable):
 - One internal unit driven by a single split external unit,
 - 2.5kW heating capacity, 2.0kW cooling capacity,
 - 120 litre hot water tank, either with immersion or heated by heat pump, both with once weekly 60°C pasteurisation cycle.
- Secondary heating system for use with air-to-air heat pump (where applicable):
 - 500 W electric radiator in bathroom.

Semi-detached

The 1919-1944 three-bedroom semi-detached dwelling is mostly 'as built' but with older retrofitted windows and doors. It has the following characteristics:

- Solid uninsulated floors.
- Cavity uninsulated walls.
- Pitched roof with 100mm of insulation.

- Double glazing with a U value of $2.8 \text{ W/m}^2\text{K}$ (16.3m^2).
- UPVC doors with a U value of $3.0 \text{ W/m}^2\text{K}$ (3.1m^2).
- Air change rate 0.72/hour.
- Gas-fired combi-boiler (where applicable):
 - 24kW output,
 - Flow temperature of 70°C ,
 - 10 radiators,
 - Single thermostat in the living room,
 - Hot water provided direct at 60°C flow temperature.
- Air-to-water heat pump (where applicable):
 - 12kW output,
 - Flow temperature of 40°C (with weather compensation),
 - 10 radiators,
 - Single thermostat in the living room,
 - 300 litre hot water tank, 45°C set point, with once weekly 60°C pasteurisation cycle.
- Air-to-air heat pump (where applicable):
 - Six internal units driven by two external unit, multi-split serving five internal units and a single split,
 - Multi-split: 10.4kW heating capacity, 9.0kW cooling capacity,
 - Single-split: 2.5kW heating capacity, 2.0kW cooling capacity,
 - 300 litre hot water tank with immersion, with once weekly 60°C pasteurisation cycle.
- Secondary heating system for use with air-to-air heat pump (where applicable):
 - 400 W electric radiator in toilet,
 - 1.1 kW electric radiator in bathroom,
 - 1.1 kW electric radiator in shower room.

Detached

The 1919-1944 four-bedroom detached dwelling has had basic retrofit measures such as cavity wall and loft insulation. It has the following characteristics:

- Both solid and suspended uninsulated floors.
- Cavity walls with 75mm of insulation.

- Pitched roof with 300mm of insulation.
- Double glazing with a U value of 2.8 W/m²K (18.8m², includes patio doors).
- UPVC doors with a U value of 3.0 W/m²K (1.5m²).
- Air change rate 0.72/hour.
- Gas-fired combi-boiler (where applicable):
 - 29kW output,
 - Flow temperature of 70°C,
 - 10 radiators,
 - Single thermostat in the living room,
 - Hot water provided direct at 60°C flow temperature.
- Air-to-water heat pump (where applicable):
 - 12kW output,
 - Flow temperature of 40°C (with weather compensation),
 - 10 radiators,
 - Single thermostat in the living room,
 - 250 litre hot water tank, 45°C set point, with once weekly 60°C pasteurisation cycle.
- Air-to-air heat pump (where applicable):
 - Six internal units driven by two external unit, multi-split serving five internal units and a single split,
 - Multi-split: 10.4kW heating capacity, 9.0kW cooling capacity,
 - Single-split: 2.5kW heating capacity, 2.0kW cooling capacity,
 - 250 litre hot water tank with immersion, with once weekly 60°C pasteurisation cycle.
- Secondary heating system for use with air-to-air heat pump (where applicable):
 - 120 W electric radiator in toilet,
 - 400 W electric radiator in bathroom,
 - 400 W electric radiator in shower room.

Mid-terrace

The pre-1919 two-bedroom mid-terrace dwelling is mostly 'as built' but with older retrofitted windows and doors and some loft insulation. It has the following characteristics:

- Both solid and suspended uninsulated floors.

