Models for Energy Characterisation of Current and Future Dwellings

Report for:
EP/I031707/1 - Transformation of the Top and Tail of Energy Networks
Work Package 2.1 Starting with Demand; 2.1.1 The New Demand
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Preface - Work Package 2.1 ‘The New Demand’

The scope of the activity within this work package is to provide information on the likely characteristics of heat and electricity use in the domestic sector moving towards 2050. With increasingly stringent energy performance legislation appearing all over Europe, the prospect of radical shifts in supplies (i.e. local micro-generation) and developments such as electric vehicles, the demands of both new and old buildings in the UK could look radically different from what we see today, where demand for heat predominates. Given that the domestic sector accounts for almost one third of UK delivered energy consumption (DECC, 2012a), a radical change in the characteristics of domestic energy demand could have profound implications for future energy networks.

To assist in envisioning how new demands may look at the level of the individual household and community, a bottom-up approach has been adopted within work package 2.1, using detailed simulation models of future buildings; these comprise a mathematical representation of the building geometry and fabric along with its key energy systems. The simulation of these models using real climate data, realistic occupancy data and load profiles as the boundary conditions provides a rich, high-resolution source of information regarding the likely disaggregated energy demands of a building. The type of data to be gleaned includes the time-varying heat demand, energy yields from different types of building-integrated microgeneration such as photovoltaics (PV), micro-combined heat and power (μ-CHP), small wind energy converters (SWECS), etc. The advantage of employing such a detailed modelling approach is that it allows users to make specific changes and observe the results, accounting for important interactions between the building and its energy subsystems.

The following report describes the dwelling and subsystem models developed as part of Work Package 2.1. These models were created using the well-established and heavily validated ESP-r building simulation tool\(^1\), which is maintained by a consortium of Universities and research groups worldwide. The nature and capabilities of ESP-r in relation to building modelling are also discussed.

\(^1\) The open source ESP-r tool can be freely downloaded from: [http://www.esru.strath.ac.uk/Programs/ESP-r.htm](http://www.esru.strath.ac.uk/Programs/ESP-r.htm)
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Overview
A previous Top and Tail report (Kelly and Tuohy, 2012) outlined the potential trajectory of energy performance in dwellings. This report looked at both the physical characteristics of the housing stock and its current and potential future energy performance. Additionally, the report highlighted some of the transformational changes that will impact on the energy performance of dwellings in the future; these are illustrated in Figure 1, which shows a possible progression from a predominantly fossil-fuelled domestic sector to a mainly electrically-powered domestic sector by 2050.

Figure 1: possible changing energy demands, fuel sources and transformational technologies in dwellings to 2050.

In order to characterise changing domestic energy performance, a series of detailed dwelling simulation models have been developed, using the report of Kelly and Tuohy (ibid) as a guide; these models feature increasing levels of energy efficiency and increased use of local heat and power sources. The specific dwelling types modelled are 1) a 4-person detached dwelling and 2) a 2/3-person flat. Together, these dwelling types account for some 44% of the UK housing stock (Palmer and Cooper, 2011). Further, the performance of these two types effectively brackets the performance of the rest of the housing stock.

The characteristics of the models developed and their capabilities are described in detail in the following sections.

Performance Simulation Using ESP-r
Before reviewing the details of the dwelling models, it is necessary to quickly review the characteristics and capabilities of the ESP-r simulation tool, as these dictate the characteristics of the building models described later in the report.
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ESP-r Building Simulation Tool

Within ESP-r (Clarke, 2001), a physical description of a building (i.e. its geometry, construction materials, systems, fluid transport paths, etc.) is decomposed into ‘zones’ and ‘networks’ (both described below). As will be seen later, a model comprising only of zones can be used to provide basic information on the thermal performance of a building; augmenting this basic, zone-based model with networks can provide more detailed information on the performance of energy sub-systems within the building such as the heating system or the electrical system.

Zones are used to describe the geometry and fabric of the building and typically represent a room or, more abstractly, a can represent a group of thermodynamically similar spaces within a building. A zonal representation of a building is shown in Figure 2. The simulation of a zone-based building model along with information on occupancy, hourly climate data and control settings (i.e. heating set point) provides basic information on its heating or cooling requirements accounting for the influence of climate, heat gains from occupants and equipment and thermal dynamics associated with the building fabric.

