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Enhanced EnHub: dynamic simulation of housing stock energy systems

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Abstract

In the UK, heating systems are the most prominent contributor to residential energy demand, with about 80% of the share. Their representation has thus been at the core of all UK-focussed Housing Stock Energy Models (HSEMs). However, these HSEMs estimate heating demand based on monthly or annual energy balances, with correspondingly approximate representations of heating systems and practices (incl. energy conversion, distribution and spatiotemporal control). This paper describes an extension to the dynamic HSEM: housing stock Energy Hub (EnHub), to rigorously simulate space heating and hot-water components (i.e. heaters, boilers, pumps, radiators, end-point registers, thermostats, taps). Baseline simulations estimate the English housing stock's energy use as 35.9 mtoe. Alternative scenarios in which heating systems are substituted across the board to district heating or ground-source heat pumps predict a reduction in demand to 30 and 18 mtoe respectively; the latter potentially being zero-carbon if the power sector.

Keywords: housing stock, dynamic energy simulation, modularity,

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domestic heating

Contents

1. Introduction

In the UK, the domestic sector is responsible for about one-fourth of national end-use energy demand [1]. This is attributed to four key services: 60% space heating, 20% domestic hot water (DHW), 17% lighting and appliances, and 3% cooking [2, 3]. Electricity is the main supply vector for domestic appliances, which has been growing in magnitude throughout the past forty years. Conversely, gas is the main supply vector for heating systems, including space heating, hot-water and cooking devices. The estimation of end-use energy demand has been supported since 1970, when formal records of energy use began [2, 3]. This demand was estimated to be 36.8 mtoe[1] in 1970; by 2011, it increased to 40.8 mtoe, passing through a peak of 49.4 mtoe in-between [3]. Although the efficiency of both household appliances and heating systems has improved, their energy demand intensity has also increased [4, 5], due to changes in ownership, and patterns of use [6, 7, 8]. Indeed, it is speculated by some, that increased intensity of use is affected by efficiency improvements—the so-called rebound effect [9, 10]. Increased indoor temperatures arising from energy efficiency (e.g. gas fired central heating systems) and conservation improvements (e.g. thermal insulation) are one such example. Given this trend, it is of value to rigorously study appliances and systems, accounting for their specification, ownership and usage, as well as their performance in use. This will help to accurately target where specifically there is greatest potential to reduce the carbon intensity of heating energy systems.

Gas fuelled boilers combined with central heating systems are the most common heating system configuration found in UK dwellings. During the past forty years, gas fuelled configurations have substituted decentralised and less efficient heating systems, such as wood-, oil- and coal-fuelled ones. They have helped to deliver healthier indoor air conditions, and more homogeneously heated spaces. Electric storage technologies have been encouraged by the introduction of off-peak tariffs, but their adoption has been relatively moderate. Other technologies such as electric ceilings, underfloor heating,

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[1] The International Energy Agency (IEA) estimates 1 mtoe to be equivalent to 11.63 TW h

communal heating, combined heat and power units and heat pumps, have increased their presence in recent years [11, 12, 13]. The ownership of dedicated domestic hot water (DHW) systems, has also grown significantly over this period, whether integrated into central heating systems or independent to them. The adoption of new heating technologies has arisen from two main factors: the centralisation of heating infrastructure, which in turn reduced purchase and installation costs; and more importantly, the development of more efficient devices (i.e. the provision of thermal energy at a lower cost).

Ideally, space heating systems—and, where appropriate, their combination with DHW systems—are designed to meet thermal requirements, on demand, that help reach an expected indoor temperature. In other words, space heating systems deliver the necessary amount of thermal energy to restore that heat which is lost through the envelope, to maintain comfort whilst minimising part-load inefficiencies. This in principle implies the representation of five inter-related phenomena: i) the heat that is released through the building envelope to the environment at a certain rate (i.e. a *heat loss parameter*, expressed in energy per differential of temperature in a given area : $\mathrm{W/(m^2\,K)}$); ii) the heat that is captured from the sun and from internal sources at a certain rate (i.e. a *heat gain parameter*, the complement to i, expressed in $\mathrm{W/(m^2\,K)}$); iii) the ability to transform energy into heat, and to homogeneously distribute it through the enclosed volume in a given period (i.e. a *heating system efficiency*, expressed as a ratio); iv) the adopted levels of indoor comfort (expressed as a *temperature set-point*); and v) the level of affordability to utilise such heating systems[2] (i.e. a *heating expenditure*,

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[2] Heating systems perform in function of heat transfers through the envelope (to or from the external environment or conjoined buildings), via conduction and associated surface convective and radiative transfers and by infiltration and exfiltration, as well as

expressed in cost per unit of energy demanded: £/kWh, £/kWh/m^2).

The resulting balance of these five aspects has historically represented most of the energy demand in UK homes, i.e. 60% (space heating) + 20% (hot water). Here, the estimation of *heat loss parameters* has been the foremost factor considered by models [14, 15, 13], their success depending to a large extent on the quality of data supporting the physical description of the stock of dwellings, as well as on the ability to abstract energy flow pathways, especially when the study targets a relatively large stock. *Heat gain parameters* have tended to be modelled using annual or monthly energy balances, perhaps adjusted to represent the utilisation of transmitted gains from solar radiation. The estimation of heat gains and losses is significantly correlated with the associated housing typologies [16, 17], due to the combination of built form and construction technologies (or fabric) employed in their period of construction, and the associated influence of building regulations upon them [18, 19, 20]. If we consider that energy conservation standards for dwellings were developed in response to the oil crisis in the 1970s, and were then maintained in the 1980s by the Housing Act [18, 21], noticeable improvements to construction technologies and materials are evident in those dwellings built since.

In the UK, a key example of the estimation of a house's thermal energy balance, through the joint representation of heat gains and losses, has been through the Building Research Establishment Domestic Energy Model (BREDEM), which in turn has been at the core of the majority of Housing Stock Energy Models (HSEMs) [13]. These generally utilise English

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the thermal gains from occupants and appliances. The rate of heat transfer (or heat transfer per unit time) is unique for each component, which means that the accumulation of heat is usually heterogeneous, and can be significantly affected by its time resolution.

Housing Survey (EHS) [22] data to assign heat loss parameters to models and weightings that facilitate extrapolation of predicted energy use to the number of houses nationwide that are represented by them. In contrast to purely statistical modelling approaches, this approach, which is described in detail in our previous study [23], offers the ability to evaluate specific interventions to improve building performance.

Whilst the EHS facilitates a thorough representation of the physical composition of the housing stock, including the types of systems adopted, a detailed assessment of heating system technologies, and their *heating system efficiencies*, has been rather limited. This, together with a desire to employ modelling approaches of complementary (to the modelling of energy demand) complexity, explains why HSEMs have tended to employ highly approximate representations of thermal energy systems (e.g. design day sizing calculations, average heating set-point temperatures, and fixed heating system efficiencies). These limitations have in turn significantly constrained the study of indoor *comfort* conditions, because dynamic indoor temperatures and humidities, and occupants' adaptive actions that influence them, cannot be estimated. On a related note, there is some evidence suggesting that the mean external air temperature in winter has increased by around 1K since 1970, whereas the mean indoor air temperature has risen by up to about 6K [24, 16, 13], though there is some speculation as to the effectiveness of the methods employed to record such temperatures; namely, a level of uncertainty caused by (dis)regarding spaces in which a lower temperature is acceptable, such as storerooms, pantries and cellars. The increase in the external temperature is likely to be associated with climatic change, whilst the significant increase in the internal temperature—and thus of energy demand—is attributable to improvements in fabric properties, in part due to more onerous regulations of heat and power conservation, the prevalence of central heating systems, and increased thermal comfort expectations [25]; another form of rebound effect.

The above shows that not only is it essential to track changes that directly influence energy conservation, but also to quantify changes on adaptability and affordability of indoor thermal energy demand, which are commonly determined by household circumstances, and which are exogenous to energy performance. For example, the costs of home improvements or of the fuel expenditure [26, 27], turn out to be important in the study of measures to improve indoor conditions, especially if heating-related expenditure is significant when compared to household disposable income. Households that are deemed to be subject to *fuel poverty*[3] are significantly more constrained to invest in energy conservation technologies, despite their technical feasibility; acknowledging that the concept of *fuel poverty* is relatively restrictive in terms of household composition.

Such inter-related indicators: *heat loss parameters* (including the typically positive difference between heat loss and heat gain), *heating system efficiencies*, *comfort* levels, and *fuel poverty*, are useful to evaluate the performance and comfort and carbon emission implications of heating systems in the housing stock. Yet an accurate representation of specific heating system configurations, and their impact on the indoor energy balance, has been essentially overlooked to date; likewise, those benefits or constraints that may eventually affect the processes of decision-making to invest in or substitute a system, or to adopt more effective usage practices. This latter

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[3] A household is considered to be in *fuel poverty* if the expenses destined to cover energy requirements surpass the national median level, or if the residual income, after paying for fuels, falls below the official poverty line [28].

is particularly complex, requiring the combination of comprehensive energy simulation with some form of social simulation of household investment and operational decisions. This paper enhances the module employed in EnHub to simulate heating energy use. The enhanced module augments the representation of heat transfer rates, and increases the level of parametrisation to evaluate indoor conditions. These additions will, in the future, support their integration with household-related models, to more faithfully simulate households' investment and operation decisions, and their energy and comfort consequences.

