A case study of modelling informing whole house energy systems-based retrofit in the UK

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Abstract

Low-carbon housing can help to mitigate climate change, increase low-carbon energy sources and reduce fossil fuel usage, whilst also reducing fuel poverty and improving the quality and condition of the built environment. Researchers at the Centre for a Low Carbon Built Environment (CLCBE) within the Welsh School of Architecture (WSA) at Cardiff University have been working with local authorities and social landlords to deliver a whole systems-based approach to domestic properties since 2008 reducing energy demand, combined with integrating renewable energy supply and storage systems.

Building energy modelling has been an essential tool at the planning stage, when taking a whole energy systems approach, to enable comparisons of different packages demand, supply and storage combinations for a property. The effectiveness of different retrofit solutions can be compared to help the decision-making process, for example, the impact of different insulation materials and thicknesses on energy consumption, carbon emissions and thermal performance. Modelling results were crucial when engaging with a range of stakeholders to co-develop retrofit strategies. This paper introduces the modelling framework used in the CLCBE whole house system-based retrofit approach. A demonstration house project completed in 2022 is presented as a case study to illustrate how modelling was used to support decision-making. Finally, the paper discusses the challenges and good practice required to ensure the quality of modelling is appropriate to assist in whole house energy systems-based home retrofitting.

1. Home energy retrofit

After signing the Paris Agreement, the UK Committee on Climate Change (2019a) recommended that the UK emissions target was to achieve net-zero greenhouse gases by 2050. The UK built environment is responsible for 25% of total UK greenhouse gas emissions, and the 29 million homes in the UK account for approximately 14% of UK greenhouse gas emissions (UK Committee on Climate Change, 2019b). The (UK Green Building Council, 2021) have indicated that most reductions in operational emissions achieved in the past two decades are a result of the decarbonisation of the electricity grid rather than improvements in the energy efficiency of buildings. There remains a vast opportunity to improve home energy efficiency, and this must be tackled if the UK is to meet net zero by 2050.

The term 'retrofit' can refer to a range of activities aimed at enhancing the energy performance of building through repairs, upgrades and maintenance to the building itself, as well as changes to power and heat provision and user controls (Maguire et al., 2020). Debates on whether to pursue deep retrofit on fewer homes or shallow retrofit on a larger number of homes with limited resources available had been ongoing. However, research indicates that a whole-house approach is the most beneficial, not only improving home energy performance but also enhancing comfort levels (Patterson, 2012, Saffari and Beagon, 2022, Jones et al., 2013). To mitigate the risks associated with deep retrofits and to promote action, a staged whole-house retrofit approach can be taken.

Various standards and initiatives have been set as targets for energy use and carbon emissions to move UK homes towards a zero-carbon future. Building Regulations Part L were updated in 2022 and includes mandatory standards for all homes, for both new and retrofitted homes. Voluntary independent standards and initiatives provide a pathway for delivering home energy retrofits beyond Regulation standards including EnerPHit, AECB CarbonLite, LETI Climate Emergency Retrofit Guide, Energisprong and RIBA 2030 Climate Challenge.

According to the National Energy Efficiency Data-Framework (NEED) annual gas and electricity consumption varies across housing according to factors such as occupant behaviour, property type and age (Department for Energy Security and Net Zero, 2023). Building energy modelling is therefore a valuable tool for exploring savings associated with these variables combined with retrofit measures to support the decision-making process to achieve selected standards for a property.

2. The role of building energy modelling

Building energy modelling plays a crucial role in both new built and retrofit projects. Building energy modelling can take into account dynamic inputs such as weather, occupancy, lighting, equipment load, building fabric and systems, and enables detailed heat-balance calculations to be made at discrete time periods over the course of a full year to calculate operational energy required to maintain a specified indoor thermal environment (e.g., space temperature, and humidity) (Coakley et al., 2014).