![Figure 2: zonal representation of a dwelling (exploded view).](image)

Networks within ESP-r are used to augment the basic, zonal information of a model and enable detailed performance of the air movement within the building or the building’s HVAC or electrical system to be simulated. In ESP-r, a network typically comprises a series of connected components, where a component described a physical entity such as a pump or piece of piping. The connections describe the topology of the system. Within the context of Top and Tail, each building model is equipped with a network model describing the building’s heating and hot water system along with a network to track the electrical power flows. Figure 3 shows a representation of a buffered, hydronic heating system network model, supplied from a heat pump that was employed in this study. The network approach to modelling of building systems (and energy systems more generally) is very

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2 Heating, ventilation and air conditioning
common in building simulation, with well-known tools such as TRNSYS\textsuperscript{3} and EnergyPlus\textsuperscript{4} employing the same method.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{buffered_hydraulic_network_model.png}
\caption{schematic of a buffered hydronic heating system network model, showing the components and their interconnections.}
\end{figure}

In turn, zones and networks can be decomposed into thousands of ‘control volumes’. In this context, a control volume is a specific region of the building (such as a wall, window, floor, enclosed air space) to which conservation equations for continuity, energy (thermal and electrical) and species can be applied and one or more characteristic equations energy and mass balance formed. The same approach can be used to decompose networks describing any one of the buildings energy sub systems (air flow, HVAC, electrical, moisture). So, a control volume could represent entities as disparate as a section of hot water pipe to a volume of moisture-saturated building fabric. A typical building model will contain thousands of such volumes, with sets of equations extracted and grouped according to energy system. The solution of these equations sets with real time series climate data, coupled with control and occupancy-related boundary conditions yields the dynamic evolution of temperature, energy and fluid flows within the building and its supporting sub-systems.

The theoretical basis of the ESP-r simulation tool and its capabilities are comprehensively described elsewhere e.g. (Clarke, 2001). The extensive validation of the ESP-r tool is described by Strachan et al. (2008).

\textbf{Space Heating Demand with Zonal Models}

ESP-r was originally developed as a means to assess the thermal performance of buildings and a basic ESP-r zonal model can therefore be used to calculate the heating or cooling requirements of dwellings at different levels of resolution. The heating or cooling demand is calculated taking

\textsuperscript{3} http://www.trnsys.com/
\textsuperscript{4} http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm
account of thermal excitations including solar gain, external temperature, infiltration of outside air, passive heat gains from occupants and equipment. The simulation output takes the form of time series temperatures and heat and mass exchanges (calculated for each control volume in the model), which explicitly account for the noted excitations, the thermal inertia of the building fabric and user defined systems control settings (e.g. room heating thermostat set points).

The calculated heating or cooling demand represents the heat that needs to be supplied to or extracted from a specific zone within the model (within user defined capacity limits) in order to obtain the user-defined set-point conditions. As an illustration, Figure 4 shows the heat demand of a space within a detached house, the mean air temperature, occupancy-related heat gains and solar gains. Notice how the demand varies with both solar gain and internal gains from people and equipment. Also as there is no cooling specified in this case, so the temperature of the space can be driven above the set-point by internal heat gains.

![Figure 4: temperature and heat demand of a space within a dwelling subject to dynamic excitations.](image)

For Top and Tail, several zon-based models (described later) have been developed, representing different dwelling types and thermal performance levels between the present and 2050.

**Networks to Augment Zonal Building Models**

Whilst profiles of the type shown in Figure 4 illustrate the time-varying heating or cooling demand (as this report deals with UK housing, hereafter this report will deal only with heating), it does not give an indication of hot-water-related energy use, nor the heating system’s primary energy consumption. In order to do this, a zone-based model needs to be augmented with a systems network to represent the space heating and hot water system. The systems network incorporates component algorithms describing the energy conversion technologies (e.g. boilers, micro-CHP), heating distribution components (e.g. piping, ducting), heat emission components (e.g. radiators, heating coils) and control (actuators, controllers and sensors). The advantage of this more detailed approach is that the various models in the network enable the calculation of the primary energy consumption along with parasitic losses from the heat distribution. Figures 5a and b show the same time period as Figure 4, only the heat to the space is now supplied by a hot water heating system, with the boiler subject to on/off cycling. The latter model provides a more realistic representation of how controlled temperatures vary within the space, based upon a more detailed depiction of systems operation. Figure 5b illustrates how the detailed model can also provide information on the hot water system performance.
Hot Water Demand