The following Section summarises the representation of heating system configurations in HSEMs, and the assumptions and limitations in their implementation. Section 3 compares different heating configurations, reports on the adoption of different configurations to a chosen archetype, and briefly outlines the incorporation of household-related parameters into the modelling approaches, further discussed in Section 4, where the results are described. Section 5 closes the paper by summarising the findings of the evaluations, and discussing the potential integration with decision-making models.

2. Representation and Implementation of Heating Systems

2.1. Purpose and Rationale

Formally, a space heating (SH) system is defined as an energy conversion and distribution system, and a configuration of storage devices, sufficient to provide heat to two or more rooms [29]. The operation of a SH system, and its resultant energy demand, depends on the efficiency of each component to transform energy into usable heat, and on the level of controllability provided by the employed technology to supply heat when indoor conditions fall below an adopted threshold: the heating set-point. This efficiency is in turn determined by the heating technology (i.e. power capacity, thermal conversion process, distribution of heat, system heat losses), and by the internal layout (i.e. dwelling size, distribution of rooms and thermal zoning, position of openings). As a result, there are certain spaces in which appropriate thermal energy demand may not be fulfilled, due to the distribution of heat throughout the dwelling (or indeed the influence of affordability on the way heat is regulated). Because of this, it is worth considering that some dwellings may complement their SH systems with auxiliary heating components, which may or may not share the main heating system's properties. Furthermore, SH systems have a certain level of controllability that makes them more or less responsive to thermal conditions. For example, modern devices are able to deliver a fine degree of control over the delivery of heat, whereas older devices are more restricted in this regard, and are usually designed to operate in a Boolean mode (i.e. fully on or fully off). As a result, it has been common for the latter to cause under- and over-heating.

DHW systems may operate independently, by warming water at the delivery point (for example, in showers); however, due to the inherent technology applied to SH systems, i.e. an amount of energy transported through a circuit which is then released at a series of end points, such as radiators, it is convenient to integrate DHW devices with SH systems.

To date, both SH and DHW systems have improved their efficiencies and controllability, by employing different materials, by replacing fuels, and by insulating their components to minimise unintended heat losses; nevertheless, their full representation, especially in terms of thermal performance, has been poorly addressed in HSEMs, with corresponding implications for uncertainty in their predictions, and the national policies that are informed by these predictions. The following sections will describe the modelling approximations (developed in previous HSEMs) to represent heating systems in dwellings, their characterisation methods and data sources, and their—enhanced—modular implementation for dynamic simulation with EnHub.

2.2. Thermal Energy Demand in Dwellings

Historically, and for practical reasons, HSEMs have assumed average indoor and outdoor environmental conditions to estimate total thermal energy demands, and hence to size heating systems to achieve thermal comfort expectations. Whilst these energy models facilitate the rapid estimation of energy use to deliver an approximation of the desired indoor conditions, they usually simplify, or even neglect, the transients involved in heat transfer. Dynamic simulation enables the possibility to calculate transient thermal storage in building materials, ventilation and infiltration rates, solar radiation gains, metabolic and appliances gains, as well as delivered heating system loads [30, 13]. This helps to evaluate thermal charges and discharges for each component, which in turn affects the resulting thermal balance of the surrounded spaces; as well as prediction of indoor thermal microclimate and associated levels of thermal comfort.

Now, to effectively perform such an evaluation, it is indispensable to collect material specifications for each component of the envelope (i.e. thermal properties, dimensions, orientation, shape), as well as of the systems employed to meet the thermal demand (i.e. power capacity, efficiency, delivery end points). Whilst it is relatively feasible to collect such specifications for one dwelling, it becomes more challenging to collect these for an entire housing stock. National cross-sectional surveys, such as the EHS, are a highly effective alternative. However, the potential utility of surveys like EHS is underutilised in existing HSEMs. For example, most UK-based HSEMs, including the comprehensive Cambridge Housing Model (CHM) [31], employ BREDEM at their cores, and thus calculate the amount of heat required to maintain the (assumed) indoor temperature at spatiotemporally average values between 17 and 19 °C [32, 33]; considerably simplifying treatment of the transients arising from indoor activities, heating system intermittency, erratic weather, or from unintended heat transfers.

EnHub was designed and developed to resolve this shortfall by extracting survey data, and by generating semantically attributed volumetric archetypes of dwellings, so these can be dynamically simulated using the `EnergyPlus` engine [23]. EnHub is written in `R` (the statistical computing software), and it is thus open and modular in structure, which means that each component is editable and verifiable (e.g. an aggregate average occupant related heat gain can be replaced with a synthetic representation of usage profiles as a function of household composition and socio-demographics; a steady-state representation of heating systems can be substituted with a dynamic time- and weather-dependent algorithm). Simulation with EnHub requires, therefore, a more thorough representation of fabric and form, which correspondingly increases the resolution of metrics describing energy performance and comfort. The simulation also improves the ability to quantify uncertainties, and to explore the potential impacts of parametric changes, destined to reduce energy demand at the stock level.

In the following section, we introduce an extension to EnHub[4] to repre-

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[4] In the initial release of EnHub [23] (v1, 2017), heating configurations were only represented as large appliances weighted with their corresponding average heating loads.

sent the ownership and performance of SH and DHW systems in the housing stock, and the corresponding integration of representations of these systems for dynamic simulation.

2.3. Characterisation and Ownership

In general, SH systems may be classified [29] according to their: i) supply configuration, which are either individual or communal; ii) fuel supply, or energy source; iii) end-point technology, which can be classified as radiator, storage heater, warm air, underfloor, electric ceiling and room heaters; iv) heating technology, these can employ a boiler, a furnace, a heat exchanger, a communal supply, or a combination of them. For each configuration, specific energy requirements are additionally demanded in line with their operating controls, pumping devices and water network designs. For instance, some configurations benefit from the effects of gravity to induce the circulation of water.

DHW systems employ similar technologies, and their operation can be an integral part of, or independent to, the main SH systems. DHW systems can be classified in three main categories [29]: i) open-vented, where a cistern is used to regulate the flow that is introduced into the hot-water tank; here, the water can be directly warmed with immersion heaters, or it can be heated inside the boiler and then stored in the tank only; ii) unvented, where the flow is regulated and pressurised with pumps, and it is warmed with immersion heaters; and iii) instantaneous, where water is warmed as it flows through the serpentine in a (typically copper) heat exchanger. There are two additional elements that characterise DHW performance: cylinder insulation and thermostat, in which this latter regulates heating activation to maintain the scheduled target temperature of the water flow.

Heating system configurations may be further differentiated according to their devices' specifications, efficiencies, auxiliary components, collocation, fuel and operation. It can thus be inferred that the combination of both SH and DHW may be highly unique, and so, as mentioned in Section 2.2, their characterisation across the stock may become challenging. For example, the method to characterise heating system configurations, described in the English Housing Survey Surveyor Briefing Manual [29], results in 81 different SH systems. When these are combined with the more than 10 standard DHW systems, and a number of auxiliary systems, the number of unique configurations increases by two orders of magnitude. To reasonably faithfully represent these in HSEMs, a method of reduction is provided in the EHS [22]. Table 1 shows the reduction and correlation of both SH and DHW systems; the former is reduced to fifteen types, and the latter to eleven. These values correspond to the 2011 version, which surveyed 14,951 dwellings, and is weighted to represent the 21 million houses in England for that year. Table 1 also shows that *gas standard* is the most common configuration (55%), followed by *gas with combi boiler* (i.e. a configuration that avoids the presence of storage heating cylinders). Other common configurations include the use of a *back boiler fuelled by gas*, and electric *storage heaters* combined with electric heaters or gas boilers. Table 1 indicates that some combinations are atypical, or even absent, at least for that year's survey. Additional factors, including parameters specified in relevant regulations (e.g. Council Directives, Boiler Efficiency Regulations, Performance Specifications, British Standards) are collated by the Standard Assessment Procedure (SAP), serving as a reference catalogue. An example of the combination of SAP and EHS information is found in the CHM [31], but as noted, this BREDEM-based model applies fixed efficiencies and power capacities, and so is unable to evaluate specific system performance.

[Table 1 about here.]

2.4. Implementation of Heating Systems in EnHub

The first stage in the EnHub workflow involves the processing of data sources—storing them as a list, so they can be accessed across modules and processes. The next stage selects a group of survey archetypes and extracts their main attributes. This selection may be performed by filtering stock attributes, by defining a sequence, or by directly picking archetypes. At this point, given that the list of data sources can be indexed and edited, we can embed a parametrisation module with which to evaluate changes to the selection (of archetypes) or to the data sources' values. Each EnergyPlus Input Data File (idf) is then built in a modular manner [23]. The main idf generation workflow in EnHub involves ten modules[5].

