

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:

23 With around 1–2% annual replacement of the UK’s housing stock, housing retrofit must play
24 a major role in reducing future energy use and CO₂ emissions. This paper presents a whole-
25 house approach for energy retrofit for five houses located in South Wales. This ‘systems
26 based’ approach combines reduced energy demand, renewable energy supply and battery
27 storage. The paper describes a combination of energy modelling, using the building energy
28 model HTB2, and field measurements to analyse the performance of the houses before and
29 after retrofit. The results indicate that significant reductions in energy use, CO₂ emissions and
30 energy costs can be achieved using a whole house approach, combining energy efficiency
31 with building integrated renewable energy generation and energy storage. CO₂ emission
32 reductions are estimated to be in the range of 50–75%, with cost savings of £402 to £621 per
33 year. The cost of carrying out the retrofitting ranges from £23,852 to £30,510. Although
34 retrofits are still relatively expensive in relation to their annual cost savings, there are
35 multiple benefits relating to reducing fuel poverty, reducing electricity grid stress and
36 contributing to national CO₂ emission reduction targets. Also, as costs of measures are further
37 reduced and energy prices likely to rise in future, the cost balance will change more in favour
38 of whole house retrofit. The paper demonstrates the advantages in using a combination of
39 energy simulation and field monitoring to investigate the performance of buildings in use,
40 which in this case concerns the impact of carrying out energy retrofits in housing.

41

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

44

45 **1 Introduction**

46 The UK is committed to achieving an 80% reduction in CO₂ emissions by 2050 (HM
47 Government, 2008). The built environment, and housing in particular, is likely to be a major
48 focus to achieve these targets. Housing currently accounts for some 29% of the UK's total
49 energy consumption (DECC, 2014a). There has been an interest in reducing energy use in
50 housing since the oil crisis of the 1970's, with the trend from low energy, to passive design,
51 sustainable design, zero carbon design (Jones, 2012). However, the emphasis has mainly been
52 on the design of new houses. Following European directives, the UK target for CO₂
53 emissions for new housing is to be nearly-zero energy by 2018 for the public sector and 2020
54 for the private sector (European Union, 2010). There are also European 2030 CO₂ emission
55 reduction targets, which includes a target of 27% energy savings and 27% renewables
56 (European Council, 2014), with an increased focus on energy efficiency.

57 The current rate of new build in Wales is around 0.4% (National Statistics, 2016), and it is
58 estimated that 75% of the UK's housing stock that will exist in 2050 has already been built
59 (Wright, 2008; Ravetz, 2008). So, in the short term, new build will not have a major impact
60 in achieving overall CO₂ emission target reductions, and it will be necessary to retrofit
61 existing housing. A range of large-scale elemental retrofit programmes have been carried out
62 in Wales, including the Welsh Government ARBED scheme (Patterson, 2012). Although they
63 have produced useful energy savings, and other benefits associated with affordable warmth
64 and improved living conditions, they have tended to use an elemental rather than a whole
65 house approach (Jones et al., 2013a) and so CO₂ emission reductions will not contribute
66 sufficiently to national targets. Alternatively, a 'whole house' or 'deep retrofit' approach
67 integrates a combination of measures tailored to a specific property. There is a cost increase
68 in going from relatively simple elemental 'shallow retrofit' measures to a multifaceted whole-
69 house 'deep retrofit' approach, as the cost of measures rise in relation to the predicted savings

70 (Jones et al., 2013a). Between 2010 and 2012 a series of ‘deep’ energy retrofits,
71 commissioned by the UK government, demonstrated CO₂ emission reductions of between
72 40% and 85%, with the cost of measures ranging from £50,000 to £168,000 (Baeli, 2013).
73 There have also been schemes, such as the ‘Target 2050’ programme by Stroud District
74 Council, where the retrofitting of 10 houses was estimated to provide between 47% to 74%
75 reduction in carbon dioxide emissions (based on household meter readings) for an investment
76 range of £18,000 to £47,000 (with the majority less than £25,000) (Stroud District Council &
77 Severn Wye Energy Agency, 2011). A small number of so-called ‘Superhome’ owners in the
78 UK have renovated their homes, reducing CO₂ emissions by 60% or more, although there
79 does not appear to be any robust cost and in-use performance data available (Fawcett and
80 Killip, 2014).

