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Dynamic Simulation tool for building energy performance assessment and improvement

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Abstract

The UK's net zero target commits the country to all but eliminate greenhouse gas emissions by 2050 relative to 1990 levels (HM GOVERNMENT, 2008). To achieve this, it will be necessary to drastically reduce emissions arising from provision of domestic heating and hot water, a sector that accounted for circa 15% of UK CO_2 emissions in 2019 (Committee on Climate Change, 2018).

The Energy Systems Catapult (ESC) has developed Home Energy Dynamics (HED), a detailed dynamic domestic modelling simulation tool-kit built in Dymola® to identify feasible combinations of improvements to a building's fabric, heating system and controls, to reduce emissions and running costs, and increase comfort based on occupant preferences. This study reports a summary of results from modelling seven homes with the HED toolkit, as part of a collaboration between ESC, a social housing provider, a local authority, and a charity.

A survey was conducted on each house and its occupants to build the house model and understand the occupancy and heating usage patterns. Monitoring data is used to calibrate the model. Simulation results are then compared with monitoring data before upgrade pathway options for each house are considered.

Upgrade options include improvements to the building's fabric, heating system and controls, and could inform energy efficiency measures implemented to support the UK's net zero target.

Whereas other modelling packages may use standard metrics when modelling a boiler, HED requires much greater detail such as the specific heat capacity of materials used in the boiler and heating system, length of pipes etc. Therefore, it supports a 'first principles' modelling approach to produce detailed dynamic models, which are adaptable and configurable.

HED is novel in its inclusion of occupancy data from householders, rather than relying on standardised occupancy patterns. Also, it demonstrates a significant reduction in the 'performance gap' typically found when comparing modelled with actual energy performance.

Introduction

This paper describes a project by Energy Systems Catapult (ESC) in collaboration with a social housing provider, a local authority, and a charity based in north east England. The aim of the project was to identify and assess the impact of different retrofit energy efficiency interventions, considering household comfort, and demonstrating the benefits of a detailed dynamic simulation to identify the best performing solution.

The detailed dynamic simulation has been performed using Home Energy Dynamics (HED), a modelling tool developed by Energy Systems Catapult (ESC). HED is built in Dymola®, an integrated environment for developing models in the Modelica language and a simulation environment for performing experiments (Bruck, et al., 2002). HED was developed during the Smart Systems and Heat project, specifically to assess the options for electrification of heat in domestic buildings. (Energy Systems Catapult, 2019 a; Energy Systems Catapult, 2019 b). HED analyses the energy performance of the building, considering the building fabric, heating and hot water systems, and occupants' behaviour. This allows a 'whole systems' approach, considering the interactions between all aspects of the home's energy use.

Method

Seven houses were identified for inclusion in the project, and their baseline energy performance were evaluated by HED. To provide the input data for the model, a survey was conducted in each of the seven houses to gather a range of information. For every house, a floorplan was produced showing the layout and dimensions of the rooms in each floor and the building orientation. Furthermore, the position, size, and typology of each window and door were recorded. Boiler location and properties were collected, as well as the type, position, and dimension of all the radiators together with the presence and the setup of thermostatic radiator valves (TRV). Other data about walls and loft insulation were collected. A list of the input data is shown in Table 1.

Table 1: Model input data from surveys

Dimensional data	Floorplan
	Room position and dimensions
	Ceiling height
	Windows position and dimensions
	Doors position and dimensions
	Storages position and dimensions
	Walls adjacency
Building fabric properties	Walls structure and insulation
	Ceiling and loft structure and insulation
	Floors structure and insulation
	Windows properties (single or double glazing)
	Door properties (materials)
Heating system	Boiler model and properties
	Piping layout and insulation
	Thermostat location
	Heating control system
	TRV valve setting

As aforementioned, HED allows a whole systems approach, including a comprehensive understanding of the occupants' behaviour. HED duly recognises how strong its influence is on the final energy performance of the building (Ahn, et al., 2017), often overlooked by other modelling packages. To identify occupancy and energy usage patterns, the occupants were asked to answer a questionnaire. The questionnaire includes more than eighty questions that are summarised in Table 2.