One of the main components at the core of this workflow is *Module E: zones and surfaces*, where EHS data is coupled with a tuple of cuboid geometries, stored as templates. The use of these cuboids helps to quickly conjoin zones, so these can be easily scaled with respect to the corresponding EHS data. This is because the cuboids already match surfaces with their appropriate construction layers or indicate their corresponding outer boundary—as required by `EnergyPlus`.

[Figure 1 about here.]

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[5] Main idf modules: *A parameters*; *B location*; *C schedules*; *D materials and constructions*; *E zones and surfaces*; *F loads*; *G energy system*; *H water*; *I renewables*; and *J outputs.*

Figure 1 outlines the EnHub workflow, highlighting the energy system module. In extending EnHub to support dynamic simulation of SH and DHW systems, a catalogue of heating system configurations (space and hot-water), whose ownership is summarised in Table 1, has been developed in the suite `OpenStudio` [34]—a Graphical User Interface (GUI) for `EnergyPlus`. This GUI helps to represent the heating systems and their interrelationships graphically. It also helps to configure each of the systems in terms of their technical specifications, which have mostly been simplified or neglected in prior HSEMs.

To develop our `OpenStudio` templates, a series of system specifications (i.e. efficiency, recovery time, responsiveness) need to be estimated. For this, we re-analysed our stock, utilising further data sources, including the National Energy Efficiency Data-Framework (NEED)[35], and the regulations and SAP tables mentioned earlier. NEED offers relevant yearly statistics regarding metered data, broken down by various property and household characteristics, which can be matched with the corresponding EHS data. Other system specifications, such as effective size (and power capacity) of each heater, is obtained during the `EnergyPlus` simulation.

[Figure 2 about here.]

[Figure 3 about here.]

Module G: energy system is mainly composed of three processes: loop, components, and scale and assignment. Here, a number of key parameters, such as heating system code, dwelling type, and dwelling size, are passed to the module. The heating system code is used as an index in the tuple of configurations, where each instance of Table 1 is represented. A loop process is employed because some heating configurations share a common structure, but are differentiated by their type and number of heaters and emitters, assigned later via the components. By way of example, the common configuration of *centrally heated with gas*[6] is illustrated in Figures 2 and 3. Hot-water is warmed in a sealed cylinder (boiler), and is then circulated to and through radiators and a hot water storage tank, from which hot water is supplied to taps and returned to the boiler for re-circulation.

Similar component-level representations are employed to represent and simulate *combi boilers*[7], *district heating systems*[8], *Air Source Heat Pump (ASHP)* and *Ground Source Heat Pump (GSHP)*[9], *warm air*[10] systems and

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[6] In *centrally heated with gas*, boiled water circulates through a semi-closed loop, which is achieved by employing pumps or by the effect of gravity. Here, the heat flow is often controlled by auxiliary components (e.g. a valve that regulates the flux of water, a controller to limit the maximum temperature in the boiler, a zone set-point).

[7] A *combi boiler* configuration has a similar structure that a traditional *centrally heated with gas* configuration; however, it removes the storage cylinder, and internally reconfigures its water connections.

[8] *District (or communal) heating* systems release a constant flow to be circulated, on demand, through radiators, and heat exchangers embedded into DHW systems. `EnergyPlus` employs district heating as the default supply technology when estimating ideal loads [36]. In EnHub, district heating is represented in the heat source, as with the other configurations, as a function of the indoor conditions of the dwelling, instead of using the idealised approach.

[9] *GSHP* and *ASHP* configurations can warm water running through a loop by employing a refrigerant that boils at a significantly lower temperature than water, yet higher than that of the air or the ground, and then transfers its heat to the water loop running through a heat exchanger, where the refrigerant condenses. However, because the extracted heat warms water at a lower temperature, as compared to the water warmed in a boiler, it is expected that the heat is released through larger radiative surfaces, and (potentially) that a backup is available. The larger surfaces compensate for the lower supply temperatures, while the backup helps to fulfil the amount of heat required by these alternative radiators to achieve the room set-point temperature. Further, it is worth mentioning that ground temperatures are relatively constant during the year, following an approximate average of the annual ambient dry-bulb temperature [37], which enables increased control over the capture and exchange of heat.

[10] The principle behind *warm air technologies* involves injecting thermal energy through ducted air, to be then distributed to air supply vents, and balanced, by effects of infiltration and ventilation, across the dwelling. Therefore, warm air configurations usually require both an air loop and a water loop, for services.

electric storage[11] heaters.

With the majority of these heating technologies, most of the heat is released into the room by convection, but some heat is also transferred by radiation and some minimal amount by conduction. The rate of radiant heat transfer depends on the intrinsic properties and temperatures of the irradiated materials, but this is consistently less responsive and thus controllable compared with convective heat transfer. Thus, the greater the proportion of heat that is transferred by radiation, the less responsive the emitter.

The number of emitters (or end-point registers), such as radiators and warm-air terminals, is adjusted according to the dwelling's size and geometry. Each of these registers is assigned to a specific surface, from those defined in *Module E: zones and surfaces.* The dependencies between modules are not sequential. For example, if underfloor heating is present (either as a survey input or as a parametric assignment), then a `Construction:InternalSource` object, which requires parameters in addition to the layers of materials, is configured in *Module D: materials and constructions.* These additions refine the evaluation of indoor thermal performance.

To summarise, the contribution to energy demand of each configuration is not only defined by the utilisation of specific fuels, but also by the systems'

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[11] The principle behind *Storage heaters* involves the discharge of heat, accumulated (by electric heater elements) during off-peak tariff times (night-time), from a low thermal diffusivity body (the brick in the heater) at a moderate rate throughout several hours (typically the day-time). Hence, indoor temperature changes at a relatively slow pace, yet more homogeneously. *Storage heaters* are represented via `RadiantConvective:Electric` elements, with an appropriate radiant fraction. These heaters are represented in `OpenStudio` as internal appliances, because there is no water involved. In practice, the supply of electrical energy to *storage heaters* occurs at different periods, and under specific intensities, as compared to wet radiators. The former depends on the ability to charge a ceramic material, which typically performs on complete daily cycles of charge and discharge; whereas the latter depends on the ability to store warm water, and the efficiency of the circulation process, for which many cycles may occur during the day.

operation, efficiency and ability to distribute heat. The faithful simulation of these systems requires multiple (virtual) sensors, and can thus only be accomplished via volumetric simulation; further justifying EnHub's generation of archetypal volumes. The explicit implementation of heating system configurations now enables us to simulate these systems with complementary rigour to that of energy demand, and to quantify thermal performance with correspondingly higher resolution and flexibility.

3. Evaluation of Heating Systems

By way of demonstration of the new energy systems simulation enhancements to EnHub, we first evaluate one of the most common dwelling archetypes [38, 20, 39] present in the UK housing stock: a *semi-detached* dwelling built during the *early post-war* epoch (portrayed in Figure 4), comparing its response to different heating configurations. We then explicitly implement the range of heating configurations across the housing stock and fully re-evaluate it.

3.1. Parametric Evaluation of an Archetypal System

By selecting an *early post-war semi-detached* typology, it is implied [18, 20] that: i) the envelope is typically plain and boxy—a characteristic for both social and private housing developments; ii) the construction materials are relatively standardised, as opposed to older constructions; iii) central heating is the common SH configuration; and iv) the shared adjacency creates a quasi-adiabatic surface, which reduces the area where heat can be transferred to the exterior, and affects the way heat is distributed throughout the interior.

[Figure 4 about here.]

The chosen semi-detached dwelling (c.f. Figures 2 and 4), has a total floor area of about 105 m^2, distributed over two-stories and a room-in-roof space. At an average height of 2.4 m, the volume is roughly 252 m^3. It is estimated that the glazing ratio[12] represents 16% of the exposed three uninsulated cavity walls. In this particular case, it is assumed from the EHS that the dwelling is located in the East-of-England region, that the front façade is facing East (highlighted in Figure 4), and that the roof is made of plain concrete tiles.

Disregarding aesthetic and structural components on the façades, that may perform as thermal bridges, the overall heat loss coefficient of this dwelling is roughly 356 W/K—this is 22% above the national average [2]. The average total solar transmittance (i.e. the *g-value*) is 0.74. In terms of infiltration, the mean air change rate is around 0.64 ACH for the living room, sleeping room, and other rooms. This weighted average for these space types is derived from BREDEM [40]; superseding the somewhat optimistic assumptions from the EHS. The evaluated rooms, or zones, are also associated with different assumed set-point temperatures (also from BREDEM), of 19 °C, 17.5 °C and 16.6 °C, respectively.

[Figure 5 about here.]

The assumed set-point temperatures depend on spatiotemporal heating practices, e.g. for spaces in which a lower temperature is acceptable. Typ-

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[12] A typical practice for this typology, i.e. early post-war semi-detached dwelling, consists in employing a glass panelled door; however, because of the typical porch configuration, this is not included in the glazing ratio parsed onto the idf generation, but only in its associated U-value. Further, it is also common for this typology to contain single-storey bay windows, which are presently simplified in the idf generation.

ically, heating systems are designed in terms of these temperatures, and therefore they may carry some initial over- or under-estimation. Figure 5 presents the distribution of heating demand during one typical year, based on the estimation of Heating Degree Days (HDDs). The Figure shows that even during the non-heating season, highlighted on the left of the chart, there is potential for heat demand (for example, during the morning), which is reduced by the contribution of internal gains, and the capacity to reduce thermal losses, which can be significant.