Proper assessment of the hot water demand for a dwelling, and particularly its impact on the performance of the building’s heating system requires an explicit heating system model as outlined previously along with an algorithm for the calculation of the of the hot water draws (from either a hot water tank or directly from the hot water system). These draws tend to be of short duration and highly variable in both time-of-draw and the draw flow rate, reducing the hot water storage temperatures over short periods of time and cause heating sources such as boilers to operate in order to recover the hot water storage set point temperature or meet instantaneous demand (where there is no storage). To represent these draws, ESP-r is equipped with a high-resolution stochastic model of domestic hot water demand (based on a validated model developed by Jorden and Vagen [2005]), which can be integrated with a heating system network model (as shown in Figure 4); this is used to produce time series hot water draw data at resolutions of 1-minute to an hour. Figure 6 shows a typical draw profile from the model for a family of 4; the model can be calibrated to accommodate different numbers of end users and different levels of hot water usage.
Calculating Electrical Generation

ESP-r is equipped with a range of microgeneration models that can be employed either as components within a systems model (micro combined heat and power (μ-CHP), fuel cells) or as elements of the zonal building model (building integrated PV). These components can generate time-series electrical data at resolutions of 1-minute to an hour, accounting for interactions with (for example) other elements within an HVAC system (in the case of μ-CHP) or building fabric (in the case of PV).

Building-integrated PV’s electrical output is dependent upon the solar radiation incident upon the PV surface (surface insolation is routinely calculated by ESP-r) and the calculated PV surface temperature, again routinely calculated as part of the building simulation process (Clarke and Kelly, 1999).

Fuel cell or combustion μ-CHP technologies are integrated as a standard components within a systems model. Ferguson and Kelly, (2006) and Beausoleil Morrison (2008) describe the calibration and verification of such models. The component algorithm accounts for the heat recovery from the combustion or electrochemical process (in the form of low pressure hot water) and also calculates the time-varying real electrical power output of the device (e.g. Figure 7), which is typically subject to thermal constraints and control action.
Calculating Electrical Demand

ESP-r is already able to calculate the time-varying electrical demand associated with lighting along with that of so-called ‘HVAC loads’ such as fans and pumps. These power consumptions are linked to the environmental performance of the host building and are influenced by external excitations such as outdoor air temperature, and the control settings employed within the simulation such as temperature and illumination set points. Typically, the real power demand is expressed as a function of the delivered service e.g. for lighting, the power demand is a function the lighting lumen output, whilst for a fan the power demand is a function the fluid flow throughput.

Non-HVAC Electrical Demand

There are different means within ESP-r to model the electrical demand of appliances. The simplest approach is to define a time series profile of heat gains from equipment on a zone-by zone basis, the electrical demand can then be calculated as a fixed fraction of this heat gain; consequently, the electrical demand and thermal impact of that demand on the requirement for heat are temporally consistent. The disadvantage of this approach is that the default time resolution of such profiles is hourly; this level of resolution is too coarse for the production of realistic electrical demand profiles, giving a false impression of variability and underestimating peak demands.

An alternative approach, which was employed with the models described here, was to create temporally-consistent, high resolution electrical and thermal demand profiles for appliances, using 3rd party software, and to import these into the ESP-r model. To this end, an electrical profile generation tool developed by Richardson et al (2010), which produces electrical appliance and lighting demand profiles at 1-minute resolution (Figure 8) was modified to: firstly, produce both thermal and electrical demand profiles that were temporally consistent; second, attribute the calculated thermal demand to nominated thermal zones; and thirdly, produce 365 individual day profiles covering a calendar year. Both the thermal and electrical profiles could then be read in to an ESP-r model during a simulation and used as boundary conditions for the solution process.

Figure 8: a typical example of an electrical demand profile (and corresponding thermal gain profile) generated using the modified tool.

