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Abstract. European governments have set ambitious retrofitting targets driven by the commitment to reduce the greenhouse gas emissions by at least 80% by 2050. The United Kingdom has the oldest housing stock in Europe, with over 2/3 of dwellings built before 1976, when building regulations started to include energy efficiency. This raises concerns over carbon emissions, health, comfort and running costs, and government's set targets and initiatives for significant improvements. Deep retrofitting by using innovative technologies with respect to aesthetics has considerable and measurable benefits, while it can be a costly and challenging process. This study examines a combination of measures undertaken in a pre-1919 dwelling in south Wales, including reduction of energy demand and the application of renewable energy supply and energy storage. A whole house performance and a systems breakdown evaluation is presented comparing the pre and post intervention status. Both monitoring and modelling tools where used, and the performance gap is also discussed. An annual reduction of 34% in space heating and 78% in electricity import was monitored with an additional electricity export of 3217kWh. This represents a total annual cost saving of £1115, at 2019 UK gas and electricity prices. The total cost of the retrofit was £55K.

1. Introduction

Building retrofitting is high up in the EU's energy efficiency agenda; the Building Performance Institute Europe (BPIE) claims that 97% of the buildings in the EU need to be upgraded [1]. Deep retrofit projects have indicate a significant improvement in energy performance of domestic dwellings [2-5]; however enumerating energy performance is a challenging process. Jones et al [3] combined modelling and monitoring to analyse holistically the energy performance before and after the interventions, and to break down the contribution in energy savings of each technology. Elsharkawy and Rutherford quantified the impact of energy efficient retrofitting on health and comfort, with a focus in condensation and internal temperatures [6]. IEA/EBC Annex 53 prescribed 6 main building energy performance categories (climate, building envelop, building services and energy systems, building operation and maintenance, occupants' activities and behaviour and indoor environmental quality) [7]. Also, in 2015, IEA/IPEEC suggested a conceptual framework for the development of building performance metrics based on an input (e.g. total energy) per output (e.g. floor area served) for a scope (e.g. specific building type) normalised by a factor (e.g. climate, HDD etc.) [8].

Following on from previous work, and combining the techniques in previous studies, the aim of this study is to present a holistic retrofit solution, providing evidence of annual performance of all the passive and active strategies used to increase the performance of the house. The research also evaluates each introduced system separately as well as the overall change in energy savings and comfort. Monitoring and modelling are the main tools used to evaluate the performance of the building and the systems' individual contribution. The study presents annual summarised figures compared against UK averaged data and also discusses differences from the average and gap between monitoring and modelling. The cost of the retrofitting, the savings, and the excess energy generation is discussed with the view to replicability.

2. Scientific methodology

A typical South Wales pre-1919 end-terrace gas heated house was selected as a representative case study within the area's building stock. The building evaluation methodology was based in monitoring techniques and protocol developed in the Welsh School of Architecture as well as literature and guidance on building metrics and performance evaluation protocols [3, 5, 7, 9-14]. The team spent one year to complete a pre-intervention phase which started from a building survey and interviews with the occupants. Then, a monitoring plan was designed, combining an in situ investigation and a twelve-months building energy use and comfort monitoring, at 30 minute intervals. These diagnostic methods explored the impact of a variety of low carbon solutions by enhancing modelling tools with dynamic profiles. The pre and post retrofit building performance were modelled in the dynamic thermal simulation tool HTB2, which proved to be reliable in whole house energy prediction in previous projects [3]. To reduce foreseeable performance gap between modelling and monitoring, the proposed modelling scenarios were based on surveys and up-to-then 7 months' measurement data.