Our semi-detached dwelling is relatively leaky; about 61% of heat is lost through ventilation and exfiltration. In terms of (sensible) heat gains, glazing contributes around 28%, whereas the heating system contributes 44%. This contribution is translated into an annual space heating use of $99.1\,\mathrm{kW\,h/m^2}$, provided by the standard central heating configuration. In combination with the DHW system, demanding $36.8\,\mathrm{kW\,h/m^2}$, the heating system accounts for some 72% of the total energy use.

[Figure 6 about here.]

Figure 6 presents the dwelling's dynamic behaviour for a typical hot and cold day. During the warm day, the magnitude of absorbed irradiation is relatively high, with the large net heat gains causing a period of overheating. This in practice could be avoided, through shading and/or ventilation. As expected, the attached wall transfers heat at the lowest rate, which influences the way thermal energy is distributed during the day. Due to the assumed orientation (East), the front façade is exposed to direct solar radiation during the morning, although this is inverted during the evening, when the façade is shaded.

[Figure 7 about here.]

Our evaluation now considers the combination of all heating configurations summarised in Table 1, emulated to meet the same thermal requirements. This is achieved by directly manipulating the *data sources* `R`-list. Figure 7 shows the different components available in the `OpenStudio` suite. These components are employed to represent specific heating configurations (space and hot-water), whose properties are adjusted according to their corresponding EHS-related data. Thus, the implementation of heating configurations, as exemplified in Figure 3, scales the number of emitters, adjusts the interconnections of the loop, and, where appropriate, links surfaces. Each configuration associates different base profiles, for which a library of heating configurations (or templates) has been designed, where loops and devices are adapted (in *Module G: energy system*).

EnHub's parametric representation of thermal energy systems allows us to study the implications on heat transfers (for each wall), indoor temperatures, and the resulting energy demand, arising from differences in the operation of the different heating configurations, opening the possibility to analyse in detail the effect caused by the substitution of a heating system configuration, or an element within it. The following section re-evaluates the housing stock and highlights the corresponding impact for each heating configuration that EnHub now supports.

3.2. Housing Stock Evaluation

During the implementation and calibration of heating system configurations, we have also improved the way in which indoor heat flow is distributed, and have included additional parameters to represent infiltration rates. As a result, both the simulation time and—albeit selectable—the generated table of results have increased (with respect to earlier versions of EnHub).

Each simulation now takes between 25 seconds (for smaller dwellings) and 150 seconds (for larger multi-storey dwellings) to complete, using a single core high-end computer. While it is possible to simulate every instance in the EHS, some of these instances are redundant, for the purpose of our study. For example, differences in tenancy, although an important feature of the stock, are not essential for the simulation of heat flow at this stage. For this reason, we employ a reduced version of the EHS (version 2011), which is obtained by weighting geometrical and attributional properties of dwellings, and hence re-sampling the original dataset via Latin Hypercube Sampling (LHS). This method provides a good approximation of the original survey dataset in terms of dwelling shape, size, envelope properties and technologies [23]. The reduced stock contains 1016 dwelling archetypes, weighted to represent the 21 million houses in England.

For this evaluation, we consider the same reference heating set-point value for all configurations (19 °C for the living room, and lower values for the rest of the house), as with BREDEM. In practice, we expect heating set-points to vary according to household preferences and associated socioeconomic situation, and potentially also to the characteristics of the system (e.g. with potentially lower set-points for less responsive systems). EnHub has the capacity to handle these specificities, and indeed to draw from distributions of case-specific set-point temperature, data-permitting. But for the present case, in which our focus is on comparing the performances of alternative systems, employing a consistent set-point choice is sufficient. Also, our EnHub simulations assumes that heating is always available to be activated (there is no emulation of a seasonal manual switch-off, e.g. as identified in Figure 5).

4. Results and Discussion

Figure 8 summarises the changes to carbon emissions associated with primary energy demand, as well as to averaged indoor temperatures, arising from the different system configurations in the reference archetype. The Figure indicates that GSHP (i.e. MSH14) configurations reduce energy demand by around 40–50%, and are able to reach the same set-point as the reference configuration (i.e. MSH1DHW1). Other configurations performing relatively well are those employing district heating (i.e. MSH11, MSH12), due to their ability to deliver heat on-demand. Here, the energy demand is reduced by nearly one-quarter, and the specified average indoor temperature is maintained. Conversely, ASHP (i.e. MSH15) configurations reduce energy demand by only 9%, but at the expense of reducing average indoor temperature by more than 1K. In other words, these systems may reach the heating set-point for only a reduced period, as opposed to other systems, although this could be addressed in practice using an optimal start controller; or indeed through simulation (or emulation) of such a controller. Also note that this is a somewhat artificial outcome of a single hypothetical system substitution. In practice, we would expect the thermal fabric to be upgraded in tandem with this substitution, to compensate for the reduced supply temperatures.

Other configurations with relatively significant decreases in indoor temperature (by nearly 2K) are those employing warm air (i.e. MSH9, MSH10), where the energy demand is reduced by less than 20%[13]. Conversely, solid

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[13] This is largely an artefact of the sensitivity of predicted temperature / energy use to representations of the *Outdoor Air Flow Air* parameter in the modelling of warm air systems, with values selected—sourced in `EnergyPlus` templates—which represent a compromise between impacts on air temperature and energy use.

and oil fuelled configurations seem to be less efficient, increasing the energy demand without significant changes to delivered indoor heat energy, but significantly increasing their carbon contribution. The most reliable configurations employ gas as the main heating system, and a number of combinations to supply hot-water such as electric boiler, gas back boiler, or district heating. All systems are intermittently active and, as indicated in Section 3.2, their heating set-points are fixed, with corresponding impacts on mean indoor temperature for less responsive systems, with relatively low supply temperatures.

[Figure 8 about here.]

Figure 9 shows the resulting cumulative distribution of indoor temperature for each configuration, distinguishing between living room, and sleeping or resting areas, as in BREDEM; and, for the purpose of comparison of typical activation time, between occupied and unoccupied periods. To achieve this, a number of profiles are created to post-process results, and to highlight the availability of more indoor performance-related indicators.

On a given day for example, a conventional gas centrally heated radiator (i.e. MSH1DHW1) intermittently demands hot water from the boiler. The water delivered here is fixed at a maximum temperature. If occupants are present, the controls (or valves) increase the amount of water that circulates through the radiators. Once the air temperature increases, the controls reduce the flux of water until the room temperature triggers the control again. The whole process, while the occupants are present, occurs repeatedly. If occupants are absent, the controls are ideally adjusted to reflect a lower target temperature. As a result, the radiators subsequently take longer to warm up, and may not even achieve the set-point temperature of the room.

This set-back period thus impacts on the effectiveness of the heating system.

The standard central gas system (i.e. MSH1DHW1), at the bottom-left of Figure 9, shows that for around half of the time the indoor temperature in the living room is below the set-point, and for around three-quarters in the rest of the house; but that this is reduced to between a quarter and a third when filtered for occupied hours. The Figure shows that there is a period of over-heating applicable to all cases, in which the unoccupied period for the rest of the house approximates to a free-running period. Both gas and electric configurations present similar responses, although the differences between zones in the electric configurations are subtle, due to the relatively smaller areas these systems are typically installed in (see for example MSH7DHW8 at the middle right of the Figure). District heating configurations present a narrow differential of temperatures around the set-point, which can be explained by their operation, their efficiency and their ability to distribute heat on demand (see Sections 2.4 and 3.1).

[Figure 9 about here.]

4.1. Stock Analysis

Our estimated total annual energy demand for the English housing stock is 35.9 mtoe, where 85% is attributed to gas fuelled configurations. Figure 10 and Table 2 highlight the impacts of our modelled systems by comparing them as a function of the total dwelling floor area for housing archetypes derived by them. Those configurations with higher energy intensity lie at the top of the table; their intensity can be explained by relatively lower efficiencies and responsiveness. The conventional gas central heating configuration with wet radiators (i.e. MSH1DHW1) represents the major accumulated energy demand and carbon contribution.

[Table 2 about here.]

[Figure 10 about here.]

These results provide an indication of the indoor response to each heating system combination, and end-point heating devices' efficiency. The ranking by median carbon emissions in Figure 11 is also indicative of the responsiveness of the system, and of the prevalence of each configuration across the stock, keeping in mind that some systems have been replaced. We take some measure of confidence from the fact that our evaluations (of the baseline scenario) estimate a total energy demand that is within 9% of that reported value by Official UK Government statistics [2].

[Figure 11 about here.]