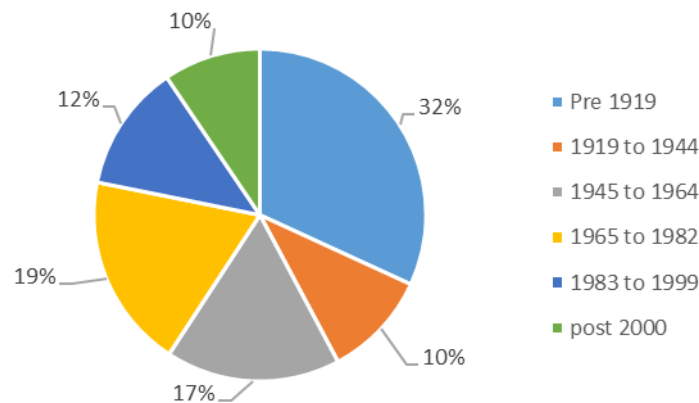
81 So, it seems that large-scale elemental retrofit programmes are not achieving CO₂ targets,
82 while whole house deep retrofits may be perceived as costly, and there is a lack of
83 measurement data to compare with predicted performance. This paper presents the findings
84 from five whole house ‘deep’ retrofit case studies, located in Wales, UK, carried out as part
85 of the SOLCER (Smart Operation for a Low Carbon Energy Region). The project was funded
86 by the European Regional Development programme (ERDF). The purpose was to investigate
87 an affordable and replicable ‘system’ based approach, applied to typical houses of different
88 construction and age, located across South Wales. For this project, the ‘systems’ based
89 whole-house approach combines reduced energy demand, renewable energy supply and
90 energy storage. It focuses on optimising the integration of technologies and design as a whole
91 for a specific building, rather than taking the more traditional ‘bolt on’ elemental approach,
92 applying individual measures across large numbers of buildings but generally with little
93 attention to the specific requirements of individual buildings. The aim was to achieve
94 significant CO₂ emission reductions at an affordable cost.

95 For all five houses, dynamic thermal simulation and energy modelling was carried out to
96 predict building energy performance within the early stages of the retrofit process and to
97 inform the selection of the package of retrofit measures. The simulation results were
98 subsequently combined with the post-retrofit monitoring data in order to analyse annual
99 energy performance and estimate potential energy, CO₂ and cost savings associated with the
100 retrofit measures. The main focus in this paper is to demonstrate how modelling and
101 monitoring can be combined to help identify the most appropriate replicable and affordable
102 combination of measures and then to help understand the resulting overall energy
103 performance.

104

105 **1.1 Background: wales housing stock**

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



111

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

113 There have been a range of subsidised housing retrofit initiatives in the UK, such as the
114 Energy Efficiency Commitment (EEC), Carbon Emission Reduction Target (CERT) and
115 Community Energy Savings Programme (CESP), which have placed obligations on energy
116 supply companies to fund programmes to reduce energy and CO₂ emissions from households.
117 For example, programmes involving these schemes have resourced the installation of over
118 five million energy-saving measures in existing houses between 2008 and 2011 (DECC,
119 2011). This is in addition to private funded work on individual houses. It has been estimated
120 that if the savings through insulation and heating efficiency improvements from 1970
121 onwards had not been made, then energy consumption in UK homes would be around twice
122 the current levels (Office of National Statistics, 2011). In Wales, the ARBED regeneration
123 programme (Welsh Government, 2013) has provided finance for local authorities and
124 registered social landlords (RSLs) to upgrade the energy performance of their existing
125 housing stock. The ‘Green Deal’ (DECC, 2010), was aimed at the private sector, but this
126 failed to deliver and was withdrawn in 2015, which together with the recent reductions of
127 government initiated funding, means that currently there is little government led finance to
128 encourage large-scale retrofit programmes.