The procurement phase followed ensuring the use of local and cost-effective supply chain. The improvements on building envelope included external (EWI), internal (IWI), loft, and overlapping (anti-thermal bridging) insulation. Also, LED light bulbs were fitted and mechanical ventilation system with heat recovery (MVHR) was installed with a delivery of fresh air to all living spaces. On the supply side, photovoltaic (PV) panels were mounted on the double pitched roof (5.9kWp), electric batteries (13.5kWh) were fitted in the attic and transpired solar collectors (TSC) were installed on the south facade feeding solar heated warm air to the ventilation system during the heating period (figure 1). The system allows the export of excess renewable electricity generation to the grid.

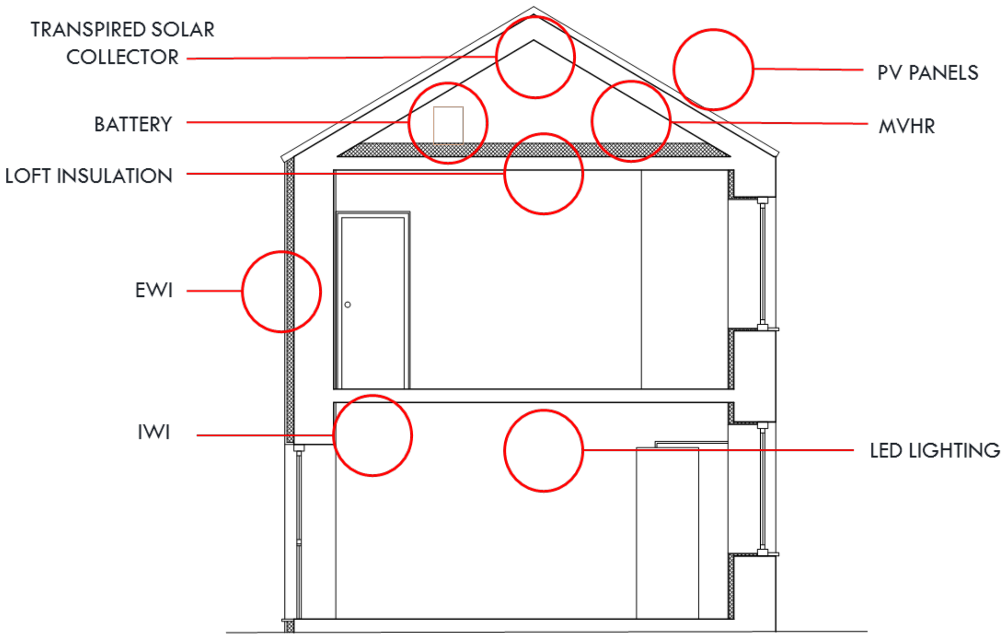

Figure 1. Case study visualisation of the interventions

A hard-wired and wireless monitoring kit was installed to facilitate undisruptive and occupants-disturbance-free data mining. The post intervention monitoring phase consisted of another set of occupants' interviews as well as extensive monitoring the building's systems and comfort over twelve-months, at 5 minutes intervals. High accuracy, calibrated electrical, gas and heat meters were used to measure the energy generated, consumed, imported, exported or stored. Environmental sensors and a weather station were used to measure comfort levels and ambient weather data; in addition, a variety of fabric tests were applied before and after the retrofitting to identify changes in air tightness, infiltration, thermal bridging and thermal resistance. The long term data were collected in a central logging device and data sets were transferred wirelessly every 5 minutes to the WSA servers for online supervision, storage and analysis. A summary of the results is presented in this study in combination with the modelling exercise to discuss the performance gap, which is expressed as a percentage of difference between the modelled and the monitored value. Also, annual data were compared against UK average energy use of a similar building.

3. Results and Discussion

Following a two-year monitoring period, form May'17 to April'19, the annual monitoring data are summarised and compared against initial modelling and national averaged data for similar type dwelling from the National Energy Efficiency Data (NEED) [15]. Figure 2 indicates the main pre and post retrofit annual figures for space heating and electricity as they were measured and modelled for the case study house. The pre-retrofit monitored electricity consumption is close (4% difference) to the UK average electricity consumption for a similar house, whereas the monitored space heating delivered through the radiators was 28% greater to the UK average. This was considered to be a result of the different heating demand profile of the tenants, a family with two children, spending most of the time at home (social housing). Another interesting indication from figure 2 is the electricity export (3217kWh measured) which could serve, in annual total figures, a second house of a similar annual electricity demand. Using 2019 UK end user electricity price (16p/kWh), the total potential excess electricity costs £515.