The results of the evaluation indicate that those configurations employing non-fossil fuels may not necessarily be suitable candidates for heating system substitution in terms of overall energy demand, unless these systems are substituted as part of a more holistic renovation treatment. In general (all things being equal), central heating systems with gas remain a reliable configuration, in terms of meeting household comfort requirements. This can be explained by their efficiency to deliver heat that has substantially improved over the years. Correspondingly, electric storage is less effective, due to its poor controllability, making this a rather undesirable choice in houses that are intermittently heated. District heating seems also to be a relatively effective configuration, although this in practice depends on local network availability. It is worth noting that the performance of the systems in practice may well differ, as heating behaviours may vary from our assumptions between systems. For example, through take-back, or as a relaxation of air temperature to compensate for higher indoor mean radiant temperature.

Finally, we have evaluated a scenario in which we replace the heating system in all of our archetypal models with either district heating or GSHP. The results, outlined in Figure 10, indicate energy intensity reductions of 35 and 97 $\mathrm{kW\,h/m^2}$, respectively, which translates to carbon reductions of 20% and 50%.

4.2. Discussion and Next Steps

The way thermal energy is transferred to/from the dwelling, and the effect that each configuration may have on indoor comfort may determine the decision to adopt an alternative technology. For example, the heat provided by a warm air configuration (highly convective), and the responsiveness of that provision, causes a different perception to that provided by a storage heater (highly radiative). This is also influenced by rates of infiltration and ventilation, and occupants' actions to regulate indoor conditions. In order to evaluate this, the consideration of location, orientation, and a more detailed layout than that provided by the EHS, is also necessary. Furthermore, reliably simulating envelope heat transfer also requires that occupants' behaviour be simulated, to encapsulate the effects of their interactions, and their corresponding thermal feedback. This is known to be a significant cause for deviations between observed and predicted energy demand.

Of course there is scope for further evaluation of indoor temperatures, supply temperatures and indoor comfort—this latter requiring more evidential data. Still, these indoor indicators significantly improve our evaluations because, in the future, they will allow us to link them with occupant's perceptions and their decisions to improve their houses, as opposed to purely statistical or deterministic steady-state approaches (e.g. BREDEM) that simplify their estimations to a snapshot of the energy use and expenditure; or that, perhaps more noticeably, employ referential efficiencies for each energy system, but are unable to characterise the implications that each technology brings about on (real and hypothetical) performances and substitutions.

Let us consider, for instance, our studied semi-detached dwelling. Here, the evaluated building assumes a similar performance to that which is adjacent to it, which in practice may not be the case. The fact that non-contiguous walls receive solar radiation at different times of the day, may affect the types of activities and related behaviours taking place indoors; this may particularly be the case for poorly insulated properties, in which heating practices are spatiotemporally inhomogeneous for reasons of affordability. The rigorous modelling of heating system configurations, as described in this paper, allows us in principle to evaluate such differences. But if we were to test a scenario involving substitution of the heating system, the predicted energy savings may not be realised in practice, due to the homeowners' choice to adopt higher mean indoor temperatures as a co-benefit. The representation of different processes of decision-making, both investment and operational, is essential in the investigation of strategies to reduce energy demand and associated carbon emissions. A strong candidate for studying this phenomenon is through multi-agent stochastic simulation [41]. In doing so, we need to enrich our archetypes to represent households in addition to housing.

5. Conclusion

HSEMs have hitherto employed simplified monthly or annual energy balances for the estimation of heating and hot water energy demand, combined with simplified fixed system efficiencies to transform these demands into delivered energy use and associated emissions. They have provided valuable support in the formulation of policy measures and strategies to reduce the carbon intensity of housing stocks. But these tools have some severe limitations that undermine their scope and the reliability of the evidence arising from them, upon which decisions may be made. In particular, these approaches cannot accommodate the simulation of: spatiotemporal indoor hygrothermal and associated comfort conditions; feedback between comfort and adaptive behaviours; inertial effects of heating systems; and system-fabric interactions. In a future that is destined to be warmer, and one in which well informed decisions are required to support the choice of systems that effectively balance the joint requirements of comfort and carbon emission reduction in cost effective ways, it is timely to resolve these shortfalls. This paper describes an extension to the new dynamic HSEM EnHub that was conceived to do just that.

This extension to EnHub rigorously simulates the range of configurations of space heating and hot-water systems, in the UK context, using `EnergyPlus`. In this way, we are now able to more accurately simulate housing stock carbon emissions and the achievement of indoor comfort, and how this is impacted on by the responsiveness of the simulated systems. We have demonstrated the application of this new capability through modelling a single semi-detached dwelling as well as the housing stock as a whole. Our findings indicate that, although the standard gas configuration may be particularly effective in delivering comfort, other less carbon-intense systems may be more attractive. For example, the (hypothetical) stock-wide substitution of systems to district heating and ground source heat pumps would deliver respectively 20% and 50% reductions in Carbon emissions. But this is somewhat unrealistic, and we intend to account for real world constraints to system substitution, and the interdependency of such choices with envelope renovation decisions, in our future work.

Our simulations estimate the national energy demand to be 35.9 mtoe, for this proof-of-principle demonstration. This is within 9% of the government benchmark [2]. However, this benchmark is itself based on (simplified) modelled data and is inherently uncertain due to simplified representations of periods of heating, temperature set-points and behavioural impacts. Nevertheless, we take confidence in the proximity between our simulation and this benchmark. Of equal, if not more importance to us, is the fidelity of our extended EnHub platform, which we believe provides a more rigorous evidence base to support the future formulation of decarbonisation policy measures.

Table 1: Matrix associating Main Space Heating (MSH) and Domestic How Water (DHW) technologies: values are the corresponding percentage of stock.

	DHW	Gas standard	Gas combi (storage)	Gas combi (instantaneous)	Gas back boiler	Oil standard	Solid boiler (coal/anthracite)	Biomass boiler	Electric boiler	Other electric	District heating without CHP	District heating with CHP
MSH	⌟	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Gas standard	**1**	55.27	-	0.31	0.03	-	0.06	0.02	1.55	0.30	0.08	-
Gas combi	**2**	-	18.72	0.01	-	-	-	-	0.02	0.04	-	-
Gas back boiler	**3**	0.03	-	0.02	7.95	-	-	-	0.14	-	-	-
Oil standard	**4**	-	-	-	-	3.77	0.01	-	0.10	0.01	-	-
Solid boiler (coal/anthracite)	**5**	-	-	0.03	-	0.02	0.63	0.02	0.18	0.01	-	-
Electric boiler	**6**	-	-	-	-	-	-	-	0.26	-	-	-
Electric storage	**7**	0.11	-	0.09	-	-	0.04	0.02	5.92	0.13	-	-
Electric room heater	**8**	0.06	-	0.06	-	-	-	0.01	1.37	0.08	0.02	-
Warm air gas fired	**9**	0.07	-	0.05	-	-	-	-	0.46	0.06	-	-
Warm air electric	**10**	-	-	-	-	-	-	-	0.06	-	-	-
District heating without CHP	**11**	-	-	0.01	-	-	-	-	0.17	0.01	1.45	0.03
District heating with CHP	**12**	-	-	-	-	-	-	-	0.01	-	0.02	0.05
Biomass boiler	**13**	-	-	-	-	-	-	-	-	-	-	-
GSHP	**14**	-	-	0.01	-	-	-	-	0.03	-	-	-
ASHP	**15**	-	-	-	-	-	-	-	0.01	-	-	-

Table 2: Energy demand and carbon contribution by floor area. (Note: Heating systems with negligible carbon contribution have been merged and replaced with district heating: MSH11DHW10.)

Heating & Hot-water Configuration	**Average Floor Area (Accumulated) [m2]**	**Accumulated Energy Demand [TWh]**	**Accumulated Carbon Emissions [mtCO2e]**	**Energy Intensity [kWh/m2]**
MSH5DHW6	81.5 (0.4%)	3.2 (0.8%)	0.8 (0.6%)	331.5
MSH4DHW8	106.4 (0.2%)	1.4 (0.3%)	0.3 (0.3%)	273.2
MSH6DHW8	46.3 (0.1%)	0.7 (0.2%)	0.4 (0.3%)	251.1
MSH1DHW3	121.3 (0.4%)	1.9 (0.5%)	0.6 (0.5%)	236.9
MSH3DHW4	99.3 (7.6%)	38.2 (9.1%)	11.2 (8.6%)	228.7
MSH9DHW8	62.9 (0.1%)	0.7 (0.2%)	0.3 (0.2%)	225.9
MSH1DHW8	89.2 (1.9%)	8.6 (2.1%)	3.0 (2.3%)	208.1
MSH4DHW5	147.8 (7.3%)	32.3 (7.7%)	7.4 (5.7%)	201.9
MSH1DHW1	98.4 (59.6%)	256.4 (61.3%)	77.5 (59.9%)	195.8
MSH4DHW6	274.9 (0.2%)	0.9 (0.2%)	0.2 (0.2%)	177.8
MSH2DHW2	88.9 (16.0%)	54.4 (13.0%)	17.4 (13.5%)	155.2
MSH7DHW8	64.0 (3.9%)	12.9 (3.1%)	7.6 (5.9%)	151.1
MSH8DHW8	72.7 (0.9%)	2.7 (0.7%)	1.6 (1.2%)	138.1
MSH11DHW10*	64.4 (1.3%)	3.7 (0.9%)	1.1 (0.8%)	131.7
		418.2	129.4	