The electrical demand profile of Figure 8 can be combined with the electrical output of the CHP device of Figure 7 along with (in this example) roof mounted PV output to produce the aggregate electrical profile for a dwelling as shown in Figure 9.
Model Details

The combination of ESP-r’s intrinsic thermal and electrical modelling capabilities along with the additional capabilities of the modified model of Richardson et al. (2010) enables a complete, temporally consistent picture of domestic energy performance to be extracted from simulation of the models described in the following sections. As mentioned previously, the function of these models is to produce data illustrating the possible energy performance of dwellings between now and 2050.

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fabric</td>
</tr>
<tr>
<td>Contemporary detached house</td>
<td>Current average</td>
</tr>
<tr>
<td>Contemporary flat</td>
<td>Current average</td>
</tr>
<tr>
<td>Retrofit house mid-2020’s</td>
<td>Improved ASHP or μCHP</td>
</tr>
<tr>
<td>Retrofit flat mid 2020’s</td>
<td>Improved ASHP or microCHP</td>
</tr>
<tr>
<td>New detached house c. 2050</td>
<td>Passive house levels</td>
</tr>
<tr>
<td>New flat c. 2050</td>
<td>Passive house levels</td>
</tr>
</tbody>
</table>

Table 1 characteristics of ESP-r dwelling variants used in Top and Tail.

The range of model variants developed for Top and Tail and their characteristics are summarised in Table 1. These models incorporate the transformational energy technologies illustrated in Figure 1 and their simulation will produce energy demand (and microgeneration production) time series data for a range of energy efficient dwellings representing the present day though to envisaged newbuild future zero-energy housing in 2050 via an intermediate stage (mid-2020’s). These models envisage
improvements to the existing housing stock and the retrofitting of more energy efficient heating sources. The core of an ESP-r zonal model is a description of the building geometry (subdivided into building zones), fabric elements, details of occupancy and air leakage. For the models shown in Table 1 the building geometry is broadly the same – changes to the dwelling fabric and systems provide the main differentiation between the variants.

**Geometry**

The detached dwelling model is shown in Figure 9a and the flat in Figure 9b and the basic model geometrical information is given in Table 2. The floor areas and volumes used are characteristic of ‘typical’ UK housing and were selected following extensive reviews of housing stock characteristics undertaken for a number of projects (e.g. Kelly and Beyer, 2008). Note that the geometric characteristics of the 2050 detached dwelling differ from the other variants in that the dwelling is equipped with a mono pitch roof in order to accommodate enough PV to offset the its annual energy requirements.

![Figure 9a: detached dwelling model (with rooftop-mounted PV array).](image)

![Figure 9b: mid-level flat model with sunspace.](image)

**Zoning**

The detached dwelling model is divided three main thermal zones: a loft zone and two composite zones describing (respectively) the areas of the dwelling hosting active occupancy such as the living room and kitchen and those areas that have low occupancy rates or that are occupied at night such as bathrooms and bedrooms, respectively. The flat model is similar but without the loft zone. This geometrically aggregated form of model captures the pertinent thermodynamic characteristics of the building’s performance and has been deployed successfully in other studies, e.g. (Clarke et al, 2008).
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Table 2: general geometric characteristics of dwelling models.

<table>
<thead>
<tr>
<th></th>
<th>Flat</th>
<th>Detached Dwelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area (m²)</td>
<td>60.3</td>
<td>82.7</td>
</tr>
<tr>
<td>External surface area (m²)</td>
<td>41.5</td>
<td>151</td>
</tr>
<tr>
<td>Occupied Volume (m³)</td>
<td>151</td>
<td>230</td>
</tr>
<tr>
<td>Glazed Area (m²)</td>
<td>7.52</td>
<td>21.45</td>
</tr>
<tr>
<td>‘Day’ zone floor area (m²)</td>
<td>21.8</td>
<td>34.8</td>
</tr>
<tr>
<td>‘Night’ zone floor area (m²)</td>
<td>38.5</td>
<td>47.9</td>
</tr>
</tbody>
</table>

Fabric and Ventilation Characteristics

The characteristics of the key fabric elements (constructions) are as shown in Table 3. Note, that the developed constructions are common to both the detached and flat dwelling types.