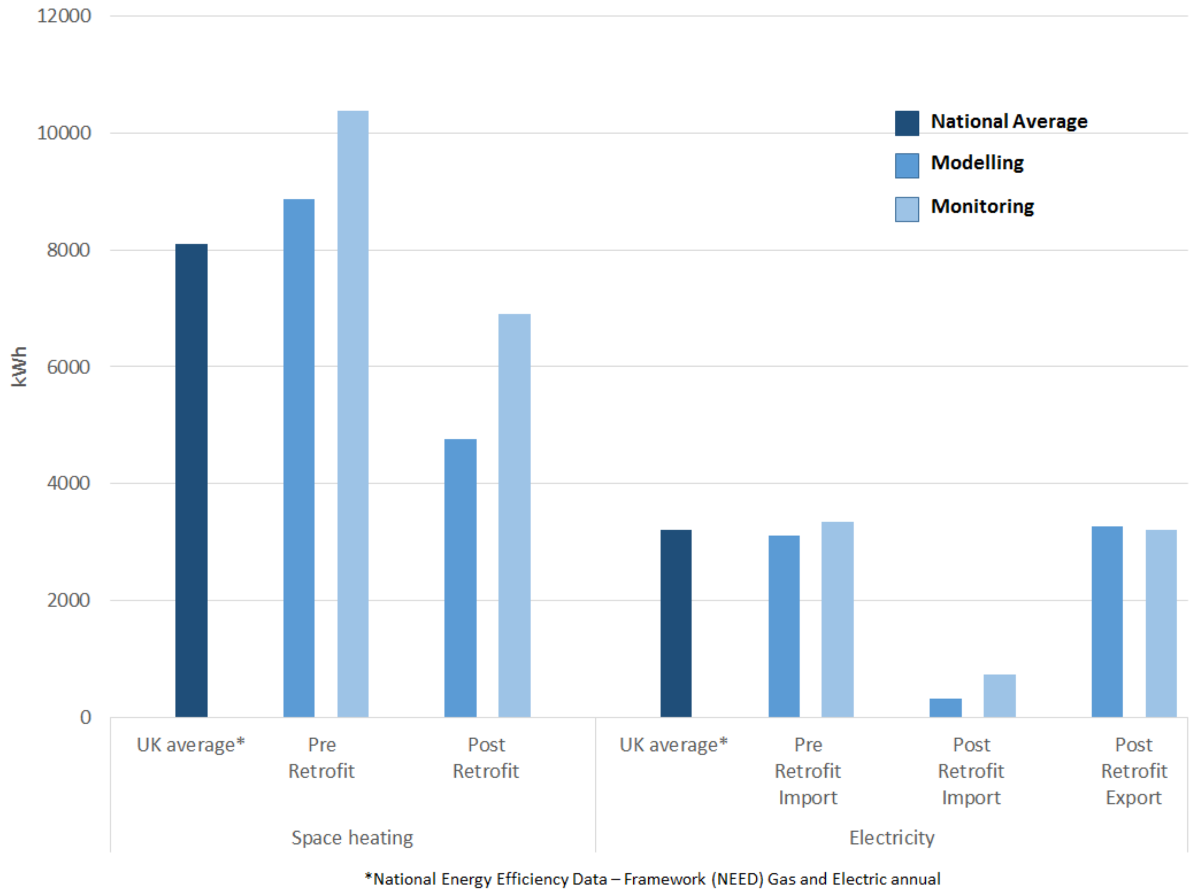

Figure 2. Monitored & modelled annual space heating and electricity balance pre and post interventions

Table 1. Case study: Annual building and systems performance overview.