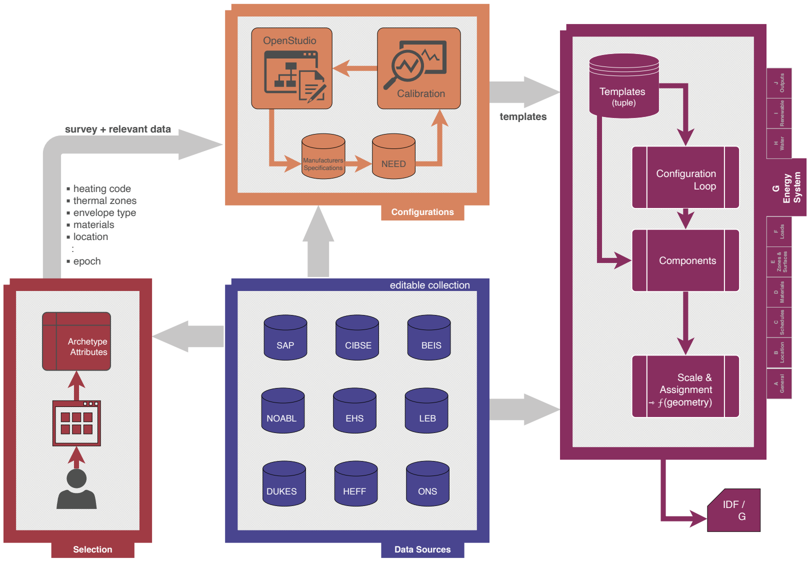

Figure 1: The energy system idf module

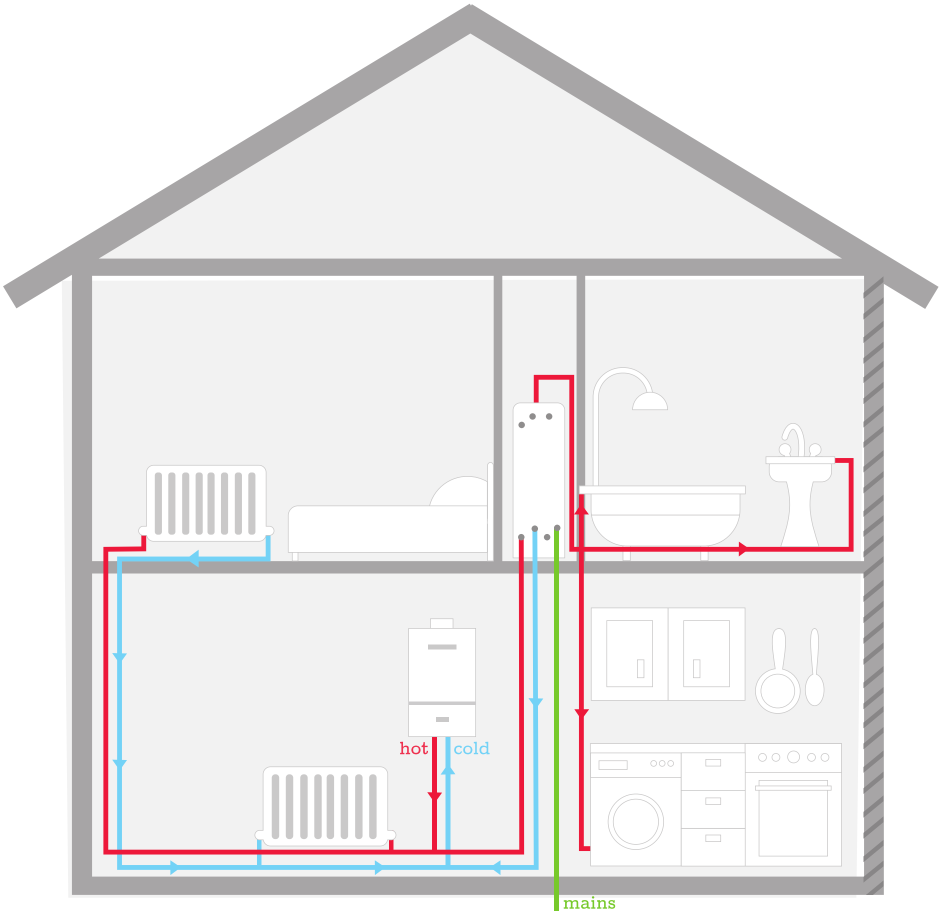

Figure 2: *Standard gas* central heating

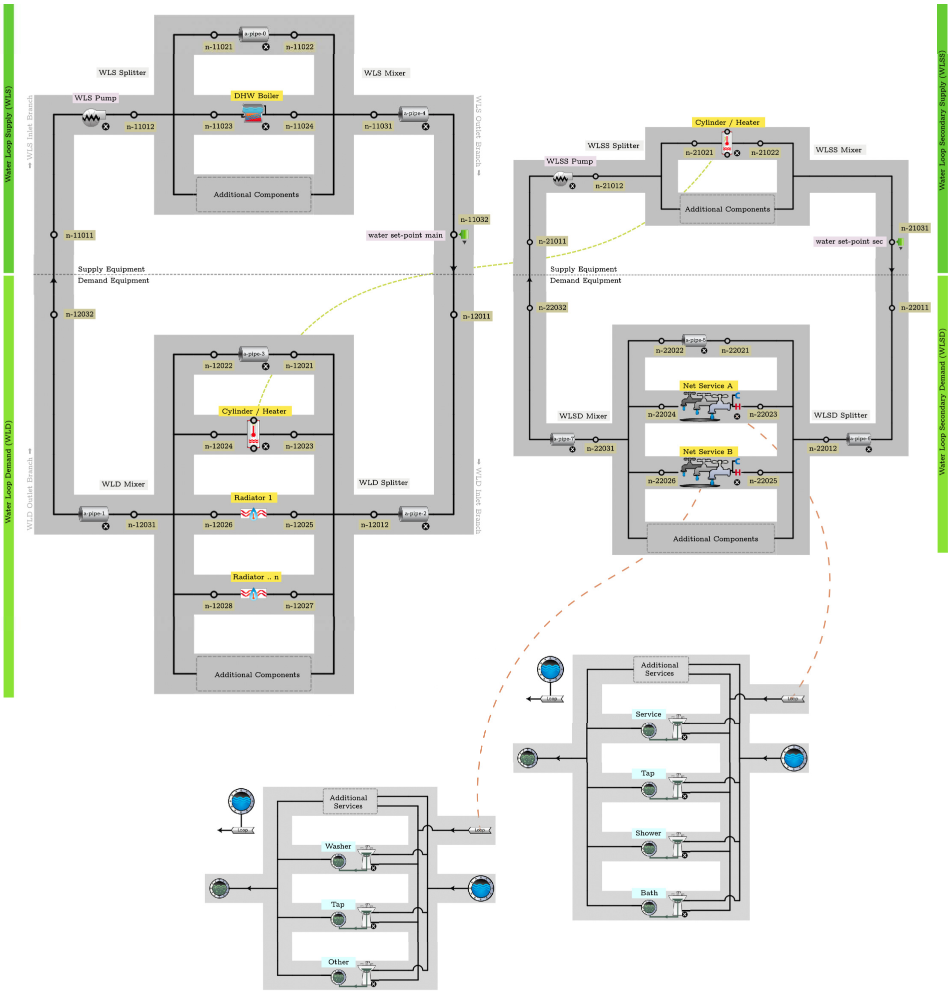

Figure 3: Implementation of a *standard gas* central heating configuration in EnHub, employing `OpenStudio`. The main configuration is shown on the top left diagram. This outlines how the DHW system is embedded, as well as how the arrangement of radiators is linked. In the DHW system, shown in the top right corner, two subsystems linked to the water cylinder are derived. The bottom diagrams show the corresponding water services on each floor.