Table 2: Summary of questionnaire topics

Household composition	Number of occupants, gender, age distribution, occupation, etc.
Heating preferences	Heating hours, preferred temperature, programmer/timer settings, heated areas, etc.
Occupancy pattern	Working hours/school time, daily routine (i.e. at what time the different rooms are occupied), windows and doors opening, etc.
Appliances	Type, number and utilization pattern of electric appliances
Energy expenses	Approximate gas and electric bills per week/month/quarter/year

With this information it is possible to create an occupancy pattern for each room within a house, showing times of day a room is occupied, and number of people. These data are combined with appliance usage data to calculate heat gains. The questionnaire also provides information on the occupants' movements around the house allowing definition of a schedule for opening windows and doors, as well as for utilisation of domestic hot water (DHW).

The heating usage pattern is defined by setting the schedule of the thermostat in the specific room in which the thermostat is located and setting the opening value for the TRV in all the other rooms. This is the case for a single zone control whereby the boiler is operated by the thermostat; the temperature in the room in which the thermostat is located decides the boiler operations, whereas the temperature in the other rooms is controlled only by the thermostatic radiator valves (TRVs).

During each house's survey, monitoring and logging devices were installed to collect data about a number of different parameters within each house, including:

- Gas and electricity consumption
- Rooms temperature
- Radiators inlet and outlet water temperature
- Boiler inlet and outlet water temperature
- External temperature

The monitoring data was collected twice during the trial period (February to April 2019) and provided a reliable base for both calibration and validation of the model.

Weather data used in HED includes hourly records of air temperature along with insolation (i.e. incident solar radiation), humidity, air pressure, and wind speed and direction. The two external temperature measurements recorded for each house (one on the front of the house, one on the rear) were found to typically deviate during daylight, with the difference indicating the amount of direct sunlight. The two measurements are combined with typical local weather data to reconstruct likely temperature and insolation data for the monitoring period for each house.

Simulations

All the data gathered during the survey and the questionnaire are inputs for the HED model simulations, which uses an Excel-based tool to prepare all the input data to build a house model in HED.

The tool consists of three main spreadsheets. The first one allows the user to input all the data about the building fabric and the heating system. In the same spreadsheet the available data about the house's type, age, orientation, and geographical location is gathered. Further, the data about the boiler is entered, together with an estimation of a room's thermal mass content, the pipe dimensions, and radiator valve type. The second sheet is used to collect the data related to the occupants' behaviour. The desired temperature profile, doors and windows opening profile, occupancy pattern, and heat gain time profile for each room, as well as the DHW utilisation profile are entered and calculated. Once both sheets are populated, the entire building and its systems will be generated in HED as a new Modelica file.

The third spreadsheet shows the results after the house is simulated in HED, to give an overview of some parameters like gas consumption, electricity consumption, and a comparison between the energy consumption in different scenarios (i.e. the effectiveness of each simulated upgrade compared to the base scenario) Figure 1 shows the top level structure of HED in the Dymola modelling environment; it consists of seven main ‘blocks’, representing the house model, household behaviour, domestic hot water (DHW) demand, weather data, heat source, heating control, and comfort metrics.