Category	Performance Indicator	Pre-retrofit Model	Pre-retrofit Monit	Post-retrofit Model	Post-retrofit Monit	Pre/Post Model Change %	Pre/Post Monit Change %	Model vs Monitor: Performance Gap %	Comments
Whole house	Electricity Use (kWh)	3106	3338	2866	2683	7.7	19.6	6.4	Electric shower is used less after the retrofitting
	Gas Use (kWh)	12911	15246	8084	10708	37.4	29.8	-32.5	Pre & Post int. temp. differences reflected in gap, + infiltration and natural ventilation differences
Energy Use	Grid Import (kWh)	3106	3338	325	727	89.5	78.2	-123.7	Battery Losses is a significant contribution to the gap
	Grid Export (kWh)	N/A	N/A	3264	3217	N/A	N/A	1.4	
	Gas Boiler (kWh)	11816	14065	6989	10024	40.9	28.7	-43.4	Pre & Post int. temp. differences reflected in gap
	Gas Cooking (kWh)	1095	1181	1095	684	N/A	42.1	N/A	No gas cooker upgrading in the modelling
	Space Heating (kWh)	8859	10383	4756	6908	46.3	33.5	-45.2	Model refer to demand, monitoring refer to delivery
	Hot Water (kWh)	1185	932	1185	726	0.0	22.1	38.7	Model refer to demand, monitoring refer to delivery
Systems Break-down	PV Generation (kWh)	N/A	N/A	5914	5493	N/A	N/A	7.1	
	Battery Charge (kWh)	N/A	N/A	1092	1307	N/A	N/A	-19.7	Battery Losses contributes to a 215kWh extra demand
	Battery Discharge (kWh)	N/A	N/A	983	1032	N/A	N/A	-5.0	
	MVHR Consumption (kWh)	N/A	N/A	131	176	N/A	N/A	-34.4	
	MVHR Heat Delivery (kWh)	N/A	N/A	1303	766	N/A	N/A	41.2	Modelled for a greater mass flow rate
	TSC Heat Delivery (kWh)	N/A	N/A	410	479	N/A	N/A	-16.8	
	LED lighting (kWh)	621	N/A	248	201	60.1	N/A	19.0	
	Total Ventilation Heat Gain/Loss (kWh)	-4585	N/A	-2944	N/A	35.8	N/A	NA	Due to air tightness - sealing and MVHR+TSC
	Internal Gain - Activity (kWh)	4409	N/A	4092	N/A	7.2	N/A	NA	
	Solar Gain (kWh)	3376	N/A	3376	N/A	0.0	N/A	NA	
	Fabric Heat Loss (kWh)	-12060	N/A	-9280	N/A	23.1	N/A	NA	Due to Insulation
Comfort	Heating Degree Days (HDD)	1926	2080	1926	1837	0.0	11.7	4.6	February and March '19 were hoter comapred to the '18
	Average Annual Int. Temp. (ºC)	18.5	19.8	20.2	20.5	-9.2	-3.5	-1.5	
	Average Heating Season Int. Temp. (ºC)	16.8	18.6	18.9	18.9	-12.5	-1.6	0.0	
	Average Summer Relative Humidity (%)	NA	63%	NA	55%	NA	12.7	NA	
Cost	Total Cost of interventions (£)	NA	NA	48000	55000	NA	NA	-14.6	Monitoring and aesthtic works is included in the monitoring