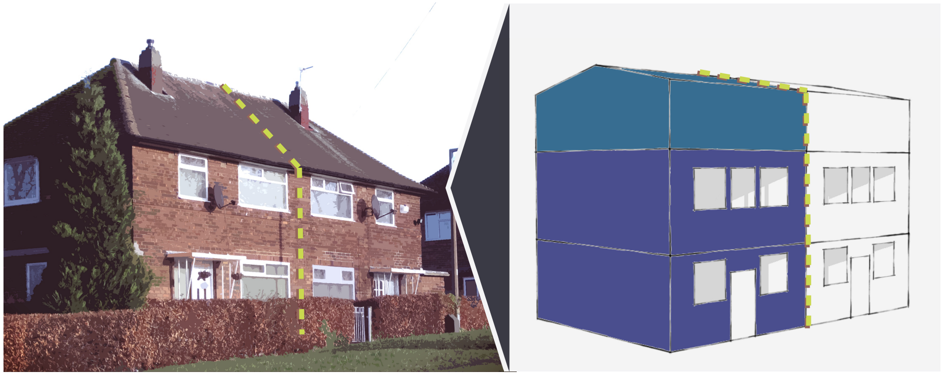

Figure 4: Abstraction of the *semi-detached* dwelling from the *post-war* epoch

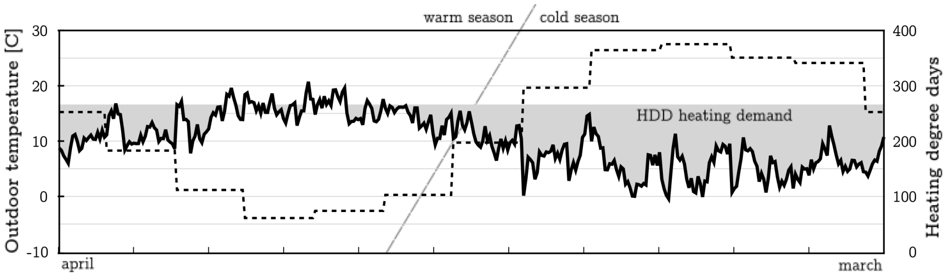

Figure 5: Monthly HDD estimation (in dotted lines), highlighting the season in which (artificial) space heating systems are expected to be active; base temperature at 17.2 °C

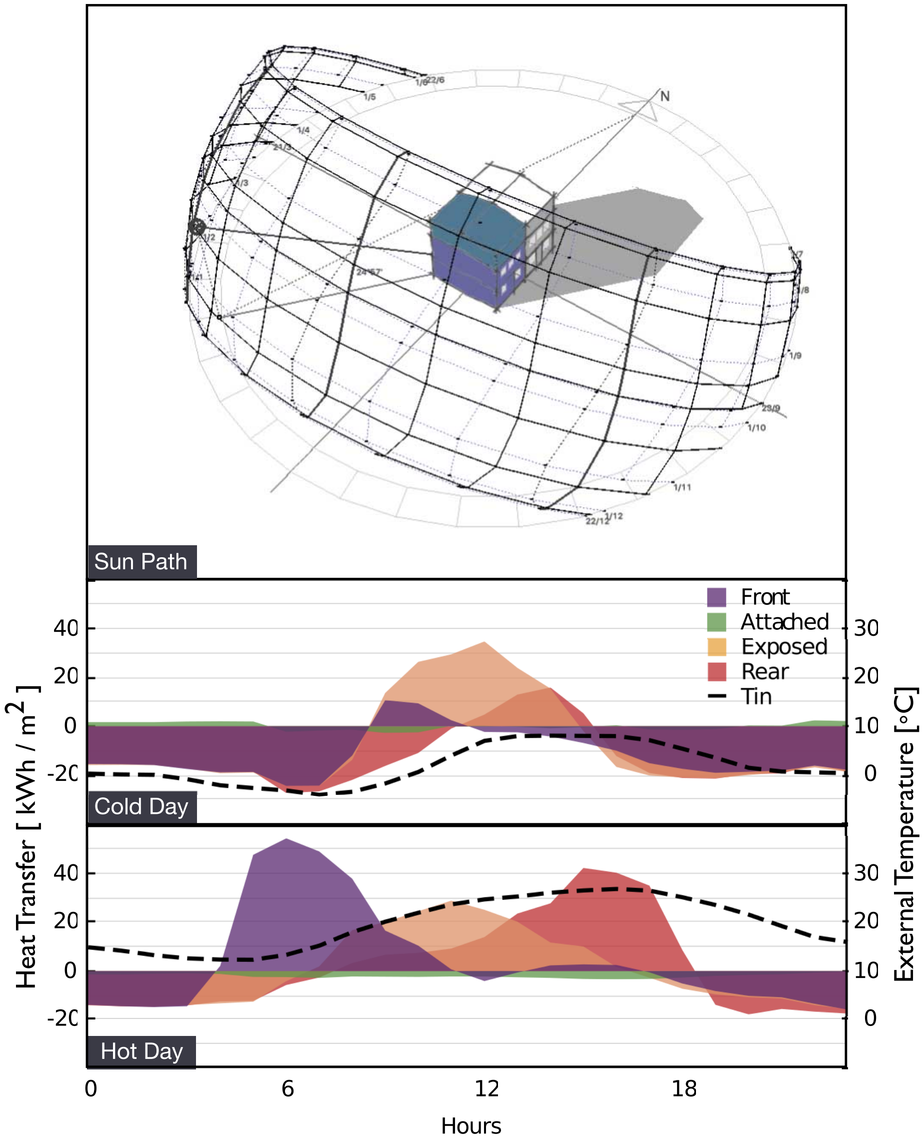

Figure 6: Thermal energy transfer: total heat flow (opaque and transparent), and external temperature

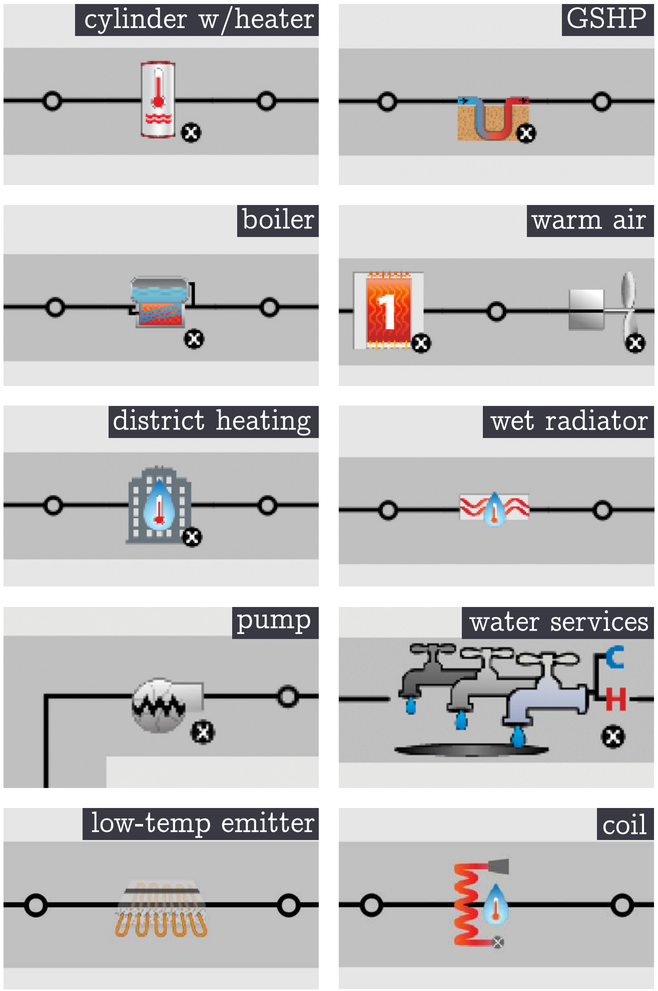

Figure 7: Example of heating components available in `OpenStudio`

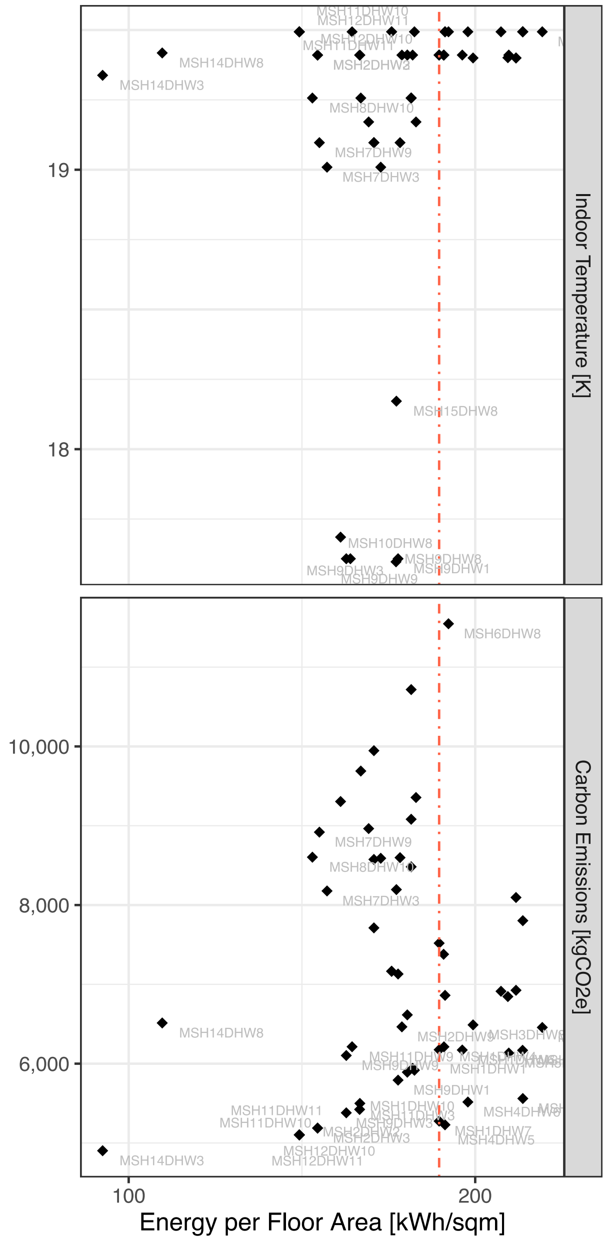

Figure 8: Resulting variation in energy demand intensity, indoor temperature and carbon emissions, for different heating configurations. The reference line (at 194 kWh/m2) corresponding to standard gas central heating (i.e. MSH1DHW1). See Table 1 to decode the space heating and hot-water configurations.