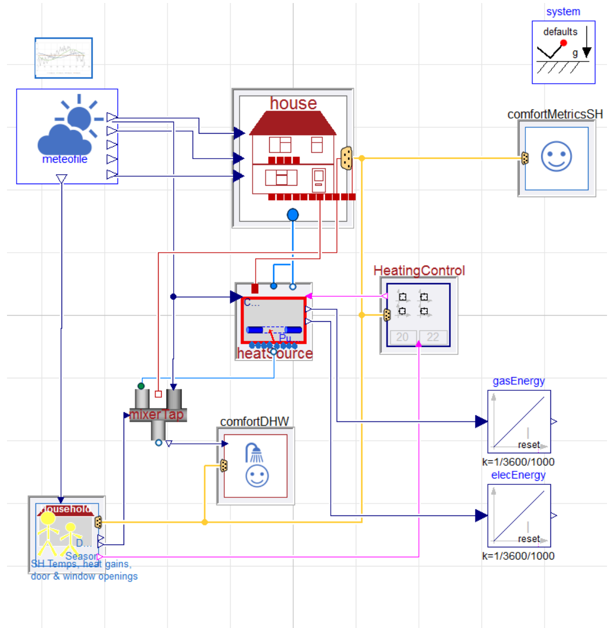

Figure 1: HED model screenshot

The weather data block or “meteofile” includes all the information about the weather data. In this project, the externally provided weather data was for Newcastle. It includes hourly records of air temperature, insolation data, humidity, air pressure, wind speed and direction. The two ‘comfort blocks’ named “comfortmetricSH” and “comfortDHW” measure the level of comfort for the space heating (SH) and DHW. This is calculated by measuring the fraction of time each metric is below the householder’s preferred temperature range.
The block “household” includes all the data about temperature setpoints, occupancy pattern, heat gains due to occupant activity, set point for DHW, and operation pattern of windows and doors.
The data from this block is used by the two comfort blocks and the “heatingcontrol” block; the latter receives the data also from the “house” block and combines the information providing the heat load value to the “heatsource” block. HED allows the user to select from a number of different heating systems, such as combi boiler, electric heating and air source heat pump; it is also possible to simulate the presence of thermal storage which acts as a buffer. The remaining block is the “house” block; here, every single room, its walls, windows and all the other components (like storage, furniture, etc.) are simulated thermodynamically. The behaviour of the building fabric and the heating system (radiators, pipes, thermal fluid) are simulated dynamically with a constant data exchange with the other blocks. HED’s simulations are based on fundamental engineering and physics principles by considering physical laws like mass balance, heat transfer relations and energy balance, following the so called “first principles” approach (C.C. Pantelides, 2013).

Initial simulation results

The simulation results from two of the seven houses in the project are presented in this section. The two houses are of different archetypes, one being a semi-detached house, (House A) and the other being a mid-terrace house (House B).
House A (Figure 2) is a two storey semi-detached house; on the ground floor are a kitchen (without radiator), living room, bathroom, hall and under-stairs storage. On the first floor are three bedrooms, landing, and a toilet.

House A was built in the 1950s and has a total floor area of 70m². The occupants are an elderly couple, who spend most of their time at home. Table 3 shows the main characteristics of the house.

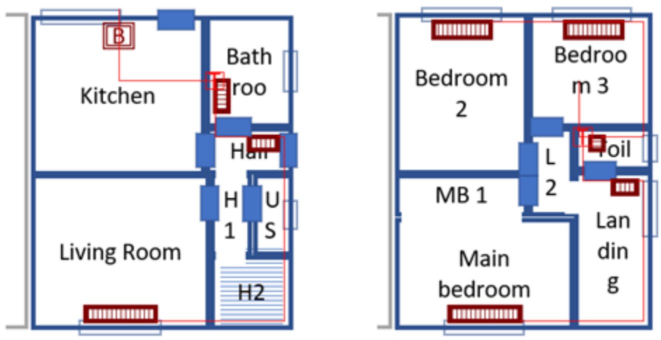

Figure 2: House A schematic floorplan

House B (Figure 3) is a mid-terrace ‘Dutch’ bungalow. The ground floor includes kitchen, living room, toilet, bathroom, one bedroom, hall and stairs; on the first floor are the main bedroom, landing, and a smaller bedroom.

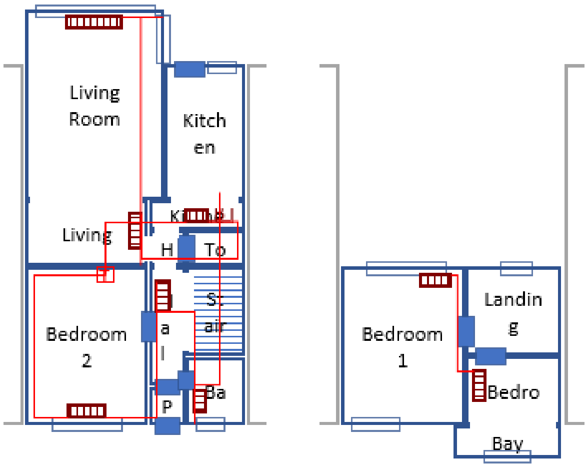

Figure 3: House B schematic floorplan

Built in the 1960s the house has a total floor area of 73m². The household is a family of three, comprising a couple and a teenage child. The father is working on a shift schedule, and the house is always occupied at weekends. Table 4 shows the main characteristics of the house.