<table>
<thead>
<tr>
<th>Fabric Element</th>
<th>Materials summary</th>
<th>‘U’-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contemporary dwellings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External walls</td>
<td>Brick air 60mm insulation concrete block air plasterboard 320mm</td>
<td>0.435</td>
</tr>
<tr>
<td>Floor</td>
<td>Concrete slab with void and carpet over plywood</td>
<td>0.700</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Plasterboard with 200mm glass wool 220mm</td>
<td>0.190</td>
</tr>
<tr>
<td>Roofing</td>
<td>Slate roof over battens (cold roof)</td>
<td>3.636</td>
</tr>
<tr>
<td>Glazing</td>
<td>6mm glass 12mm air 6mm glass air filled not coated 24mm</td>
<td>2.811</td>
</tr>
<tr>
<td>Retrofit 2020’s dwellings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External walls</td>
<td>Brick air 100mm insulation concrete block air plasterboard 360mm overall</td>
<td>0.303</td>
</tr>
<tr>
<td>Floor</td>
<td>Concrete slab with insulated void (100mm) and carpet over plywood</td>
<td>0.242</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Plasterboard with 300mm glass wool 320mm</td>
<td>0.129</td>
</tr>
<tr>
<td>Roofing</td>
<td>Slate roof over battens (cold roof)</td>
<td>3.636</td>
</tr>
<tr>
<td>Glazing</td>
<td>Triple glazing air filled and not coated 42mm overall</td>
<td>1.897</td>
</tr>
<tr>
<td>Zero Carbon dwellings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External walls</td>
<td>Weatherboard air SIP panel with 300mm insulation service void plasterboard 484mm</td>
<td>0.104</td>
</tr>
<tr>
<td>Floor</td>
<td>200mm insulation under concrete slab with void and carpet over plywood</td>
<td>0.151</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Plasterboard with 400mm glass wool 420mm</td>
<td>0.098</td>
</tr>
<tr>
<td>Roofing</td>
<td>Slate roof over battens (cold roof)</td>
<td>3.636</td>
</tr>
<tr>
<td>Glazing</td>
<td>Triple glazing argon filled low-e coatings 42mm</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Table 3 characteristics of the constructions used in both the detached and dwelling models.
Systems Characteristics

The following sections detail the main characteristics of the systems sub-models deployed within each of the building model variants. The systems topology is similar when deployed in each of the two main building types, any significant differences (i.e. in terms of capacity are noted).

Conventional Heating System Model for Contemporary Building

Based on the work undertaken in a previous Top and Tail report reviewing the characteristic of contemporary housing and looking forward to how these could change in the future (Kelly et al, 2012), the conventional detached dwelling and flat model are equipped with a, boiler-fuelled, hydronic heating system i.e. where the boiler supplies low pressure hot water to radiators and a dedicated hot water tank as shown in Figure 10.

Figure 10: topology of hot water heating system in the conventional dwelling and flat models.

The characteristics of the main components are detailed in Table 4a.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>The boiler has a capacity of 18kW at full load and is configured to supply hot water at 80°C; the design return temperature is 70°C.</td>
</tr>
<tr>
<td>Water Tank</td>
<td>The water tank has a capacity of 200L for the detached dwelling and 120L for the 2 person flat.</td>
</tr>
<tr>
<td>Radiators</td>
<td>The radiators for the dwelling are represented by two aggregate devices serving the living day and night spaces of the dwellings.</td>
</tr>
<tr>
<td>Water pump</td>
<td>The water pump operates when the boiler is active supplying a flow rate of 0.4kg/s giving a temperature difference of approximately 10°C across the boiler.</td>
</tr>
<tr>
<td>3-port valve</td>
<td>The 3-port valve is controlled in order to give priority to the hot water tank when it is below set point temperature.</td>
</tr>
</tbody>
</table>

Table 4a: characteristics of the main constituents in the conventional heating sub-model.

The control strategy employed with the system can be generally labelled as ‘hot water priority’, where the firing of the boiler is controlled based on both the temperature of the living space zone in the model and the temperature of the hot water tank, set point details are shown in Table 4b, which
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provides details of the different control regimes operating in the heating system. If the temperature of either the zone or the hot water tank is too low then the boiler fires to bring them to temperature. If the temperature of both is too low then the 3-port valve diverts all of the flow to the hot water tank until its temperature set-point is obtained, once this is achieved flow is diverted back to the radiators – this approach is commonly employed in UK domestic heating systems.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler temperature control</td>
<td>Boiler fires ‘on’ or ‘off’ depending upon temperature of living zone which is maintained between 19 and 21°C, and the hot water tank controlled between 50 and 60°C limits. For either control, the boiler will be on until the upper limit is reached and then remain inoperative until the sensed temperature falls back to the lower temperature limit.</td>
</tr>
<tr>
<td>Boiler time control</td>
<td>The default operating time for the boiler is 0700-0900hrs and 1700-2300hrs; which assumes intermittent occupancy of the dwelling.</td>
</tr>
<tr>
<td>3-port valve</td>
<td>The three port valve diverts all flow to the hot water tank of this is below 60°C, flow is restored to the radiator circuit when this is achieved.</td>
</tr>
</tbody>
</table>