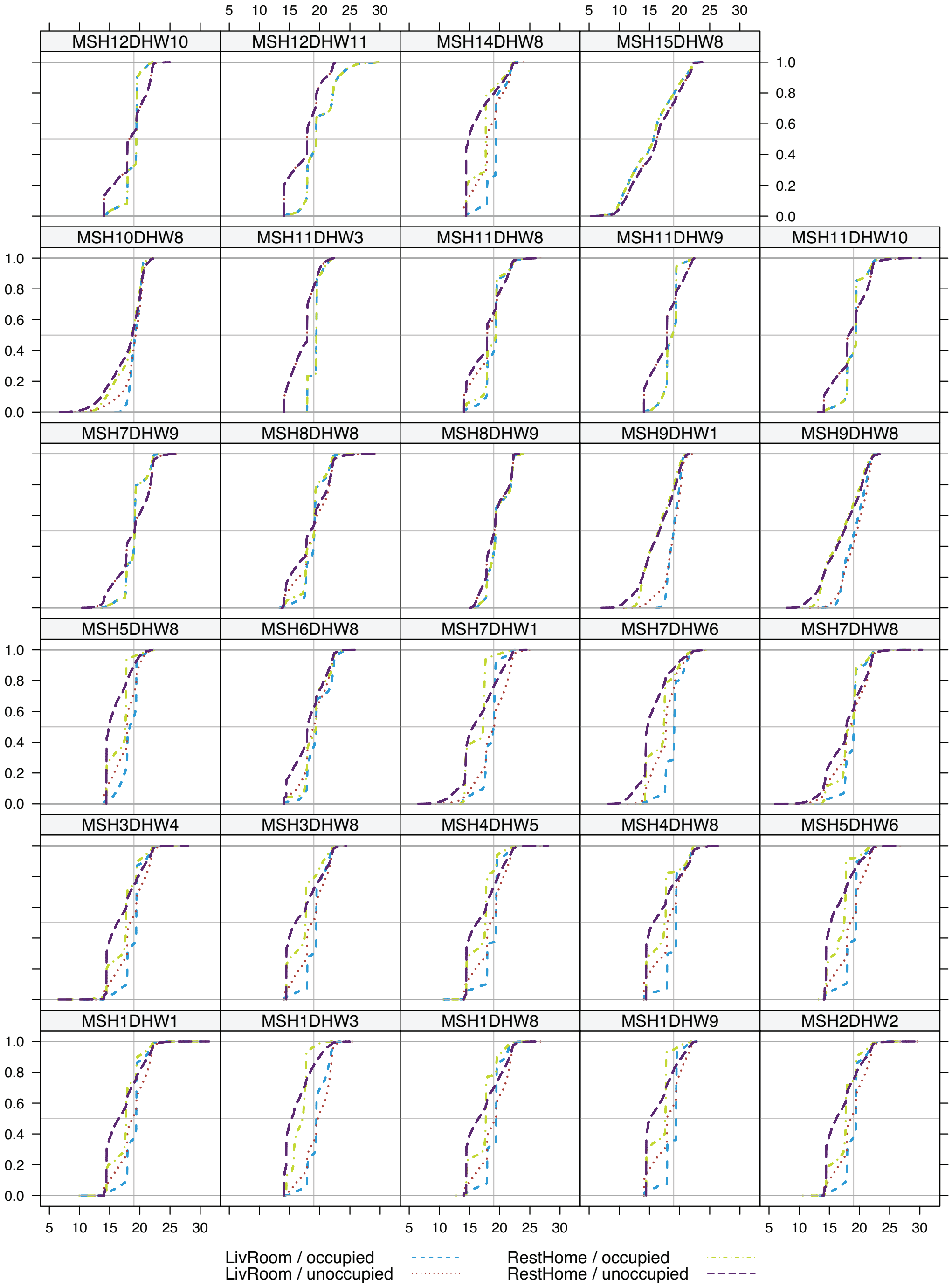

Figure 9: Cumulative distribution of temperatures between living and rest-of-dwelling zones, by heating configuration, distinguishing between occupied and unoccupied periods.

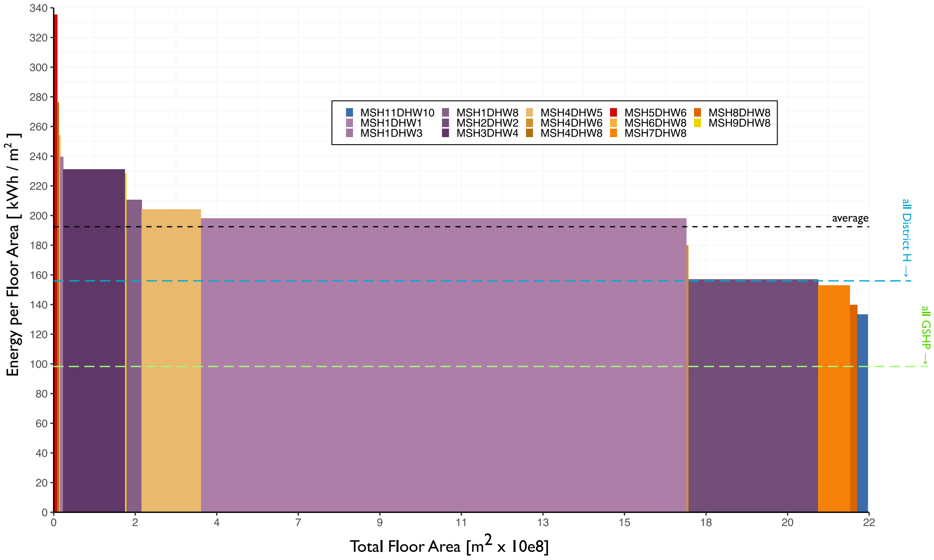

Figure 10: Energy demand by floor area intensity
Total floor area (→) x Energy intensity (↑) = Domestic sector energy demand (□).
The colours are indicative of the heating and hot-water configuration.

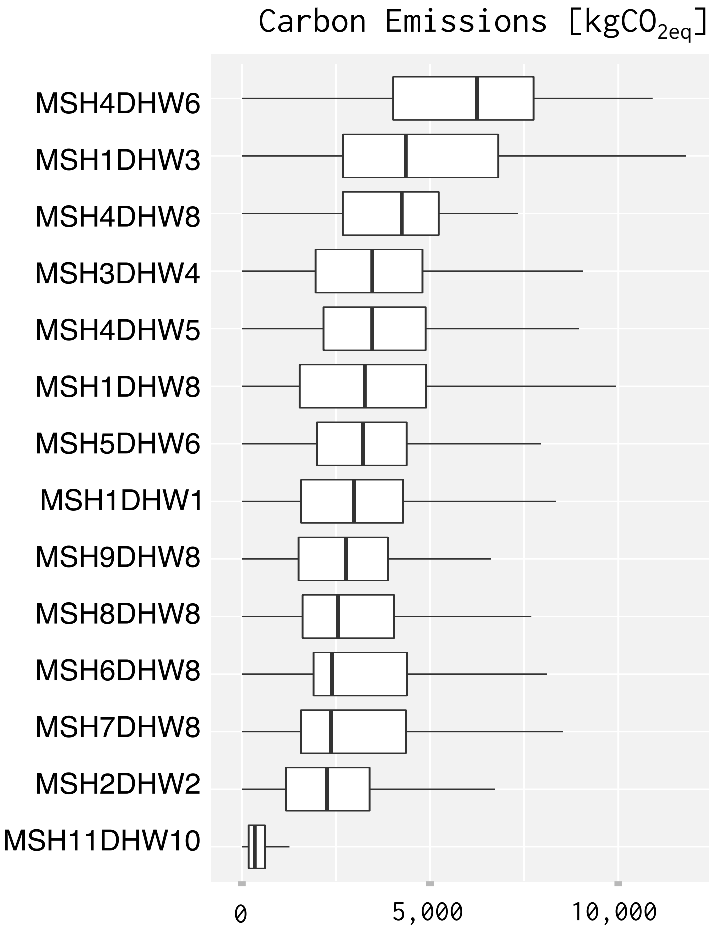

Figure 11: Average carbon contribution, by heating configuration

Abbreviations

ASHP Air Source Heat Pump

BREDEM Building Research Establishment Domestic Energy Model

CHM Cambridge Housing Model

DHW domestic hot water

EHS English Housing Survey

EnHub housing stock Energy Hub

GSHP Ground Source Heat Pump

GUI Graphical User Interface

HDD Heating Degree Day

HSEM Housing Stock Energy Model

idf EnergyPlus Input Data File

IEA International Energy Agency

LHS Latin Hypercube Sampling

NEED National Energy Efficiency Data-Framework

SAP Standard Assessment Procedure

SH space heating

UK United Kingdom

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