The first Building Energy Simulation (BES) tool, BRIS, was compiled in 1963 by the Royal Institute of Technology, Stockholm (Brown, 1990). In the 1990s, more sophisticated BES programs, such as DeST and EnergyPlus, were developed (Singh and Sharston, 2021). As computing power increased, building energy simulation tools became more accurate in predicting a building's thermal and energy performance (Singh and Sharston, 2021).

In the context of low-carbon retrofit homes, modelling offers valuable insights into the impact of potential low-carbon retrofit strategies or technologies on energy performance and environmental impact to support the decision-making process (Rodrigues et al., 2018, Heo et al., 2015). For example, modelling results were essential for assessing the effectiveness of different insulation types, materials and thicknesses in reducing energy consumption (Loucari et al., 2016). They can also be used to evaluate the thermal performance of combinations of retrofit interventions, identify overheating risk and specify the most suitable strategies to enhance occupants' comfort and satisfaction level (Hao et al., 2022, Ibrahim and Pelsmakers, 2018). In addition, not only for current and standard weather condition, building energy modelling can predict both energy and thermal performance considering of the impact of climate change or local microclimate.

The main downside of building energy modelling is the potential for discrepancies in energy consumption predictions. Building energy models struggle to accurately predict real-world energy consumption performance due to variations in occupancy patterns, schedules and the complexity of the built environment (Kontokosta, 2014). Therefore, calibration through the reconciliation of model outputs with measured data, is essential to achieve accurate and reliable results (Coakley et al., 2014). Other downsides associated with building energy modelling are that they are computationally intensive requiring expert skill sets, time-consuming for detailed data collection and analysis and present challenges when extrapolating the results at a larger scale (Dobosi et al., 2020, Cárdenas-Rangel et al., 2021).

3. A modelling framework for a whole-house systems-based retrofit approach

Since 2008 researchers at the CLCBE have been implementing affordable and replicable low-carbon solutions in the built environment. Collaborating with industry, government, academia and the public, the team have delivered more than 40 domestic projects that optimise a 'whole house energy systems-based approach' combining energy demand reduction, renewable energy supply and energy storage solutions to strive towards net zero-carbon built environment that is replicable, affordable and appropriate for the context (Patterson and Perisoglou, 2024, Cardiff University, 2023). A well-designed whole-house retrofit can make a home more energy efficient, reduce carbon emissions and energy bills and improve living conditions. The whole house energy systems-based retrofit approach employs a process to ensure a cost effective and appropriate package applied to each house type (Figure 1). Building energy modelling is a key tool to support decision making at the design stage.

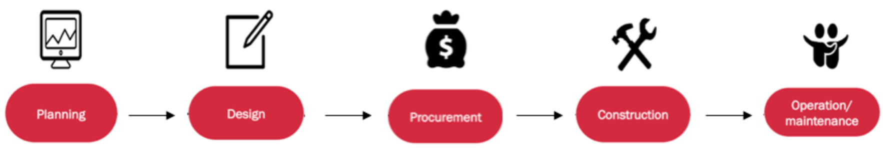

Figure 1: CLCBE whole house energy systems-based approach

3.1 Modelling software

As summarised by (Pan et al., 2023), three categories of building energy modelling methods are available: 1) simplified evaluation methods 2) detailed physical methods and 3) statistical and regression methods. Building energy modelling provides detailed physical methods for predicting previously unobserved behaviour of a complex system when given system properties, conditions and a set of well-defined laws, such as energy balance, mass balance, conductivity, heat transfer (Coakley et al., 2014).

A range of recognised building energy simulation tools have been developed globally, including HTB2, EnergyPlus, TRNSYS, DOE-2, DesignBuilder, IES-V and, ESP-r. HTB2 is a flexible tool for predicting the energy and environmental performance of buildings, developed at the Welsh School of Architecture (Lewis and Alexander, 1990) which has been extended and improved over time. Simulation results have been found to be comparable with EnergyPlus, TRNSYS and ESP-r (Neymark et al., 2011). HTB2 has been used to conduct dynamic thermal and energy modelling for CLCBE research due to its adaptability allowing flexible inputs. The calculated operational energy is converted to primary energy and carbon emission with the updated factors in SAP 10.2 (BEIS, 2021).