129 Energy savings and CO₂ emission reductions should not be seen as the sole benefit of retrofit
130 programmes. Housing standards have a considerable impact on health and quality of life, for
131 example, on major health issues such as cardiovascular disease, accidents and mental health
132 (Jones, Patterson, & Lannon, 2007). The Marmot Review has called for action on policy level
133 to reduce health inequalities, which, on the housing side, includes ensuring healthy standard
134 of living for all, and creating and developing healthy and sustainable places and communities
135 (Marmot et al., 2010). An estimated 30% of the population in Wales lives in fuel poverty,
136 which measured with an official indicator of 10%, is above the UK national average of 15%
137 (BEIS, 2017), where affordable warmth is the main concern. Substandard housing, which are

138 often hard to heat, is estimated to cost the National Health Service (NHS) some £2.5 billion a
139 year through building-associated health-related issues (National Housing Federation/
140 ECOTEC, 2010). Also, any wide-scale application of energy-efficiency measures should
141 accept that some of the benefits would be realized as increased warmth and not just energy
142 savings. It is estimated that this ‘take back’ through improved comfort may account for up
143 50% of the energy-saving measures (Lomas, 2010).

144

145 **1.2 Retrofit strategies**

146 Energy use and the resulting carbon emissions of houses can be reduced significantly through
147 whole-house retrofits. Energy retrofit technologies are designed to reduce energy demand,
148 especially space heating, which in the UK comprises around 66% of the domestic energy use
149 (DECC, 2014b). Fabric insulation is generally considered to be the most effective strategy. It
150 has been reported that cavity wall insulation can potentially reduce up to 40% heat loss
151 through the walls (EST EEBPH, 2003). Older solid wall houses can be upgraded through roof
152 and external wall insulation (EWI), which may reduce heat loss by 50%-80% (Roberts, 2008).
153 However, there are concerns that the insulated wall performance may not be achieved in
154 practice due to construction details and poor workmanship (HM Government, 2015).
155 Insulating existing ground floors can prove disruptive and is only likely to be viable during
156 major refurbishment programmes (BRE, 2005). Although many lofts already have some level
157 of insulation, loft ‘top-ups’ can be cost effective, bringing them to a minimum thickness of
158 270mm, the same as current Building Regulations for new build. Improving air tightness can
159 also reduce heat loss from ventilation (Everett, 2007), and can be an ancillary benefit from
160 upgrading the building fabric, particularly windows and doors. Ideally, upgrading the
161 building envelope should be accompanied by a more energy-efficient system sized for the
162 reduced heat loss, with modern boilers achieving over 90% efficiency (Everett, 2007).

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

173 Building integrated renewable energy supply can be used to contribute to the reduced energy
174 demand. The current average annual solar resource in the UK is estimated to be 101 W/m^2
175 (Burnett et al., 2014), or $2.4 \text{ kWh/m}^2/\text{day}$. Solar PV panels have efficiencies typically of up to
176 20%, depending on the type of PV technology used (Roedern and Ullal, 2008). The
177 electricity generated from Solar PV can be stored using batteries, maximising its use onsite,
178 and only surplus power exported to the grid.

179

180 **2 Method**

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

185 **2.1 Whole house retrofit strategy**

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

- 188 1. At the start of each retrofit, a survey was carried out to determine what retrofit measures
189 were generally appropriate for the specific house. All stakeholders were involved in the
190 project decision-making process, including the project management team, contractors,
191 property owners, modellers and residents. The surveys were based on a fabric first
192 approach, including external wall insulation, loft insulation, improved glazing and air
193 tightness. This was followed by consideration of heating and ventilation systems and
194 renewable energy.
- 195 2. The options for retrofit measures were modelled for each house in order to estimate their
196 impact on energy consumption, CO₂ emissions, and operating cost savings.
- 197 3. An optimum package of measures for each house was selected, considering budget limit
198 and work timetables, and the installation took place. Acceptability of budgets and
199 operational maintenance issues were discussed with the social landlords.
- 200 4. The five SOLCER retrofit case studies were then monitored over a two-year period.