In this study, annual figures are presented as an easy to read comparative tool between modelling and monitoring and between pre and post intervention status. Table 1 presents an overview of the performance of the house including different depths of analysis shown in relation to the categories of the performance indicators. A whole house energy performance is described in terms of the annual energy used in electricity and gas. A gas reduction of 4538kWh (29.8%) and an electricity import reduction of 2611kWh (78.2%) was measured. Electricity use is relatively easier to predict, which leads to the modelling and monitoring results to be in good agreement (6,4% gap). The monitored change in electricity use between the pre and post retrofit (19.6%) is considered to be due to behavioural change in the use of the electric shower as well as supplementary electric radiative heaters that are now not needed. The modelled and monitored gas use was reduced by approximately 1/3. however, the absolute numbers are different, and the performance gap between modelled and monitored values is significant. Heating Degree Days (HDD), presented in table 1 below, indicate that the heating season of 2017-18 was different than the 2019-20 one (12%). February and March 2019 were milder than the year before, and also milder than the CIBSE averaged weather data that was used in the modelling process. Also, the air infiltration rate used in this modelling process was based in reference data which does not respond to the individual occupants who keep the kitchen back door open to enhance the natural ventilation and reduce the CO2 produced by smoking, which significantly contributes to heat losses during the heating season. All these reasons were considered to contribute to the predicted versus monitored difference in gas use, as well as the space heating requirements and a further modelling calibration and monitoring normalisation is needed in a performance gap study.

A thorough look into the energy use and the systems breakdown reveals the considerable reduction of electricity imported as a result of the combination of the PV panels and the battery. 38% of the electricity demand is covered by the battery and another 35% by the PV panel, directly resulting an annual self-sufficiency of 73% (that is, the time the house operates independent of the grid). An interesting finding is the benefit of the west-east PV panel which allows for a smaller inverter to be used and at the same time matches better the daily electricity usage profile of the household. On the other hand, the modelling/monitoring disagreement in battery charge may be an indication of reduced battery performance because of the temperature variations in the attic and the excessive times that the battery was fully charged (not used) in the clear sky summer days.

After the team explained the new systems to the occupants, there was a behaviour change in the use of electrical appliances, which were used more within sunshine hours, when the photovoltaic panel was able to fulfil the electrical loads. LED lighting enhanced electricity savings (201kWh) whereas MVHR's fan increased the electricity use (176kWh). The heat delivery of the MVHR is different between monitoring and modelling; this is due to a reduction in air change rates to eliminate drafts in the living spaces. The TSC system contributed 479kWh; however, it needs to be mentioned that it reduces the effectiveness of the MVHR, since part of this energy would be delivered by the MVHR in TSC's absence as described in Perisoglou et al [16]. The insulation decreased the fabric heat loss of the building and the infiltration and the MVHR controlled the moisture in the living spaces which was a major benefit in comfort, as indicated by the monitoring process and interviews.

The total cost of the interventions was £55K which is relatively high comparing to a new building cost but within the cost range of similar projects [2, 3]. Approximately 1/3 of the cost relates to aesthetic improvements, which included relocation of the boiler, new rainwater downpipes, integrated gutters, new roof eaves, and the TSC-PV architectural integration, and also the monitoring and testing which would be avoided in a commercial project.

4. **Conclusions**

This case study shows a 34% reduction in space heating and a 78% reduction in electricity import for a deep retrofit semi-detached dwelling in south Wales. All the technologies used are available in the market; however, some bespoke cladding and ducting work needed to provide a good standard of aesthetics to the envelope, and to interlink the solar air heating system to the MVHR. The pre-intervention base case is in good comparison with UK average house energy use, indicating that a number of these technologies could be widely replicated. Also, the annual electricity export (3217kWh) equals the annual electricity demand of a second similar dwelling with a potential of £515 savings (storage depended). The reduction in electricity import resulted to £418 saving annually whereas another £182 were saved from the gas reduction. Outcomes of each system were also examined and their contribution to the total energy reduction was evaluated indicating that the PV and battery can further interact with the grid with further financial and grid balance benefits. The paper also indicates that occupants that spend time at home during the day are benefited from west - east pitch roof to achieve an improved distribution of the photovoltaic generation throughout the day. The MVHR reduced the moisture and the CO2 in the living spaces with a direct health benefit. The total cost of the retrofit was £55K; however a third of this could be avoided in a commercial application.

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