Five energy retrofit houses in South Wales

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Highlights:

1. Combines computer energy simulation and field measurements to analyse the seasonal energy performance of five whole-house energy retrofits.

2. Presents the annual energy, CO2 and cost savings associated with combining energy efficiency measures, building integrated solar PV, and battery storage.

3. Presents the costs of retrofitting with an emphasis on affordability.

4. Estimates the in-house energy use of battery storage and associated costs and cost savings.

Abstract:

With around 1−2% annual replacement of the UK's housing stock, housing retrofit must play a major role in reducing future energy use and CO_2 emissions. This paper presents a whole-house approach for energy retrofit for five houses located in South Wales. This 'systems based' approach combines reduced energy demand, renewable energy supply and battery storage. The paper describes a combination of energy modelling, using the building energy model HTB2, and field measurements to analyse the performance of the houses before and after retrofit. The results indicate that significant reductions in energy use, CO_2 emissions and energy costs can be achieved using a whole house approach, combining energy efficiency with building integrated renewable energy generation and energy storage. CO_2 emission reductions are estimated to be in the range of 50−75%, with cost savings of £402 to £621 per year. The cost of carrying out the retrofitting ranges from £23,852 to £30,510. Although retrofits are still relatively expensive in relation to their annual cost savings, there are multiple benefits relating to reducing fuel poverty, reducing electricity grid stress and contributing to national CO_2 emission reduction targets. Also, as costs of measures are further reduced and energy prices likely to rise in future, the cost balance will change more in favour of whole house retrofit. The paper demonstrates the advantages in using a combination of energy simulation and field monitoring to investigate the performance of buildings in use, which in this case concerns the impact of carrying out energy retrofits in housing.

Key Words: Energy retrofit, Housing, Energy simulation, Building energy monitoring, Energy costs, Battery storage.

1 Introduction

The UK is committed to achieving an 80% reduction in CO_2 emissions by 2050 (HM Government, 2008). The built environment, and housing in particular, is likely to be a major focus to achieve these targets. Housing currently accounts for some 29% of the UK's total energy consumption (DECC, 2014a). There has been an interest in reducing energy use in housing since the oil crisis of the 1970's, with the trend from low energy, to passive design, sustainable design, zero carbon design (Jones, 2012). However, the emphasis has mainly been on the design of new houses. Following European directives, the UK target for CO_2 emissions for new housing is to be nearly-zero energy by 2018 for the public sector and 2020 for the private sector (European Union, 2010). There are also European 2030 CO_2 emission reduction targets, which includes a target of 27% energy savings and 27% renewables (European Council, 2014), with an increased focus on energy efficiency.

The current rate of new build in Wales is around 0.4% (National Statistics, 2016), and it is estimated that 75% of the UK's housing stock that will exist in 2050 has already been built (Wright, 2008; Ravetz, 2008). So, in the short term, new build will not have a major impact in achieving overall CO_2 emission target reductions, and it will be necessary to retrofit existing housing. A range of large-scale elemental retrofit programmes have been carried out in Wales, including the Welsh Government ARBED scheme (Patterson, 2012). Although they have produced useful energy savings, and other benefits associated with affordable warmth and improved living conditions, they have tended to use an elemental rather than a whole house approach (Jones et al., 2013a) and so CO_2 emission reductions will not contribute sufficiently to national targets. Alternatively, a 'whole house' or 'deep retrofit' approach integrates a combination of measures tailored to a specific property. There is a cost increase in going from relatively simple elemental 'shallow retrofit' measures to a multifaceted whole-house 'deep retrofit' approach, as the cost of measures rise in relation to the predicted savings

(Jones et al., 2013a). Between 2010 and 2012 a series of 'deep' energy retrofits, commissioned by the UK government, demonstrated CO_2 emission reductions of between 40% and 85%, with the cost of measures ranging from £50,000 to £168,000 (Baeli, 2013). There have also been schemes, such as the 'Target 2050' programme by Stroud District Council, where the retrofitting of 10 houses was estimated to provide between 47% to 74% reduction in carbon dioxide emissions (based on household meter readings) for an investment range of £18,000 to £47,000 (with the majority less than £25,000) (Stroud District Council & Severn Wye Energy Agency, 2011). A small number of so-called 'Superhome' owners in the UK have renovated their homes, reducing CO_2 emissions by 60% or more, although there does not appear to be any robust cost and in-use performance data available (Fawcett and Killip, 2014).

So, it seems that large-scale elemental retrofit programmes are not achieving CO_2 targets, while whole house deep retrofits may be perceived as costly, and there is a lack of measurement data to compare with predicted performance. This paper presents the findings from five whole house 'deep' retrofit case studies, located in Wales, UK, carried out as part of the SOLCER (Smart Operation for a Low Carbon Energy Region). The project was funded by the European Regional Development programme (ERDF). The purpose was to investigate an affordable and replicable 'system' based approach, applied to typical houses of different construction and age, located across South Wales. For this project, the 'systems' based whole-house approach combines reduced energy demand, renewable energy supply and energy storage. It focuses on optimising the integration of technologies and design as a whole for a specific building, rather than taking the more traditional 'bolt on' elemental approach, applying individual measures across large numbers of buildings but generally with little attention to the specific requirements of individual buildings. The aim was to achieve significant CO_2 emission reductions at an affordable cost.