201



202 *Figure 2: The 5 retrofit houses before and after retrofitting*

203 *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

204

205 Table 1 presents the applied retrofit measures relating to energy demand reduction, renewable

206 energy supply and energy storage, alongside the overall costs. Three of the older houses had

207 EWI applied. Retrofits 1 and 4 were of a solid wall construction, with the latter having

208 internal wall insulation applied to the front elevation to retain the external stone finish.
209 Retrofits 2, 3 and 5 had cavity wall construction. Retrofit 2 had the existing gable cavity wall
210 insulation removed and refilled. Two of the houses, Retrofits 1 and 5, were empty houses, so
211 measures could be applied without any occupant disruption, and retrofit 1 had MVHR
212 installed. For the remaining three retrofits, measures were carried out with the occupants in
213 residence. All houses had an integrated PV roof replacing the existing southerly roof, and in
214 most cases the existing roof was in need of replacement. The first three retrofit houses had
215 lead acid batteries installed for electricity storage, whereas the last two used lithium batteries,
216 as their cost and performance became acceptable as the project developed. The battery size
217 was chosen in relation to the area of PV that could be fitted to the roof, and the predicted
218 electricity demand based on the number of occupants. All houses retained their existing gas
219 heating systems, with Retrofits 1,2 and 3 having a new boiler installed.

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

230

231 **Table 2: Air leakage rates measured before and after the retrofit installation (estimated**
 232 **ventilation rates used in the energy modelling are in brackets, in air change per hour at**
 233 **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

234

235 The costs of retrofitting were in the range £23,852 to £30,510 (Table 1), which is at least 50%
 236 lower than the earlier UK government programme of retrofits (Baeli, 2013) and comparable
 237 to the Stroud programme (Stroud District Council & Severn Wye Energy Agency, 2011).

238 Energy retrofitting may be linked to carrying out other general ‘refresh’ improvements, such
 239 as re-roofing and re-rendering, to maintain housing standards, and so costs could potentially
 240 be further reduced.

241 The retrofit houses were monitored from the completion of the refurbishment for a period of
 242 two years from January 2015. The data used in this paper is from January 2016 to December
 243 2016, which contained a period of unchanged occupancy.

244 **2.2 Energy simulation**

245 Energy simulation modelling was first used during the planning stage of the retrofitting
 246 process, using the computer simulation framework VirVil SketchUp (Jones et al., 2013b).

247 This was developed at the Welsh School of Architecture, Cardiff University, and is based
 248 around the well-established dynamic building energy model, HTB2 (Lewis and Alexander,
 249 1990). Input data includes: the hourly climate for the location; building materials and
 250 construction; space layout; system and occupancy profiles. The HTB2 software has
 251 undergone a series of extensive testing and validation, including the IEA Annex 1 (Oscar

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

256 The modelling exercise estimated the energy demand and the total net CO₂ emissions before
257 and after retrofitting. CO₂ emission factors (BRE, 2014) were used to estimate CO₂ emissions
258 associated with the predicted values of electricity and gas energy supply. The operating
259 energy costs were estimated from the current domestic fuel prices. Income from the
260 electricity generated by the solar PV was estimated using information from the UK
261 Government's feed-in tariff scheme (Ofgem, 2017).