3.2 CLCBE modelling framework for a whole-house energy system approach

Modelling is conducted in two stages: 1) base case modelling and 2) retrofit design modelling.

3.2.1 Base case modelling

The purpose of base case modelling is to set up a model for the home as it was before retrofit work is carried out and also to ensure modelling results match monitored thermal and energy performance data for validation. Key inputs to the model include 1) weather data 2) building fabric 3) internal gains and patterns 4) building systems and 5) indoor environment (Figure 2).

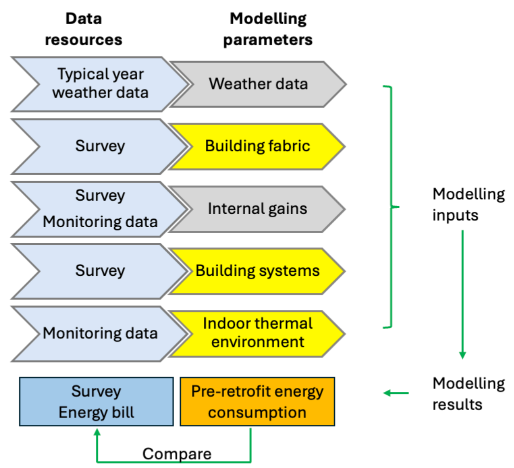

Figure 2: Base case modelling framework - inputs and results

Surveys, pre-retrofit monitored indoor environment data, energy usage and one-off tests in are carried out at the planning stage of the retrofit, using the following tools:

- The Practical Retrofit Early-Stage Survey (PRESS-1) tool has been developed to be used at the very early stage of a retrofit by local authorities and social housing staff (Patterson, 2023). Information on building location, building construction, ventilation, heating, appliances and lighting, energy bills, potential retrofits, residents and floor plans are collected at a basic level.

- A semi-structured interview is conducted by researchers to collect residents' opinions on thermal comfort and energy, as well as how they use their homes.
- A digital twin is used to capture building information and document the pre-retrofit condition.
- Tinytag monitoring equipment is used to collect indoor air temperature and relative humidity data.
- One-off tests included blower door tests for air-tightness, thermograph imaging and u-value tests are used to collate building performance information.

Modelling results obtained from HTB2 included energy consumption, compared with pre-retrofit monitored energy usage data and energy bills if available. Since the inputs of the base case model were based on the existing condition, modelled energy consumption should be comparable to the actual usage. However, due to the large number of inputs required by building energy model and unavoidable, un-measurable input parameters, it was challenging to validate the modelling results with monitored data. Once discrepancies were identified between the modelled and monitored data in the base case, a range of uncertainty parameters would be adjusted, such as internal gain patterns, natural ventilation rate. The model was considered ready for the 'next phase' – to compare whole-house energy system solutions -when modelling results matched the monitored conditions within allowable tolerances as per ASHRAE Guideline 14 (ASHRAE, 2014). If the property was vacant, the internal gains and the indoor thermal environment was set to standard values. The pre-retrofit energy consumption was compared to relevant national average value, such as NEED.

3.2.2 Retrofit design modelling

The purpose of retrofit design modelling was to evaluate the cumulative savings of potential retrofit solutions associated with operational energy usage, cost to buy and run and carbon emissions. The potential strategies explored follow demand reduction, efficient HVAC systems and renewable supply and storage systems (Figure 3). Modelling results were normalised to compare with low carbon retrofit standards and guidance.

The savings of various low carbon solution packages in operational energy consumption, carbon emissions and cost savings were compared. Decisions were made with the local authority and residents, with the most appropriate package of measures confirmed with detailed specifications.