For all five houses, dynamic thermal simulation and energy modelling was carried out to predict building energy performance within the early stages of the retrofit process and to inform the selection of the package of retrofit measures. The simulation results were subsequently combined with the post-retrofit monitoring data in order to analyse annual energy performance and estimate potential energy, CO_2 and cost savings associated with the retrofit measures. The main focus in this paper is to demonstrate how modelling and monitoring can be combined to help identify the most appropriate replicable and affordable combination of measures and then to help understand the resulting overall energy performance.

1.1 Background: wales housing stock

The total number of dwellings in Wales is around 1.4 million, with the largest percentage constructed before 1919, and some 78% constructed before 1983 (Figure 1) (Valuation Office Agency, 2014), which is when energy efficiency was first introduced in the UK building regulations. Housing in Wales is relatively older than in other parts of the UK. Older houses can prove harder to treat, for example, due to their solid-wall construction.

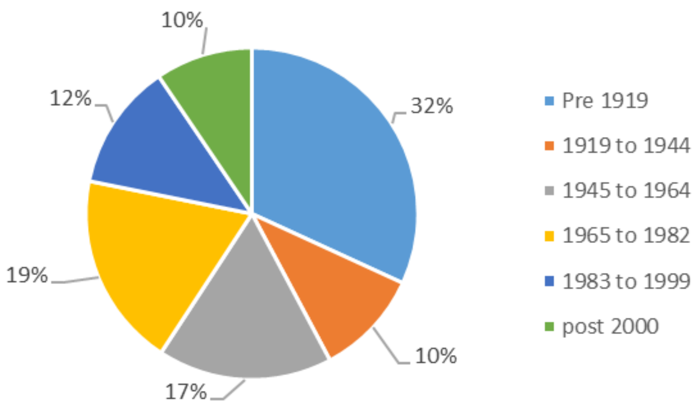

Figure 1: Welsh housing age breakdown (Valuation Office Agency, 2014)

There have been a range of subsidised housing retrofit initiatives in the UK, such as the Energy Efficiency Commitment (EEC), Carbon Emission Reduction Target (CERT) and Community Energy Savings Programme (CESP), which have placed obligations on energy supply companies to fund programmes to reduce energy and CO_2 emissions from households. For example, programmes involving these schemes have resourced the installation of over five million energy-saving measures in existing houses between 2008 and 2011 (DECC, 2011). This is in addition to private funded work on individual houses. It has been estimated that if the savings through insulation and heating efficiency improvements from 1970 onwards had not been made, then energy consumption in UK homes would be around twice the current levels (Office of National Statistics, 2011). In Wales, the ARBED regeneration programme (Welsh Government, 2013) has provided finance for local authorities and registered social landlords (RSLs) to upgrade the energy performance of their existing housing stock. The 'Green Deal' (DECC, 2010), was aimed at the private sector, but this failed to deliver and was withdrawn in 2015, which together with the recent reductions of government initiated funding, means that currently there is little government led finance to encourage large-scale retrofit programmes.

Energy savings and CO2 emission reductions should not be seen as the sole benefit of retrofit programmes. Housing standards have a considerable impact on health and quality of life, for example, on major health issues such as cardiovascular disease, accidents and mental health (Jones, Patterson, & Lannon, 2007). The Marmot Review has called for action on policy level to reduce health inequalities, which, on the housing side, includes ensuring healthy standard of living for all, and creating and developing healthy and sustainable places and communities (Marmot et al., 2010). An estimated 30% of the population in Wales lives in fuel poverty, which measured with an official indicator of 10%, is above the UK national average of 15% (BEIS, 2017), where affordable warmth is the main concern. Substandard housing, which are often hard to heat, is estimated to cost the National Health Service (NHS) some £2.5 billion a year through building-associated health-related issues (National Housing Federation/ ECOTEC, 2010). Also, any wide-scale application of energy-efficiency measures should accept that some of the benefits would be realized as increased warmth and not just energy savings. It is estimated that this 'take back' through improved comfort may account for up 50% of the energy-saving measures (Lomas, 2010).

1.2 Retrofit strategies

Energy use and the resulting carbon emissions of houses can be reduced significantly through whole-house retrofits. Energy retrofit technologies are designed to reduce energy demand, especially space heating, which in the UK comprises around 66% of the domestic energy use (DECC, 2014b). Fabric insulation is generally considered to be the most effective strategy. It has been reported that cavity wall insulation can potentially reduce up to 40% heat loss through the walls (EST EEBPH, 2003). Older solid wall houses can be upgraded through roof and external wall insulation (EWI), which may reduce heat loss by 50%-80% (Roberts, 2008). However, there are concerns that the insulated wall performance may not be achieved in practice due to construction details and poor workmanship (HM Government, 2015). Insulating existing ground floors can prove disruptive and is only likely to be viable during major refurbishment programmes (BRE, 2005). Although many lofts already have some level of insulation, loft 'top-ups' can be cost effective, bringing them to a minimum thickness of 270mm, the same as current Building Regulations for new build. Improving air tightness can also reduce heat loss from ventilation (Everett, 2007), and can be an ancillary benefit from upgrading the building fabric, particularly windows and doors. Ideally, upgrading the building envelope should be accompanied by a more energy-efficient system sized for the reduced heat loss, with modern boilers achieving over 90% efficiency (Everett, 2007).