Table 3: House A data

External walls	Bricks with insulated cavity, rendered externally, plasterboard and plaster internally
Internal walls	Bricks, plasterboard and plaster on both sides
Floors	Suspended timber floors, vinyl flooring in kitchen, bathroom and toilet, carpet elsewhere
Roof	Pitched roof 250mm insulation
Windows	UPVC Double glazing.
Doors	Internal: wooden. External: composite or UPVC
Heating system	Ideal Logic C30 combi boiler, maximum power output for SH 24 kW
Heating terminals	Double panel single convector (DPSC) and single panel single convector (SPSC) radiators with dual piping system, TRVs present
Thermostat location	Hall

Table 4: House B data

External walls	Cavity wall, 50mm insulation, tile-hung, insulated, timber framed wall. Plasterboard and plaster internally
Internal walls	Brick, plasterboard and plaster on both sides
Floors	Solid non insulated, vinyl flooring in kitchen, bathroom and toilet, carpet elsewhere
Roof	Pitched roof 250mm insulation
Windows	UPVC double glazing
Doors	Internal: wooden. External: composite or UPVC
Heating system	Ideal Logic C30 combi boiler, maximum power output for SH 24 kW
Heating terminals	Double panel single convector (DPSC) and single panel single convector (SPSC) radiators with single piping system, TRVs present
Thermostat location	Hall

Calibration

After running the model(s) for the first time to set the baseline, it is necessary to calibrate the model. To do so, the model is run with ‘boundary conditions’ for a chosen time window, and compared with measured data for the same time period, and fine-tuned by adjusting a small set of estimated input parameters to achieve an acceptable level of fidelity.

The first step in the calibration process is to format and review the measured data. An Excel-based tool is used to import data from separate files provided by each logger or meter. Data is synchronized, firstly to identify which radiator temperature is flow / return and producing a set of overview charts for specified time intervals that show all the heating system parameters i.e. water temperatures, room temperatures, etc. All these data are inspected manually to identify possible issues, such as: missing measures, wrongly labelled data, measurements errors or problems in the monitoring period (data gaps). This allows identification of a suitable time-period with reliable and gap-free data, suitable for the calibration.

Once a suitable calibration data set is identified, it is possible to generate some of the model boundary conditions, such as the space heating (SH) and domestic home water (DHW) usage time sequences, and the local weather data.

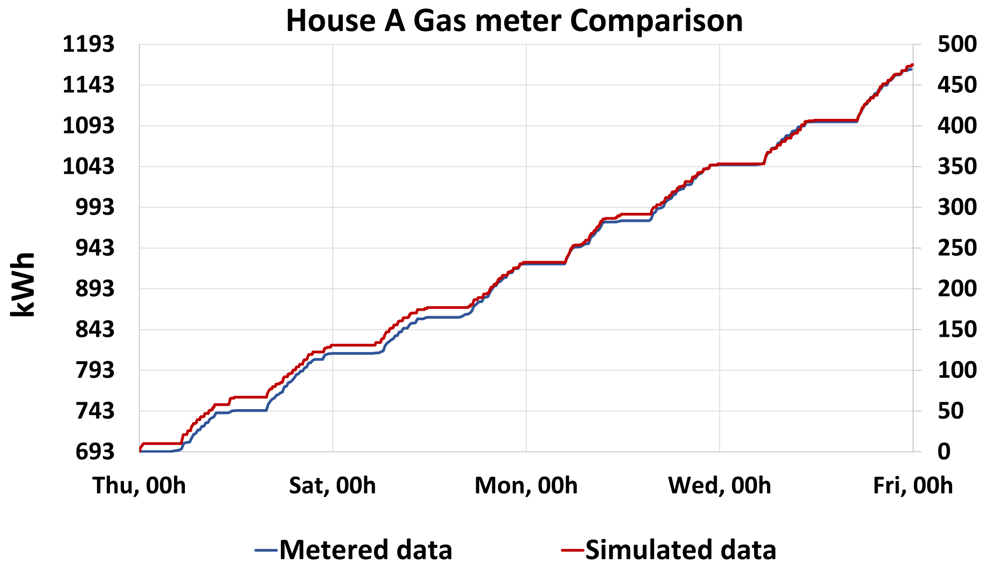

Figure 4: House A gas consumption

(left axis is cumulative metered data, and the right axis is for the specific simulated week, both in kWh)

Heating profiles were extracted from the boiler inlet and outlet temperature data. Hot water usage was primarily identified by the drop in inlet temperature seen as a hot tap is turned on, and space heating demands by changes in the boiler SH outlet temperature not associated with DHW events. Outlet temperature settings for the boiler were deduced from the appropriate measurement profiles (i.e. the temperature profiles in the SH pipes). It was not possible to use boiler gas usage rates to deduce domestic hot water flow rates due to the low frequency of smart meter data, so these were assumed to be 9 litres/min (a typical average) except where upon inspection of the data this resulted in unusually high DHW demand.