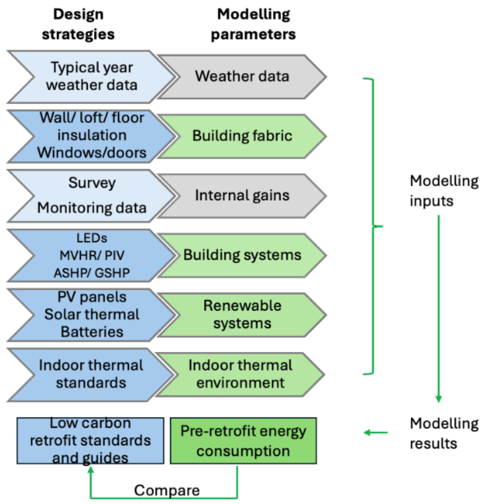

Figure 3: Retrofit design modelling framework - inputs and results

4. CLCBE Case study

The CLCBE research team worked with Wales & West Housing Association (WWHA) to identify and install a combination of appropriate, affordable and replicable retrofit solutions for one 1970s end-terrace house.

The house, in Bridgend, South Wales, is a typical end-terraced house built in the 1970s. Data about the home was collected using the PRESS tool (REF TO BE ADDED). The total floor area of the house is 85m^2 over two floors with an average room height of 2.3m. Figure 4 shows the front elevation of the property. Figure 5 illustrates the floor plans of the house. It had a brick, cavity wall construction with concrete roof tiles. Spaces included a porch, kitchen/diner, living room and toilet on the ground floor, with three bedrooms and a bathroom on the first floor. The most recent EPC for this property was conducted in 2015. The rating was band C (73), which was higher than the average rating for Welsh homes of band D (61) (Welsh Government, 2019).

Figure 4: Front elevation of the case study house

Figure 5: Floor plans of the case study house

4.1 Base case modelling of case study house

Building energy modelling was carried out using HTB2 to identify the pre-retrofit energy performance. Data was collected using via surveys and monitoring to calibrate the building energy model as follows:

1) Wales & West Housing Association conducted an initial pre-retrofit survey using the PRESS-1 tool (REFERENCE).
2) Pre-retrofit monitoring included an airtightness test, thermographic imaging, and U-value tests.

- Airtightness test

  A blower door test was carried out to quantify the airtightness of the house. The air infiltration rate of the pre-retrofit home was 13.2m^3/hr/m^2 at 50 Pascal. Comparing to 8m^3/hr/m^2 at 50 Pascal which is the worst acceptable air tightness of new built dwelling by the current building regulations, the case study was very leaky. The detail of the locations of air leakage was investigated using high accuracy air velocity sensors and thermography testing during the blower door test where the building was over-pressurised. High leakage was observed around doors and windows, especially around the kitchen windows, as indicated in Figure 6.

- Thermographic imaging

  Thermographic images confirmed higher levels of heat loss through gaps around windows. In addition, significant heat loss along skirting boards was also revealed. High levels of thermal bridging were identified along the lower area of the west-facing external wall and along the north and west second floor ceiling and attic hatch.

Figure 6: Thermographic imaging results (above: window frame; below: skirting board)

- U-value tests

  The external wall was a cavity wall with filled polystyrene bead insulation. The U-value test was conducted on the north-facing external wall in the living room during heating season to confirm the heat transfer through the external wall. The test was performed for 2 weeks to ensure a robust data set was captured. The resulting U-value was 0.62W/m^2/K (Figure 7). At the time of construction, Building Regulations set U-value of an exposed wall was between 1.0W/m^2/K (1976 Building Regulation) and 0.6W/m^2/K (1985 Building Regulation).