Mechanical Ventilation Heat Recovery (MVHR) has the potential to reduce space heating losses by pre-heating the supply air through recovering heat from the stale exhaust air. MVHR can also improve indoor air quality by providing a constant rate of fresh air. It works well in an airtight house, however, for a property with poor airtightness, or if the system is not correctly installed or commissioned, it can potentially increase energy use (White, 2016). Electrical energy demand can be reduced using LED lighting and energy-efficient appliances. LED lamps can typically save 80% electricity compared to conventional incandescent lamps (DoE, 2014), and last longer with less maintenance. Low energy electrical appliances can significantly reduce energy use (Borg and Kelly, 2011) but their operation can vary greatly with occupant behaviour.

Building integrated renewable energy supply can be used to contribute to the reduced energy demand. The current average annual solar resource in the UK is estimated to be 101 W/m^2 (Burnett et al., 2014), or 2.4 kWh/m^2/day. Solar PV panels have efficiencies typically of up to 20%, depending on the type of PV technology used (Roedern and Ullal, 2008). The electricity generated from Solar PV can be stored using batteries, maximising its use onsite, and only surplus power exported to the grid.

2 Method

The package of energy saving measures applied to an individual house should be appropriate to its specific needs and will differ from house to house. The five retrofit cases investigated represented a range of house types and ages (Figure 2). The houses are all in the social housing sector and owned by Registered Social Landlords (RSLs).

2.1 Whole house retrofit strategy

The procedure for carrying out retrofitting employed a staged process to ensure that a cost effective and appropriate package of measures was applied to each house type:

1. At the start of each retrofit, a survey was carried out to determine what retrofit measures were generally appropriate for the specific house. All stakeholders were involved in the project decision-making process, including the project management team, contractors, property owners, modellers and residents. The surveys were based on a fabric first approach, including external wall insulation, loft insulation, improved glazing and air tightness. This was followed by consideration of heating and ventilation systems and renewable energy.
2. The options for retrofit measures were modelled for each house in order to estimate their impact on energy consumption, CO_2 emissions, and operating cost savings.
3. An optimum package of measures for each house was selected, considering budget limit and work timetables, and the installation took place. Acceptability of budgets and operational maintenance issues were discussed with the social landlords.
4. The five SOLCER retrofit case studies were then monitored over a two-year period.

Figure 2: The 5 retrofit houses before and after retrofitting

Table 1: Information summary of the 5 case study retrofits

	Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5
Basic information	Pre-1919, 67 m^2 2-bed end-terrace, solid wall, gas boiler.	1960s , 70 m^2 3-bed semi-detached, cavity wall, gas combi-boiler.	2000s, 86 m^2 3-bed semi-detached cavity wall gas boiler	Pre-1919, 74 m^2 2-bed mid-terrace, solid wall, gas combi-boiler	1950s, 80 m^2 3-bed semi-detached, cavity wall, gas combi-boiler
Retrofit measures	EWI (100mm); Loft insulation (300mm); Low-E double glazing; MVHR; LED lighting; New gas boiler with hot water tank.	Gable cavity wall insulation Front 1st floor EWI (50mm); Loft insulation (300mm); MVHR; LED lighting; New gas combi boiler.	Loft insulation (300mm); Positive pressure ventilation supply from loft space. LED lighting; New gas boiler and hot water tank.	Rear EWI (100mm), Front internal wall insulation; Loft insulation (300mm); Floor and roof insulation to the rear extension; LED lighting.	EWI (100mm) Overclad to existing cavity wall insulation; Loft insulation (300mm); LED lighting.
PV	2.5 kW$_p$ PV roof	2.7 kW$_p$ PV roof	4.5 kW$_p$ PV roof	2.6 kW$_p$ PV roof.	3.97 kW$_p$ PV roof:
Energy storage	Lead acid battery: 4.8 kWh feed LEDs and hot water.	Lead acid battery: 8.5 kWh feed LEDs and fridge.	Lead acid battery: 18 kWh feed all electrical appliances.	Lithium battery: 2.0 kWh feed all electrical appliances	Lithium battery: 10 kWh feed all electrical appliances.
Costs	£30,452	£27,438	£30,446	£23,852	£30,510

Table 1 presents the applied retrofit measures relating to energy demand reduction, renewable energy supply and energy storage, alongside the overall costs. Three of the older houses had EWI applied. Retrofits 1 and 4 were of a solid wall construction, with the latter having internal wall insulation applied to the front elevation to retain the external stone finish. Retrofits 2, 3 and 5 had cavity wall construction. Retrofit 2 had the existing gable cavity wall insulation removed and refilled. Two of the houses, Retrofits 1 and 5, were empty houses, so measures could be applied without any occupant disruption, and retrofit 1 had MVHR installed. For the remaining three retrofits, measures were carried out with the occupants in residence. All houses had an integrated PV roof replacing the existing southerly roof, and in most cases the existing roof was in need of replacement. The first three retrofit houses had lead acid batteries installed for electricity storage, whereas the last two used lithium batteries, as their cost and performance became acceptable as the project developed. The battery size was chosen in relation to the area of PV that could be fitted to the roof, and the predicted electricity demand based on the number of occupants. All houses retained their existing gas heating systems, with Retrofits 1,2 and 3 having a new boiler installed.