Table 4b: control regimes operating in the heating system model.

Additionally, the detached dwelling is equipped with a roof-mounted PV array of 15 panels with a peak capacity of 3.7kW - typical of a PV installation in the UK (OFGEM, 2013). The roof of the dwelling has a pitch of 35°.

Microgeneration-based Heating System Models (used in mid2020’s retrofit models)
The microgeneration-based heating systems models are integrated with the mid-2020’s, retrofit dwelling models; here the conventional gas boiler has been replaced with either an air source heat pump (ASHP) or a gas-engine-based micro CHP unit (details in Table 5a). The heat is still supplied to the dwellings via a hydronic heating distribution system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>micro-CHP</td>
<td>The gas-powered CHP unit has a nominal power output of 2kWe and 5.6kW thermal; the nominal efficiency is 85% (Ribberink and Entchev, 2013); the unit can be controlled either in on/off mode or can be modulated to follow the thermal demand.</td>
</tr>
<tr>
<td>ASHP</td>
<td>The air source heat pump has a peak thermal output of 6kW and a nominal COP of 3.0, the maximum supply temperature of supply from the device is approximately 65°C.</td>
</tr>
</tbody>
</table>

Table 5a: characteristic of the heat sources used to replace the boiler in the mid-2020’s models.

The basic topology of the heating system is the same as that shown in Figure 8; with the boiler replaced by either a μ-CHP device or an air source heat pump. The size of ASHP/micro-CHP units installed here is more than adequate to satisfy the heating demand of the mid-2020’s retrofit dwelling.

The μ-CHP device is described in more detail in (Kelly and Beausoleil Morrison, 2008), whilst the ASHP model is described in (Kelly and Cockroft, 2010).

The control characteristics of the system incorporating the ASHP need to be adapted to accommodate the lower water temperature output of this type of device as shown in Table 5b.
Controller | Description
--- | ---
ASHP temperature control | ASHP operates depending upon temperature of living zone which is maintained between 19 and 21°C, and the hot water tank controlled between 45 and 55°C limits. For either control, the ASHP will operate as per the boiler in Table 5a.
Boiler time control | The default operating time for the boiler is 0600-0900hrs and 1600-2300hrs; which assumes intermittent occupancy of the dwelling (the pre-heat time of the ASHP is extended to allow for lower temperature output).
3-port valve | The three port valve diverts all flow to the hot water tank of this is below 55°C, control strategy is as per the boiler.

Table 5b: control regimes operating in the heating system model featuring the ASHP.

Low Carbon Heating System Models
The systems models used with the envisaged 2050 dwelling, shown in Figure 11, are radically different to those shown in Figure 8. Heat distribution is convective, via a mechanical ventilation heat recovery system (MVHR); such systems are already being employed in so-called Passive House designs. The heat source for the system is an air source heat pump; this is used in conjunction with a thermal buffer, which allows the heat pump to be operated flexibly. The role of the heat pump is to charge the thermal buffer. Heat for space heating and water heating is supplied via a hot water pump, which draws heat from the buffer tank; this supplies hot water to a heating coil in the MVHR system for space heating and a coil in the hot water tank for water heating.

The 2050 model also includes solar water heating, which supplies the hot water tank and a grey water heat recovery system (GWHR); this collects waste water from the baths, showers etc., which is used to pre-heat the incoming cold-feed to the hot water tank via a heat exchanger.