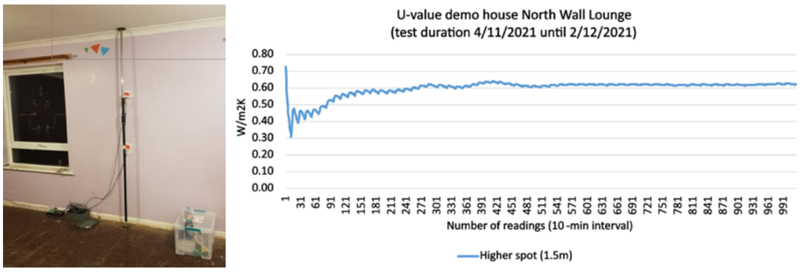

Figure 7: U-value test – location of equipment and output

Table 1 summarises the inputs to the base case model.

Table 1: Summary of base case energy modelling inputs

Components		Current Conditions	Values
Building fabric	Loft/hatch insulation	190mm loft insulation	0.19 W/K/m^2
	External wall	Cavity wall with filled insulation	0.62 W/K/m^2 (tested)
	Window/ door	Double glazing	2.70 W/K/m^2
	Air tightness	Gaps around the window frames	13.2m^3/hr/m^2 at 50 Pascal (tested)
Building services	Lighting	62% LED lighting	8 X 9W/800 lumens 5 X 60W/800 lumens
	Ventilation	Natural ventilation	--
	Space heating	Vaillant gas boiler	Efficiency 95%
	Domestic Hot Water	Via main heating system	45L/person/day
Renewable energy generation systems	PV	No PV panels	--
Energy storage systems	Battery	No battery	--
Internal gains	Small powers	Lighting and other small powers: 06:00-09:00, 17:00-22:00 every day Fridge is on 24 hours every day	3688kWh/year*
	Occupants	2 adults and 2 children Weekdays: 17:00 to 9:00 at home Weekend: all day at home	
Heating setpoint	Internal air temperature	22:00 to 6:00 and 9:00 to 17:00: 16□C 6:00 to 9:00 and 17:00 to 22:00: 21□C	

- The average mean electricity consumption (kWh) for floor area 51-100m^2 from 2005 to 2021 (Department for Energy Security and Net Zero, 2023)

A formula is used to estimate the energy required to for domestic hot water:

$$E = (C \times V \times \Delta T) \div PR$$

Where E = energy in kWh
C = Specific heat of water - 4.187 kJ/kgK, or 1,163 Wh/kg°C
V = volume of water to heat
ΔT = Th-Tc
Th = temperature of hot water
Tc = temperature of input cold water
PR = performance ratio (it includes losses of heat through pipes and tank), default value = 0.9

To heat up 180L water from 15°C to 55°C, the required energy is 9.3kWh/day.

As the house was vacant during the retrofit process, it was not possible to monitor the energy and thermal performance of the house as it was in use or collect energy bills before the retrofit to validate the model. Data from National Energy Efficiency Data (NEED) Framework was used to validate the base case model. According to NEED, the annual mean energy consumption for a similar sized property at the time was 193.4kWh/m^2(Department for Energy Security and Net Zero, 2023) which is3.9% higher than the modelled base case at 185.9kWh/m^2.

4.2 Retrofit case study design modelling

Based on the existing condition of the house and available budget, the whole house energy systems-based approached was applied to design the most suitable package for this property. A fabric first approach was applied since the fabric was in poor condition, confirmed by the poor result from the air tightness test. External wall insulation, loft and hatch insulation, new, improved windows and doors were included within the approach to improved air tightness to reduce the demand for space heating and improve comfort and wellbeing of the residents. This fabric first approach was followed by the use energy efficient heating, ventilation and lighting systems to ensure that emissions could be reduced and comfortable living conditions could be achieved. Renewable energy supply and storage systems were added to the approach with the associated specification made considering roof orientation, size and surrounding shading conditions. Within the modelling, the renewable energy generated and stored was used to offset the energy supplied to heating, cooling, ventilation and lighting system. Relative savings of each retrofit intervention in operational energy usage, fuel usage, carbon emission and energy bills were calculated.

The retrofit interventions were co-designed in collaboration with WWHA to ensure that available funding, future resident needs, and operation and maintenance requirements were considered. Modelling results supported the design Table 2 summarises the designed retrofit solutions and the associated performance targets.