Air leakage measurements were carried out before and after the retrofit to assist in the modelling exercise, and the results are presented in Table 2. The air leakage rates for an indoor-outdoor pressure difference of 50Pa were measured by a blower door pressurisation test according to the standard of BS EN13829:2001. A blower door fan system was fitted to the main entrance doorway, and the tests carried out with all internal flues and chimneys sealed. The air change rates were then estimated based on the measured air leakage rates (Table 2) according to the LBL Infiltration Model (Sherman and Modera, 1986) and these were used in the energy modelling. No fabric improvements were carried out for Retrofit 3, so the pre-retrofit air leakage rate still applied. Retrofit 5 was not available to carry out the post-retrofit air leakage tests.

Table 2: Air leakage rates measured before and after the retrofit installation (estimated ventilation rates used in the energy modelling are in brackets, in air change per hour at atmospheric pressure (h^{-1}))

	Retrofit 1 $m^3.h^{-1}.m^2$ (h^{-1})	Retrofit 2 $m^3.h^{-1}.m^2$ (h^{-1})	Retrofit 3 $m^3.h^{-1}.m^2$ (h^{-1})	Retrofit 4 $m^3.h^{-1}.m^2$ (h^{-1})	Retrofit 5 $m^3.h^{-1}.m^2$ (h^{-1})
Before retrofit	13.5 (0.75)	9.6 (0.54)	7.4 (0.36)	8.9 (0.48)	7.9 (0.41)
After retrofit	7.0 (0.39)	7.6 (0.43)	Not available	10.1 (0.55)	Not available

The costs of retrofitting were in the range £23,852 to £30,510 (Table 1), which is at least 50% lower than the earlier UK government programme of retrofits (Baeli, 2013) and comparable to the Stroud programme (Stroud District Council & Severn Wye Energy Agency, 2011). Energy retrofitting may be linked to carrying out other general ‘refresh’ improvements, such as re-roofing and re-rendering, to maintain housing standards, and so costs could potentially be further reduced.

The retrofit houses were monitored from the completion of the refurbishment for a period of two years from January 2015. The data used in this paper is from January 2016 to December 2016, which contained a period of unchanged occupancy.

2.2 Energy simulation

Energy simulation modelling was first used during the planning stage of the retrofitting process, using the computer simulation framework VirVil SketchUp (Jones et al., 2013b). This was developed at the Welsh School of Architecture, Cardiff University, and is based around the well-established dynamic building energy model, HTB2 (Lewis and Alexander, 1990). Input data includes: the hourly climate for the location; building materials and construction; space layout; system and occupancy profiles. The HTB2 software has undergone a series of extensive testing and validation, including the IEA Annex 1 (Oscar

Faber and Partners, 1980), IEA task 12 (Lomas, 1994) and the IEA BESTEST (Neymark et al., 2011). By linking HTB2 with SketchUp it can simulate multiple buildings in a community, considering overshadowing impacts from neighbouring buildings, landscape features and topography (Jones et al., 2013b).

The modelling exercise estimated the energy demand and the total net CO_2 emissions before and after retrofitting. CO_2 emission factors (BRE, 2014) were used to estimate CO_2 emissions associated with the predicted values of electricity and gas energy supply. The operating energy costs were estimated from the current domestic fuel prices. Income from the electricity generated by the solar PV was estimated using information from the UK Government's feed-in tariff scheme (Ofgem, 2017).

The five retrofit properties are located between Cardiff and Swansea, in South Wales, UK. The modelling used the following information:

- Weather data: HTB2 accepts a meteorological file, which can be converted from the weather data format EPW file using ‘Weather File Convertor’, a sub-software within the HTB2 suite. All five retrofit houses were simulated with the same weather conditions. The original EPW file was the Test Reference Year (TRY) weather file for Cardiff, sourced from the 2006 CIBSE Weather Data. This uses a 21-year baseline, with average months selected from 1983 to 2005. The weather station, which is located at Cardiff Airport, is within 25 miles of all five retrofit houses. Post-monitoring simulations used weather data collected on site.
- Building data: HTB2 uses the dimensions of the house and the building fabric construction details. Data from the literature (Allen E. and Pinney A., 1990; Zimmermann et al., 2012) was used to develop the occupancy energy use profiles, including heating, internal gains from people, lighting and other appliances. The houses with the same number of occupants are set with the same internal gains. Occupancy profiles are set with

the same schedule but vary with the actual number of occupants in the houses. The ventilation rate was based on measurements from the air leakage tests (see Table 2), which was further adjusted for monthly wind speed and ventilation system (BRE, 2014).

2.3 Post-retrofit energy monitoring

Building monitoring can identify how the building works in relation to its design and to further enhance both the comfort and energy efficiency (Gram-Hanssen, 2010 & 2011). The five retrofit houses were monitored after the energy interventions. It was not possible to carry out pre-retrofitting monitoring. Before and after comparisons were therefore based on a combination of pre- and post-retrofit modelling and post retrofit monitoring. All retrofit houses were monitored for more than a year of unchanged and continuous occupancy from January 2016 to December 2016.

All sensors were calibrated or tested before installation. A mixture of wireless and wired sensors were connected to data loggers. The logging time interval was five minutes and the data was synchronised and remotely collected via SIM cards and transferred to a central database for analysis.