The occupants' questionnaire responses were used to understand occupancy and behaviour such as use of electrical and gas appliances (cooking, secondary heating etc.). In some cases, comparing the questionnaire data to the measured data showed discrepancies (e.g. a rise in kitchen room temperature when the heating was off and occupants reported no cooking behaviour). This led to changing the occupants' reported appliance use schedule, deferring to the measured data.

Once the boundary conditions extracted from the measured data are applied to the house model, the calibration starts with achieving a good match of radiators output power, adapting the balancing valves and the TRV.

When a match in radiator power output is achieved, it is possible to look at the room temperatures and improve the match where necessary by adjusting some parameters like insulation levels (only if the insulation values are estimated and a precise measurement was not possible), ventilation, and thermal mass of room content (i.e. furniture). As the radiator output depends on air temperature, sometimes several iterations are necessary to achieve a close match of both ventilation and thermal mass of room contents.

For House A, the calibration was performed and the simulation is re-run for the period 28th February 2019 to 8th March 2019, as shown in Figure 4. The results were excellent with an almost perfect match between simulated and metered gas consumption.

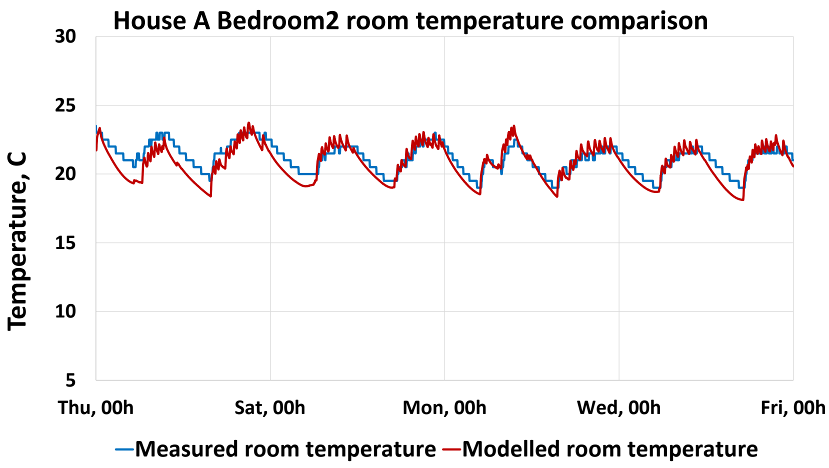

Figure 5: House A Bedroom2 temperature behaviour

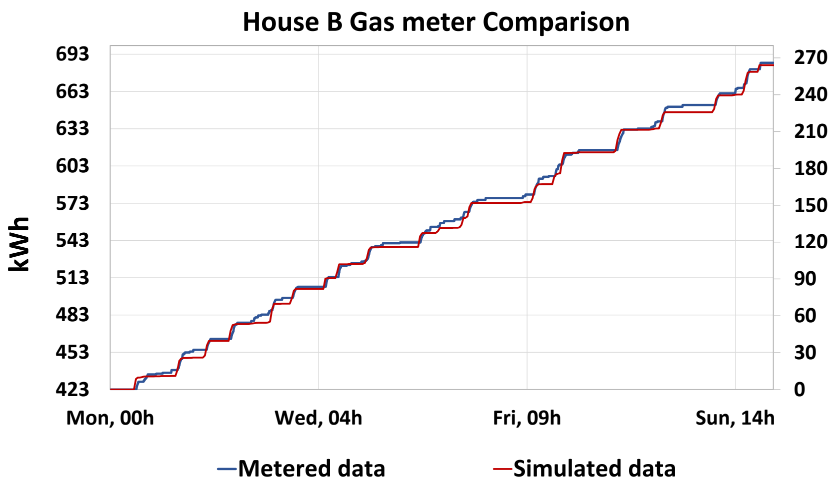

Figure 6: House B Gas consumption

(left axis is cumulative metered data, and the right axis is for the specific simulated week, both in kWh)

Figure 5 shows the temperature behaviour in one of the bedrooms, again the modelled data is very close to the actual measurements, showing the level of accuracy possible using HED.