![Figure 11: low carbon heating system featuring heat pump, MVHR, solar thermal collectors and grey water heat recovery.](image-url)
Climate Data

Typically, ESP-r is used with climate data files that hold hourly readings of solar radiation, temperature, wind speed and wind direction. Such climate files (so-called test reference years) are available for a wide variety of locations around the globe (Crawley et al, 1999). However, when analysing the performance of solar-dependent microgeneration such as PV, hourly solar data can give a misleading indication of the power output characteristics in that the use of the hourly solar data generates artificially smooth electrical output, which exhibits little of the characteristic variability seen in practice (e.g. Richardson and Thomson, 2011). To rectify this situation, high-resolution, synthetic solar data has been created for the Top and Tail models, which uses the hourly solar data as a starting point and the applies a technique based on a 1st order Markov chain (Richardson and Thomson, 2011) to generate data at 1-minute resolution. The resulting data has been compared to real high resolution solar data and exhibits similar variability (McCracken, 2011). Figure 12 shows an example of hourly and stochastically generated minutely data for a spring day.

Figure 12: Hourly and stochastically generated 1-minute solar data.

To climate data sets are available for use with the Top and Tail models: a UK Northern exemplar – using data from Dundee and a UK Southern exemplar using data from Gatwick; used together these climate sets provide a useful spread of climatic conditions against which to assess the performance of future dwellings. The general characteristics of the climate sets are shown in Tables 6a and 6b.

<table>
<thead>
<tr>
<th></th>
<th>Air Temperature (°C)</th>
<th>Direct Normal Radiation (W/m²)</th>
<th>Diffuse Horizontal Radiation (W/m²)</th>
<th>Wind Speed m/s</th>
<th>Wind Direction (0° – North)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>8.5</td>
<td>95.5</td>
<td>63.1</td>
<td>5.2</td>
<td>198.9</td>
<td>80.3</td>
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<tr>
<td>Max</td>
<td>24.0</td>
<td>996.0</td>
<td>403.0</td>
<td>19.7</td>
<td>n/a</td>
<td>100.0</td>
</tr>
<tr>
<td>Min</td>
<td>-6.1</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>n/a</td>
<td>35</td>
</tr>
</tbody>
</table>

Mean Horizontal Solar Flux (W/m²) 105.0
Annual Horizontal Insolation (kWh) 919.7

Table 6a: characteristics of ‘warm’ climate set.
Table 6b: characteristics of cooler climate set.

<table>
<thead>
<tr>
<th></th>
<th>Mean Horizontal Solar Flux (W/m²)</th>
<th>Annual Horizontal Insolation (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Temperature (°C)</strong></td>
<td>108.2</td>
<td>947.7</td>
</tr>
<tr>
<td><strong>Direct Normal Radiation (W/m²)</strong></td>
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<td>-</td>
</tr>
<tr>
<td><strong>Diffuse Horizontal Radiation (W/m²)</strong></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Wind Speed m/s</strong></td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td><strong>Wind Direction (0° – North)</strong></td>
<td>171.6</td>
<td>360.0</td>
</tr>
<tr>
<td><strong>Relative Humidity (%)</strong></td>
<td>79.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

## Conclusions

A set of detailed building simulation models have been developed, which can be used to characterise the change in energy performance of the UK housing stock up to 2050.

The model types bracket the range of dwellings seen in the UK – these are a large detached dwelling and a smaller flat. Together, these two dwelling types comprise some 44% of the UK housing stock.

Six variants have been developed (details given in Table 1) representing a contemporary flat and detached house, potential mid-2020’s flat and detached house and potential 2050 flat and detached house. The building fabric and energy systems in these models change to represent a steady improvement in energy performance and a shift towards all-electric energy systems.

The improvements in fabric energy performance occur due to improved insulation of external surfaces, the use of triple glazing and drastic improvement in air tightness. The range of energy efficient systems incorporated within the models include PV rooftop arrays, solar thermal collectors, heat pumps, μ-CHP, thermal buffering, grey water heat recovery and electric vehicle charging.

The models have been developed such they can produce thermal and electrical demand data at a high level of temporal resolution. To facilitate this, consistent appliance electrical demand and heat gain profiles have been created for each of the model variants along with high resolution solar data for a Southern and Northern UK climate.

The models can be used to generate a broad range of data particularly, heat demand profiles; heat and power profiles for microgeneration technologies such as PV and heat pumps respectively; and aggregate electrical demand profiles. Profiles can be generated for a user-defined period ranging from a single day through to a year and for time resolutions ranging from an hour down to one minute.

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References