Three types of monitoring data were collected, as follows:

(i) Weather data, including external air temperature, wind velocity, global horizontal solar radiation, relative humidity, ambient air pressure and rainfall.
(ii) Comfort related data, including indoor temperature in the main living spaces.
(iii) Metered energy data associated with the solar PV, inverters, batteries, MVHR, heating, and electrical appliances.

3 Results

The analysis of modelling and monitoring was carried out using the following approach:

- Modelling was applied to estimate the potential retrofit improvements and select the final package of measures for each house.
- Monitoring was used to measure the post-retrofit performance.
- The modelling and monitoring results were combined to further understand the impact of the retrofit measures. This process used the on-site weather data, the measured indoor air temperatures, and measured hot water and cooking loads.
- Further modelling was used to explore optimising battery performance.

3.1 Modelling results

Figure 3 presents the annual energy modelling results for the pre-retrofit and post-retrofit energy demand and energy supply. The results are broken down into total annual gas and electricity supply, space heating, domestic hot water use, electricity use (appliances and lighting) and cooking. The estimated energy and cost savings are presented in Table 3. Electricity savings range from 37% to 84%, and gas (space heating and domestic hot water heating) savings generally range from 6% to 56%. Retrofit 3 had little improvement to its fabric and no predictable impact from other measures. CO_2 emission reductions range from 49% to 74%. Cost savings range from 52% to 85%, which equates to between 402 and 661 £/annum based on current gas and electricity costs and feed-in tariffs.

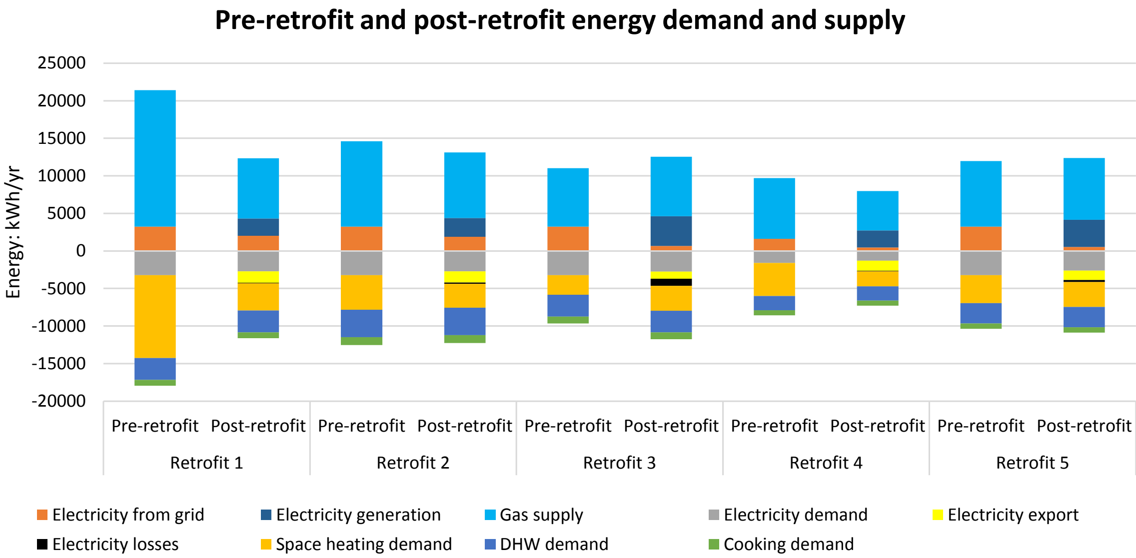

Figure 3: Predicted pre-retrofit and post-retrofit energy demand, supply

Table 3: A summary of performance optimisation through domestic retrofit

	Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5
Reduction of electricity imported from the grid	37%	41%	79%	72%	84%
Gas reduction	56%	23%	0	35%	6%
CO_2 reduction	64%	49%	54%	74%	61%
Cost savings	62%	52%	85%	81%	84%

3.2 Comparing monitoring and modelling results

The post-retrofit values from the monitoring and modelling results are presented in Table 4. Temperature values are for the heating season period, whereas energy values are annual. The external heating season average air temperature is similar, within 1°C, for all monitored retrofit houses. The modelling used the same weather data for all retrofit houses. The internal monitored average temperatures were generally within 1°C of the modelled values, which had their set points adjusted from the initial modelling carried out at the start of the programme (when the modelling was used to inform the selection of retrofit measures), based on the measured data. The temperature (thermostat) set-points used in the modelling were based on observations of typical measured internal air temperatures during the heating season for each retrofit. The modelling set-point remained the same for the heating season, that is, it was not continually adjusted to match the measured internal air temperature data. The annual global solar radiation was similar for both modelled and monitored situations. The associated PV electricity generation values were also similar, indicating that the modelling of solar PV electricity generation is reliable. The measured electricity consumption varied from the assumed modelled values as might be expected due to the specific occupancy patterns of the retrofit houses. However the predicted gas consumption was relatively similar, generally with around 10%, with only Retrofit 1 showing a larger (21%) difference. This implies that the model reliably predicts overall heating energy performance, accepting the adjustment of internal air temperature modelling set points based on measured data.