- Solid uninsulated walls.
- Pitched roof with 100mm of insulation.
- Double glazing with a U value of $2.8 \text{ W/m}^2\text{K}$ (9.7m^2).
- UPVC doors with a U value of $3.0 \text{ W/m}^2\text{K}$ (3.2m^2).
- Air change rate 0.58/hour.
- Gas-fired combi-boiler (where applicable):
 - 16kW output,
 - Flow temperature of 70°C ,
 - 7 radiators,
 - Single thermostat in the living room,
 - Hot water provided direct at 60°C flow temperature.
- Air-to-water heat pump (where applicable):
 - 5kW output,
 - Flow temperature of 35°C (with weather compensation),
 - 7 radiators,
 - Single thermostat in the living room,
 - 200 litre hot water tank, 45°C set point, with once weekly 60°C pasteurisation cycle.
- Air-to-air heat pump (where applicable):
 - Five internal units driven by a multi-split unit,
 - 10.4kW heating capacity, 9.0kW cooling capacity,
 - 200 litre hot water tank with immersion, with once weekly 60°C pasteurisation cycle.
- Secondary heating system for use with air-to-air heat pump (where applicable):
 - 300 W electric radiator in bathroom.

Appendix B – Appliance use details

Three occupancy profiles were selected, each of which has an appliance use profile.

Family of four – adults work from home; children are at school during weekdays:

- TV – 120W – 360 mins/day, weekdays and weekends, evenings.
- Laptop and Monitor – 156W – 420 mins/day, weekdays, daytime.
- Router – 7W - 24 hours/day, weekdays and weekends.
- Kettle – 2,200W – 10 mins/day, weekdays, 12 mins/day, weekends, throughout.
- Microwave – 1,500W – 5 mins/day, weekdays and weekends, mornings.
- Hob and extractor – 2,170W – 60 mins/day, weekdays and weekends, lunchtimes and evenings.
- Oven – 2,000W – 60 mins/day, weekends, evenings. Dishwasher – 1,050W – 60 mins/day, weekdays and weekends, evenings.
- Fridge freezer – 112W – 24 hours/day, weekdays and weekends.
- Washer/Dryer – 2,200W – 60 mins/cycle, 6 cycles/week, daytime.
- Vacuum – 500W - 30 mins/use, 2 uses/week, daytime.
- Hairdryer – 2,000W – 20 mins/day, weekdays and weekends, mornings.
- Iron – 1,310W – 60 mins/day, weekends, daytime.

Family of three – one adult works from home, the other is out during office hours on weekdays, and the child is at school during weekdays:

- TV – 120W – 360 mins/day, weekdays and weekends, evenings.
- Laptop and Monitor – 78W – 420 mins/day, weekdays, daytime.
- Router – 7W - 24 hours/day, weekdays and weekends.
- Kettle – 2,200W – 7 mins/day, weekdays, 9 mins/day, weekends, throughout.
- Microwave – 1,500W – 5 mins/day, weekdays and weekends, mornings.
- Hob and extractor – 2,170W – 60 mins/day, weekdays and weekends, lunchtimes and evenings.
- Oven – 2,000W – 60 mins/day, weekends, evenings.
- Dishwasher – 1,050W – 60 mins/day, weekdays and weekends, evenings.
- Fridge freezer – 112W – 24 hours/day, weekdays and weekends.
- Washer/Dryer – 2,200W – 60 mins/cycle, 6 cycles/week, daytime.
- Vacuum – 500W - 30 mins/use, 2 uses/week, daytime.
- Hairdryer – 2,000W – 15 mins/day, weekdays and weekends, mornings.

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- Iron – 1,310W – 60 mins/day, weekends, daytime.

Couple – one adult works from home, the other is out during office hours on weekdays:

- TV – 120W – 60 mins/day, weekdays and weekends, evenings.
- Laptop and Monitor – 78W – 420 mins/day, weekdays, daytime.
- Router – 7W - 24 hours/day, weekdays and weekends.
- Kettle – 2,200W – 5 mins/day, weekdays and weekends, throughout.
- Microwave – 1,500W – 3 mins/day, weekdays and weekends, mornings.
- Hob and extractor – 2,170W – 30 mins/day, weekdays and weekends, lunchtimes and evenings.
- Oven – 2,000W – 60 mins/day, weekends, evenings.
- Dishwasher – 1,050W – 60 mins/cycle, 2 cycles/week, evenings.
- Fridge freezer – 112W – 24 hours/day, weekdays and weekends.
- Washer/Dryer – 2,200W – 60 mins/cycle, 2 cycles/week, daytime.
- Vacuum – 500W - 15 mins/use, 2 uses/week, daytime.
- Hairdryer – 2,000W – 5 mins/day, weekdays and weekends, mornings.
- Iron – 1,310W – 60 mins/use, 1 use/week, daytime.

This publication is available from: <https://www.gov.uk/government/collections/heat-pump-research>

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