Table 2: Solutions and targets for the case study house

COMPONENT		RETROFIT SOLUTIONs	TARGET PERFORMANCE
Building fabric improvements	Loft/hatch insulation	Top up existing loft insulation to 300mm. Insulate and draughtproof the loft hatch.	0.13W/K/m^2
	External wall	External wall insulation (EWI) for the whole house, including the front porch. Insulate plinth to minimise thermal bridging.	0.18W/K/m^2
	Window/ door	Replace existing windows and doors with high performance windows and doors No trickle vents for the windows	1.4W/K/m^2
	Air tightness	Seal skirting boards throughout Ensure windows and doors are fitted properly by a FENSA registered installer/contractor	5m^3/hr/m^2 at 50 Pascal
Building services upgrades	Lighting	100% LED lighting	13 X 9W/800 lumens
	Ventilation	Install a mechanical ventilation with heat recovery (MVHR) unit	31l/s with 95% efficiency (Welsh Government, 2022)
	Heating	Install an air source heat pump (ASHP)	8kW, COP at A2/W35 (EN 14511): 4.14
Renewable energy generation systems	PV	Bolt on Photovoltaic Panels on south facing roof	4.92kWp/ Eff. =21%
Energy storage systems	Battery	Install a lithium battery	9.5kWh
Note	Research suggested the gap between ASHP manufacturer's COP and the in-situ performance is −16% for 8.5 kW ASHPs (Chesser et al., 2021). COP 3 was used for the simulation.		

A range of interventions such as double glazing vs triple glazing (Figure 8), internal vs external wall insulation, external wall insulation with various thicknesses and air source heat pump with various COPs were modelled during the design stage to understand the impact of the different options. For example, the simulation results suggested that there was a 2% energy saving achieve by triple glazing comparing to double glazing in this case study. However, there was a temperature increase of approximately one degree on the internal surface of glazing that could reduce the risk of draft and improve the residents' thermal comfort. Considering the focus of the case study project to demonstrate affordable and replicable strategies, double glazing was chosen for the house.

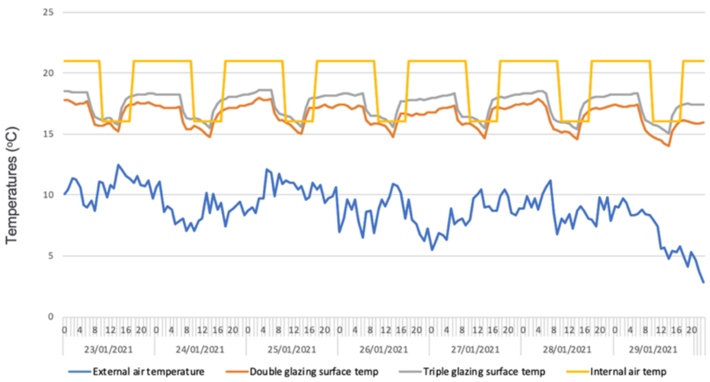

Figure 8: Hourly temperature in a typical week during heating season when comparing double and triple glazing in the case study house

Table 3 shows the predicted cumulative (Welsh Government, 2022)(Welsh Government, 2022)energy consumption, carbon emission and savings of each strategy. The most impactful strategies were External Wall Insulation (EWI), new windows and doors, Air Source Heat Pump (ASHP) and Photovoltaics (PV) + Battery.

- A building fabric upgrade delivered 39.8% reduction in space heating demand and 20.3% in total Energy Use Intensity (EUI). This aligns with other studies that suggested the range of savings in energy bill was between 16% to 56% (Lilley et al., 2017).
- LEDs saved an overall EUI of 2%. The saving was low because of two-thirds of the existing lighting were LED and the other ones were Compact Fluorescent Light bulbs. For 800 lumens, LEDs consume 9Wh every hour, while CFLs use 12Wh. The life span of LEDs is 50000 hours, and the life span of CFLs is 8000 hours only. A more significant impact can be observed in life cycle analysis.
- Mechanical Ventilation and Heat Recovery (MVHR) provides filtered fresh air into the home and reduces the risk of condensation. The introduced preheated fresh air increased the space heating demand by 2.5%.