Table 4: A comparison of monitoring and modelling results

			Retrofit houses	**Retrofit1**	**Retrofit2**	**Retrofit3**	**Retrofit4**	**Retrofit5**
			Number Occupants:	**2 adults & 1 child**	**2 adults & 2 children**	**2 adults & 2 children**	**1 adults & 1 children**	**3 adults and 2 children**
Performance Indicator		**Data Type**	**Unit**					
I	External temperature heating season average	Monitoring	^0C	7.8	8.7	8.4	7.8	8.2
		Modelling	^0C	7.5	7.5	7.5	7.5	7.5
II	Internal temperature heating season average	Monitoring	^0C	18.1	19.5	18.5	16.6	19.5
		Modelling	^0C	18.7	18.8	19.8	17.1	19.7
III	Global solar radiation annual average	Monitoring	W/m^2	107.8	116.8	118	106.7	109.5
		Modelling	W/m^2	114	114	114	114	114
		Difference	%	+5.8	-2.4	-3.4	+6.8	4.1
IV	PV electricity generation annual total	Monitoring	kWh	2150	2395	3439	2007	3458
		Modelling	kWh	2280	2480	3964	2283	3626
		Difference	%	+6.0	+3.5	+15.3	+13.8	+4.9
V	Electricity Import from grid annual total	Monitoring	kWh	1668	3256	3728	656	1524
		Modelling	kWh	2032	1902	667	451	518
		Difference	%	+21.8	-41.6	-82.1	-31.3	-66.0
VI	Electricity Export to grid annual total	Monitoring	kWh	1106	1508	1037	1124	2625
		Modelling	kWh	1498	1509	959	1332	1262
		Difference	%	+35.4	+0.1	-7.5	+18.5	-51.9
VII	Electricity	Monitoring	kWh	2711	4143	6131	1539	2447

	Consumption annual total	Modelling	kWh	2727	2712	2748	1311	2622
		Difference	%	+0.6	-34.5	-55.2	-14.8	+7.2
VIII	Gas consumption annual total	Monitoring	kWh	10570	9841	8553	5918	9038
		Modelling	kWh	8026	8733	7900	5251	8233
		Difference	%	-24.1	-11.3	-7.6	-11.3	-8.9

Figure 4 compares the overall annual electricity consumption for the modelled and monitored results, together with the UK average domestic annual gas consumption for reference. The monitoring results show a wide range of values across the retrofit houses. Retrofits 1, 4 and 5 indicate close comparison between the measured and modelled results (with the modelled electricity patterns of use based on information from the literature as explained earlier), whereas the modelled and monitored values for Retrofits 2 and 3 are very different. The actual electricity energy use depends on the user behaviour and large variations are to be expected. Retrofits 2 and 3 have a relative high occupancy with occupants spending much of their time at home, which may account for their relatively high electricity use.

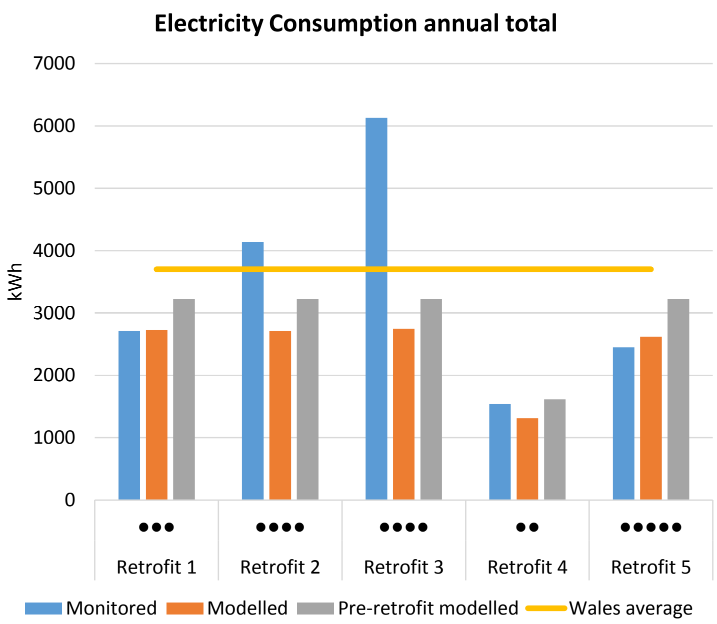

Figure 4: Comparison of annual modelled and monitored electricity consumption.

The balance of measured annual electricity demand and supply is summarised in Figure 5. The Figure illustrates the amount of PV generation used directly in the houses, and the electricity exported to the grid and imported from the grid. The grid imported electricity ranges from 656 kWh/annum to 3728 kWh/annum, and 1037 kWh/annum to 2625 kWh/annum for grid export electricity (see also Table 4). Retrofit 3 has the highest demand consumption and therefore the lowest export to the grid. Retrofit 5 has the highest export to the grid and together with the PV electricity used directly, is energy positive in relation to electricity use.