For House B, the calibration was performed and the simulation is re-run for the period 4th March 2019 to 11th March 2019. In this case, the simulation and actual measurements were again almost perfect, both in terms of gas consumption (Figure 6) and temperature profile in one of the rooms (Figure 7).

After the calibration, the model is been used to evaluate a range of upgrade options to improve energy efficiency, comfort, and to prepare the house for low carbon heating solutions such as a heat pump. The upgrades options include:

- Multizone control if the house currently only has single (i.e. one thermostat with optional TRVs)
- Upgrade windows and doors if they are pre-2002
- Top up loft insulation if currently less than 250 mm
- Add 60 mm of cavity wall insulation if cavities are currently uninsulated (or equivalent for solid walls not applicable in this study)
- Add 75 mm of floor insulation if not already present (with option for peripheral insulation for solid floors)
- Radiator upgrades to double panel double convector
- Draught proofing to reduce natural ventilation to 0.5 air changes per hour

Each of these upgrade measures is evaluated individually (but with multizone control mandatory, as this allows a more reliable comparison for building fabric measures) over a two-week winter period. The energy savings due to each retrofit intervention are assessed in comparison to the base case, comparing the proportional reduction in energy consumption, and change in comfort and warm up times. Upgrades are not applied in a particular order, but are analysed one-by-one and then in combination.

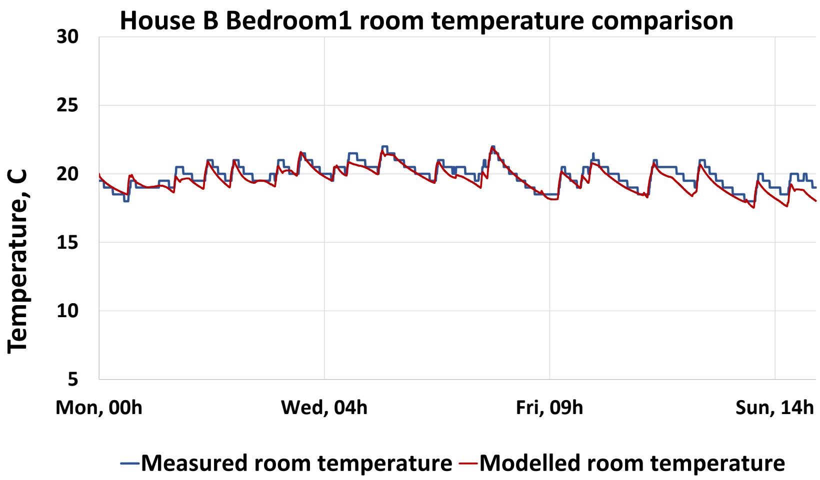

Figure 7: House B Bedroom1 temperature behaviour

Table 5: House A Upgrades results

Case	Gas/Electricity usage for SH and DHW (kWh)	Energy saving wrt base case	Fraction of time too cold[1]	Warm-up time (minutes)[1]
1. Base case single zone control, dual pipe heating system	898	0.0%	0.08%	55
2. Multizone control with dual pipe heating system	844.9	5.9%	0.02%	27
3. Multizone control with doors/windows keep closed	773.1	13.9%	0.02%	27
4. As Case 3 + draught proofing	712.4	20.7%	0.02%	21
5. As Case 3 + floor insulation	663.7	26.1	0.0%	20
6. As Case 3 + draught proofing + upgrading 3 radiators	685.9	23.6%	0.0%	14
7. As Case 6 + 8kW ASHP + 200 litre hot water cylinder	223.4	73.6%	0.04%	35

The final recommendations take into account not only the energy savings but also practicalities such as space, cost and disruption, aiming to find the most feasible way to achieve the required levels of energy savings and comfort. The room warm-up times (time a room requires to reach its desired temperature setpoint) are used to indicate which radiators are likely to need upgrading for use with a lower temperature heating system such as a heat pump. Table 5 and Table 6 show the results in terms of energy saving and comfort for different upgrade pathways.