- With an energy efficient ASHP to provide space heating and domestic hot water, the overall EUI used in the house was further reduced by 72.1%. The designed retrofit package predicted to reduce the overall EUI by 88.5% through the whole house energy systems-based interventions.

According to updated factors in SAP 10.2 (BEIS, 2021), primary energy and carbon emission decreased by 85.8% and 91.9% respectively. Because of the cost variation between the main gas and electricity, the predicted overall savings on the energy bill was 71.4%.

Table 3: Cumulated energy simulation results of each strategy in the demonstration house

Solutions	EUI	Space heating demand reduction	EUI reduction	Primary energy consumption	Primary energy reduction	Carbon emission	Carbon emission reduction	Energy bill	Energy bill reduction
	kWh/m^2	kWh/m^2	%	kWh/m^2	%	kg	%	£	%
Base case	**185.9**	**-**	**-**	**226.2**	**-**	**3046.1**	**-**	**1049.2**	**-**
+ Loft insulation	184.6	-1.3%	-0.7%	224.7	-0.6%	3023.0	-0.8%	1045.2	-0.4%
+ EWI	162.1	-22.8%	-12.2%	199.2	-11.4%	2620.0	-13.3%	975.3	-6.7%
+ New windows and doors	150.0	-15.7%	-7.4%	185.6	-6.8%	2404.7	-8.2%	938.0	-3.8%
+ LEDs	147.8	1.3%	-1.5%	182.0	-1.9%	2384.6	-0.8%	898.5	-4.2%
+ MVHR	154.6	3.8%	4.6%	191.3	5.1%	2478.4	3.9%	966.6	7.6%
+ ASHP	81.0	-68.3%	-50.2%	121.5	-36.5%	935.9	-62.2%	1134.8	17.4%
+ PV+Battery	21.4	0.0%	-73.6%	32.1	-73.6%	247.2	-73.6%	299.7	-73.6%
Total savings	**-164.6**	**-77.5%**	**-88.5%**	**-194.1**	**-85.8%**	**-2798.9**	**-91.9%**	**-749.5**	**-71.4%**
Fuel prices (3.64p for main gas and 16.49p for electricity standard tariff), emission factors (0.21kg/kWh for main gas and 0.136kg/kWh for electricity standard tariff) and primary energy factors (1.130 for main gas and 1.501 for electricity standard tariff) were used in the calculation and referred to SAP 10.2 (BEIS, 2021)									

4.3 Completion of the case study whole house retrofit

A rigorous procurement process was conducted to ensure the most appropriate solutions and qualified contractors were selected for the project. The winning bidders passed all mandatory requirements and scored the highest for the technical and cost evaluation. A meeting with all successful contractors took place on site before works commenced, where the project was introduced including an explanation of why the different components of the system were selected in the decision-making process. The schedule of work was discussed and issues such as space availability and challenging installation steps were solved together. The meeting enhanced contractors' understanding of how their work interacted with the other components of the system and allowed them work out the details with other contractors. This aided communication throughout the whole process. For example, the battery installer and the electrician worked together to find the best location for the battery, and the MVHR installer and the loft insulation installer worked out the sequence of their work together. All activities associated with the delivery of the demonstration project were managed by WWHA Principal Contractor who played an integral and highly collaborative and key role in the whole progamme. On-site installation started in May 2022 and was completed in December 2022 due to the long lead time for the supply and installation of the battery (Figure 9 and 10). The installation of all equipment aimed to comply with appropriate Regulations, be easily accessible for maintenance and repair, as well as minimise the impact on residents' storage space. All systems were fully commissioned after the installation. Once the construction was complete, a new EPC was produced, achieving an EPC band A rating (95).