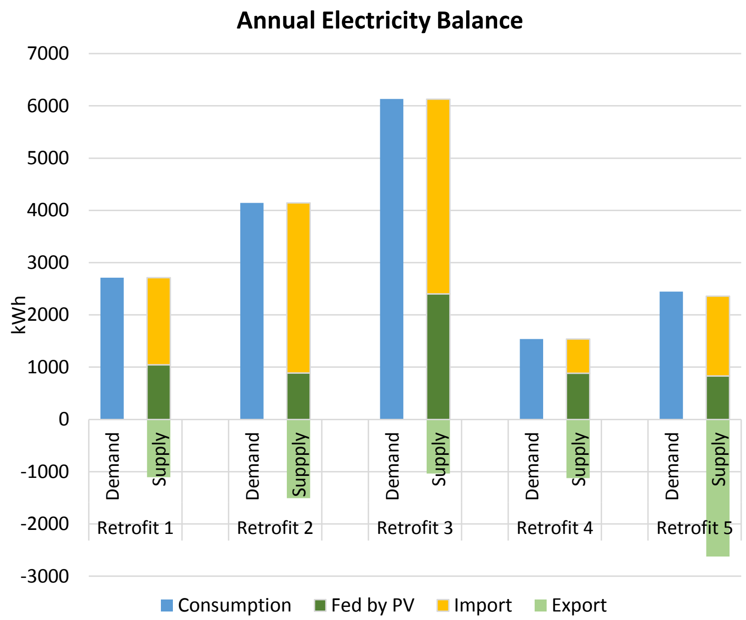

Figure 5: The balance of measured annual electricity supply and use.

Figure 6 compares the annual gas consumption for the modelled and monitored results together with the UK average domestic annual gas consumption for reference. Interestingly, all cases except Retrofit 1 are below the UK average consumption values for both pre- and post-retrofit results. This may be due to the variation of building age, previous energy efficiency measures carried out, number of occupants and associated occupant behaviours. The modelled and monitoring results compare quite well and the modelling indicates significant energy savings from the application of thermal insulation to the external envelope as summarised in Table 3.

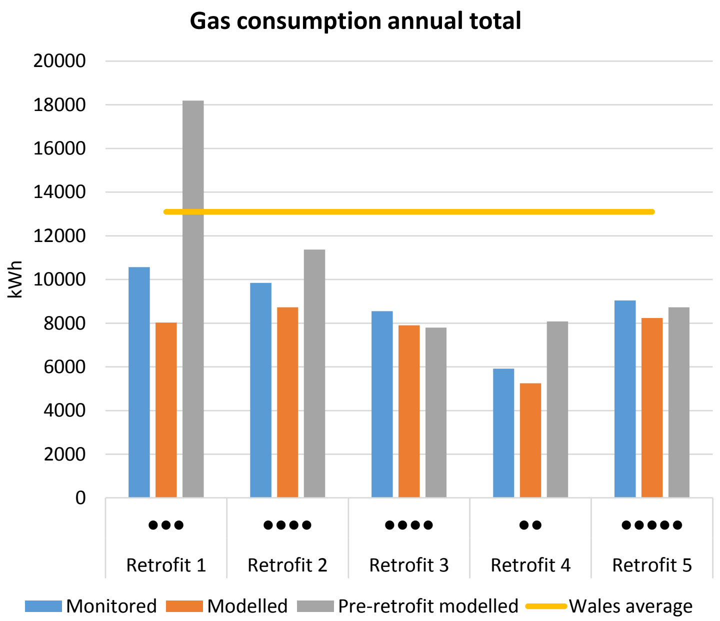

Figure 6: Comparison of annual modelled and monitored gas consumption.

3.3 Analysis of battery storage

The first 3 houses had lead acid battery storage, whilst Retrofits 4 and 5 had lithium Ion batteries. The lead acid batteries had concerns. Firstly, they need to retain 50% charge to maximise their operating lifetime, which resulted in energy drawn from the grid when there was no solar PV available. The monitoring also projected a drop off in performance of around 5% per year. It was decided to model the benefits of installing a 10 kWh lithium battery system to all five retrofit houses, with battery power available to all electricity usage in the houses. Figure 7 compares the retrofit electricity consumption for three cases: before retrofit, after retrofit with battery storage (10 kWh Li) and after retrofit without battery storage. The battery storage provides a greater proportion of PV electricity to the house than would be used directly from the PV panels. Without the batteries there is greater export to the grid. There are losses associated with battery storage, but these are predicted to be relatively small. The imported electricity cost and the generation and export electricity incomes are calculated using the existing feed-in tariff arrangements for generation and export (13.19 P/kWh import; 4.11 P/kWh generation; 4.91 P/ kWh export), in order to estimate the annual electricity cost benefits of using batteries. The cost savings from adding the batteries were calculated by comparing the electricity import costs of the post-retrofit cases with batteries and those cases without batteries. The results from the modelling are compared in Figure 8 and presented in Table 5 for the five retrofit houses. The analysis indicates that the inclusion of a battery has a cost benefit of between around £100 -to £200 per year. Lithium batteries have a lifetime of 12−15 years and so the investment cost is still high (500−700 £/kWh), for example, for a 10 kWh battery a minimum of £5000 investment is needed (Naumann et al., 2015, & market data for 2017: Wind&Sun Ltd, PowerTech Systems, SimpliPhil Power). However, maximising the use of renewable energy within the house can take pressure of the electricity grid, and as battery costs come down and potentially grid energy costs rise, the financial balance is likely to become more favourable in future.