Discussion

The results displayed in Figure 4 to Figure 7 highlight how HED is able to provide simulation results with an excellent level of accuracy. The gas consumption and temperature pattern are modelled with high precision, indicating that once calibrated, the tool can replicate the energy consumption and thermal behaviour of the system, and demonstrates a significant reduction in the 'performance gap' that can limit simulation tools that adopt standardised values for parameters such as occupancy and household behaviour (Ahn, et al., 2017). Occupancy and household behaviour, and detailed dynamic simulations both require a more precise definition of input parameters and boundary conditions, but the additional time required is compensated by the fidelity of the simulation.

Simulating the building and its heating system at such a detailed level allows the user to analyse the effect of any energy efficiency upgrade applied to the building with great confidence. As shown in Table 5 and Table 6, HED provides not only information on the change in energy consumption and potential savings, but gives also a view of the resulting comfort levels and warm up times. These details are required to define the best upgrade pathway, by ensuring that energy savings are delivered without compromising the wellbeing of the householders.

[1] Weighted average

Table 6: House B Upgrades results

Case	Gas/Electricity usage for SH and DHW (kWh)	Energy saving wrt base case	Fraction of time too cold[1]	Warm-up time (minutes)[1]
1. Base case – single zone control, single pipe heating system	572.6	0.0%	13.5	157
2. Multizone control with dual pipe heating system	608.9	-5.6%	0.0	53
3. Multizone control with doors/windows keep closed	594.9	-3.9%	0.0	54
4. As Case 3 + draught proofing	535.2	6.5%	0.0	37
5. As Case 3 + peripheral floor insulation	536.1	6.4%	0.0	35
6. As Case 5 + draught proofing + upgrading three radiators	477.5	16.6%	0.0	15
7. As Case 6 + 8kW ASHP + 200 litre hot water cylinder	174.5	69.5%	0.0	36

Conclusion

In this study, seven houses in Newcastle were surveyed, monitored and modelled. These houses have been analysed in detail to show the potential impact of building fabric and heating system upgrades using Energy Systems Catapult's tool, Home Energy Dynamics (HED). The results for two of the houses are reported in this paper. The study demonstrates that HED can analyse upgrade options, simultaneously considering the impact on energy demand, impact on heating performance and thermal comfort, and informing upgrade choices. The detailed dynamic simulation carried out in HED is precise and provides a good approach to understand the best decarbonisation pathway for a domestic building. It also demonstrates a significant reduction in the 'performance gap' typically found when comparing modelled with actual energy performance. The comparison of modelled and actual data from the houses shows an almost perfect correlation. HED is currently a prototype tool; future development is focused on improving the user interface of the modelling tool-kit, and increasing the number of heating systems available in the library, as well as providing detailed information on CO_2 emission and primary energy utilisation.

Acknowledgements

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References

Ahn, K.-U., Kim, D.-W., Cheol-Soo, P. & de Wilde, P., 2017. Predictability of occupant presence and performance gap in building energy simulation. *Applied Energy,* Volume 208, pp. 1639-1652.

Bruck, D., Elmqvist, H., Mattsson, S. E. & Olsson, H., 2002. *Dymola for Multi-Engineering Modeling and Simulation.* s.l., s.n.

C.C. Pantelides, J. R., 2013. The online use of first-principles models in process operations: Review, current status and future needs. *Computers and Chemical Engineering,* Volume 51, pp. 136-148.

Committee on Climate Change, 2018. *Reducing UK emissions – 2018 Progress Report to Parliament.* s.l.:s.n.

Energy Systems Catapult, 2019 a. *Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes.* [Online] Available at: https://es.catapult.org.uk/wp-content/uploads/2019/11/SSH1-Pathways-to-Low-Carbon-Heating-Report-FINAL.pdf [Accessed 30 April 2020].

Energy Systems Catapult, 2019 b. *Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes - Appendicies.* [Online] Available at: https://es.catapult.org.uk/wp-content/uploads/2019/05/SSH1-Pathways-to-Low-Carbon-Heating-Report-Appendicies-FINAL.pdf [Accessed 30 April 2020].

HM GOVERNMENT, 2008. *Climate Change Act 2008.* [Online] Available at: http://www.legislation.gov.uk/ukpga/2008/27/contents [Accessed 06 May 2020].