Figure 9: The case study house following retrofit

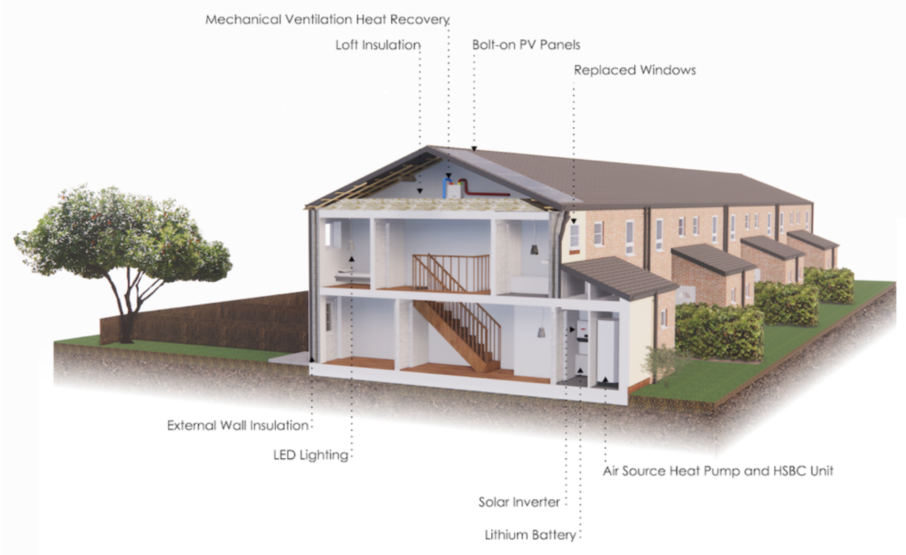

Figure 10: Architectural drawing of the case study house illustrating the location of the low carbon solutions

The house remained empty during January 2023 as a demonstration home, where more than 100 visitors from local and national government, social housing sector, industry and academia attended. Following this the house was rented to new tenants. An easy-to-use CLCBE Home User Guide app was developed to help residents understand the solutions installed in the house and operate their home effectively. Monitoring equipment were installed in the house to collect post-retrofit thermal and energy performance data. The monitoring data will be published once a full year of data has been collected and analysed.

5. Discussion and Conclusions

The case study house has demonstrated that the CLCBE whole house energy systems-based retrofit approach can help mitigate climate change by reducing carbon emissions, increase the use of low-carbon energy sources, reduce fossil fuel usage and help reduce fuel poverty through reduced bills and improve the built environment. It proved a practical approach towards reaching the net zero target for 2050. The whole house energy systems-based retrofit achieved over 90% reduction in overall EUI and carbon emissions. The savings in primary energy were just below 90%, while the savings in energy bills were close to 80%.

During the design process, building energy modelling contributed to the co-design decision-making process between stakeholders, allowing different options to be considered. Using building energy simulation tools, designers/researchers can conduct modelling to estimate annual operational energy savings and reductions in carbon emissions. The main challenges recognised through the modelling process for the case study included 1) how to achieve an accurate representation of real-world retrofit savings with some missing variables in a timely manner and 2) how to speed up the process and scale up the modelling to ensure all 29 million homes in the UK achieve the zero-carbon target by 2050.

Three good practices were identified to ensure modelling quality. First, calibration with pre-retrofit monitored data or standards plays an essential role in validating the design model. In most cases, data for weather and building fabric were available. The key parameters to adjust were internal gains and nature ventilation to calibrate the model. Second, the choice of propriate performance indicators were crucial to support design decision making. The objective and primary indicator was annual operational energy saving. It was the base for calculating primary energy savings, associated carbon emission reduction and cost implications. The savings in energy bills, together with capital cost and payback time, provided confidence with social housing landlords and residents. Last but not least, through the modelling of a range of low carbon retrofit projects, setting up a standardised practice in building energy modelling for whole house energy systems-based home retrofitting could support good practice.

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