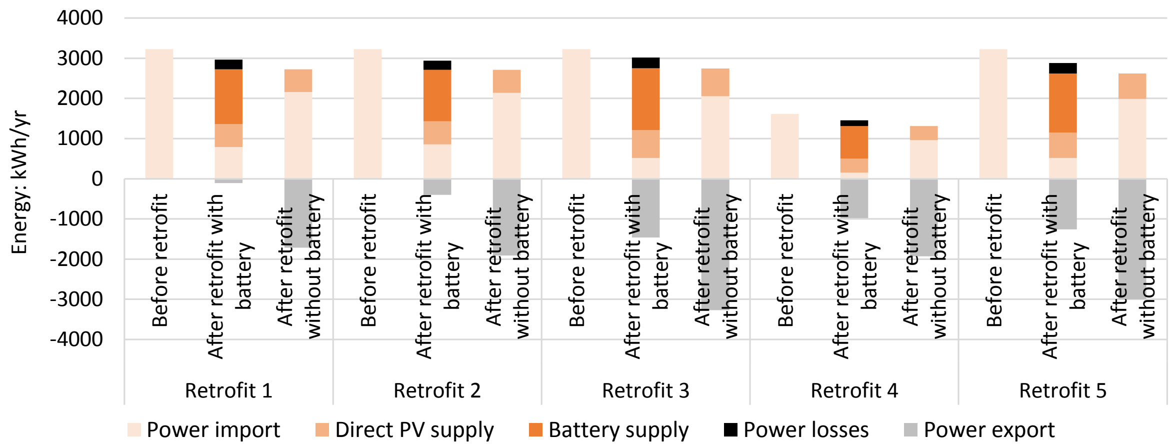

Figure 7: Comparing energy performance, before retrofit and after retrofit, with and without battery storage (10kWh Li).

Table 5: A summary of electricity import and cost for different scenarios (before retrofit, after retrofit with 10kWh Lithium-ion battery,and after retrofit without battery)

Retrofit	Pre-retrofit		Post-retrofit with battery		Post-retrofit without battery	
	kWh/annum	£/annum	kWh/annum	£/annum	kWh/annum	£/annum
1	3227	426	793	105	2161	285
2	3227	426	859	113	2140	282
3	3227	426	515	68	2054	271
4	1614	426	153	20	958	126
5	3227	426	518	68	1992	263

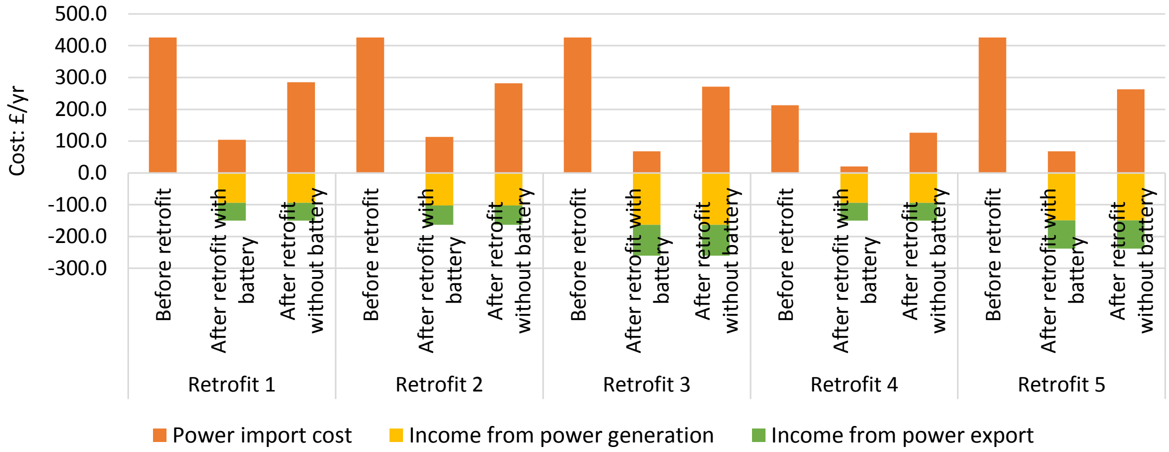

Figure 8: Comparing cost savings before retrofit and after retrofit, with and without battery storage (10kWh Li)

4 Conclusion

The analysis of the five retrofit houses has indicated the potential for significant reductions in energy use, CO_2 emissions and energy costs. This is achieved using a whole house approach, combining energy efficiency with building integrated renewable energy generation and energy storage. CO_2 emission reductions are shown to be in the range of 50−75%, with cost savings of £402 to £621 per year. The cost of retrofits ranges from £23,852 to £30,510, so justifying an energy retrofit on a simple payback from annual energy cost savings is difficult. However, there is a range of other factors that might influence the decision for a whole house approach. For example, the building fabric itself may need refurbishment, including re-rendering and re-roofing, in which case the additional costs for applying energy measures will be easier to justify. Energy retrofitting will also reduce fuel poverty, which will in turn improve the health and well-being of occupants, and potentially reduce the load on the health and social services.

The combination of energy modelling and monitoring has improved understanding the energy savings achieved, with up to 56% reduction in heating and up to 84% reduction in electricity imported from the grid. The use of battery storage can provide annual cost savings of around £200. Using batteries with solar PV can reduce electricity grid stress, through more renewable electricity being used at source. In future as controls get 'smarter', grid import and export can be managed for the most efficient operation, and as battery costs continue to be reduced, they will become economically viable.

As whole-house retrofit scales up in numbers, the costs will be further reduced. Already we are experiencing considerable cost reductions (by at least 50%) in comparison with earlier whole house retrofit studies. If the UK is to achieve its CO_2 emission reduction targets, then housing retrofit must play a major role.

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