262 The five retrofit properties are located between Cardiff and Swansea, in South Wales, UK.

263 The modelling used the following information:

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

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

280 **2.3 Post-retrofit energy monitoring**

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

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

292 Three types of monitoring data were collected, as follows:

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

298

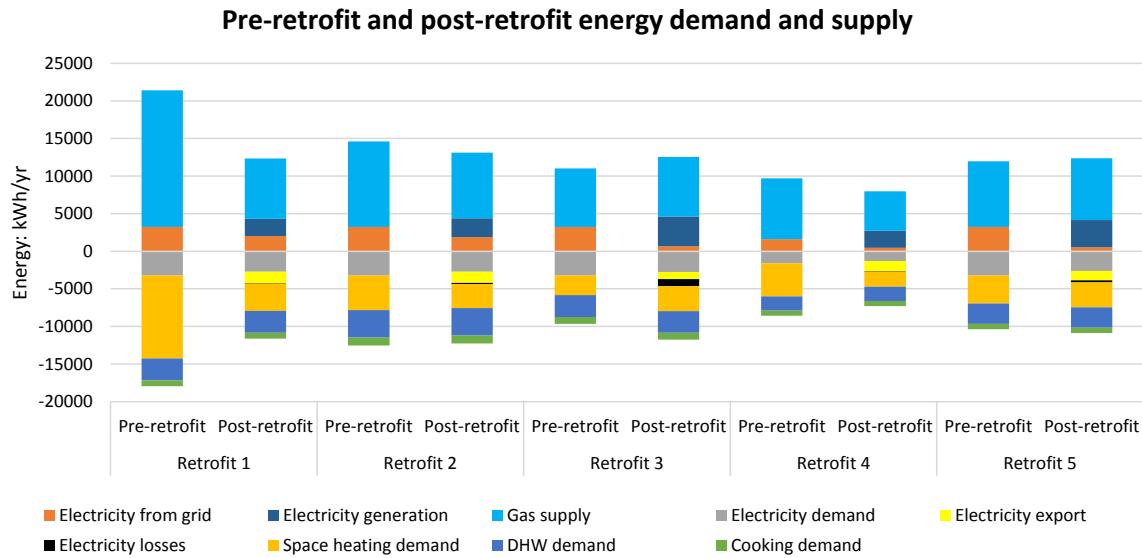
299 **3 Results**

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

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

308 **3.1 Modelling results**

309 Figure 3 presents the annual energy modelling results for the pre-retrofit and post-retrofit
310 energy demand and energy supply. The results are broken down into total annual gas and
311 electricity supply, space heating, domestic hot water use, electricity use (appliances and
312 lighting) and cooking. The estimated energy and cost savings are presented in Table 3.
313 Electricity savings range from 37% to 84%, and gas (space heating and domestic hot water
314 heating) savings generally range from 6% to 56%. Retrofit 3 had little improvement to its
315 fabric and no predictable impact from other measures. CO₂ emission reductions range from
316 49% to 74%. Cost savings range from 52% to 85%, which equates to between 402 and 661
317 £/annum based on current gas and electricity costs and feed-in tariffs.



318

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

320 **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%
CO₂ reduction	64%	49%	54%	74%	61%
Cost savings	62%	52%	85%	81%	84%

321

322 **3.2 Comparing monitoring and modelling results**

323 The post-retrofit values from the monitoring and modelling results are presented in Table 4.

324 Temperature values are for the heating season period, whereas energy values are annual. The

325 external heating season average air temperature is similar, within 1°C, for all monitored

326 retrofit houses. The modelling used the same weather data for all retrofit houses. The internal

327 monitored average temperatures were generally within 1°C of the modelled values, which had

328 their set points adjusted from the initial modelling carried out at the start of the programme

329 (when the modelling was used to inform the selection of retrofit measures), based on the

330 measured data. The temperature (thermostat) set-points used in the modelling were based on

331 observations of typical measured internal air temperatures during the heating season for each
332 retrofit. The modelling set-point remained the same for the heating season, that is, it was not
333 continually adjusted to match the measured internal air temperature data. The annual global
334 solar radiation was similar for both modelled and monitored situations. The associated PV
335 electricity generation values were also similar, indicating that the modelling of solar PV
336 electricity generation is reliable. The measured electricity consumption varied from the
337 assumed modelled values as might be expected due to the specific occupancy patterns of the
338 retrofit houses. However the predicted gas consumption was relatively similar, generally with
339 around 10%, with only Retrofit 1 showing a larger (21%) difference. This implies that the
340 model reliably predicts overall heating energy performance, accepting the adjustment of
341 internal air temperature modelling set points based on measured data.

342 **Table 4: A comparison of monitoring and modelling results**

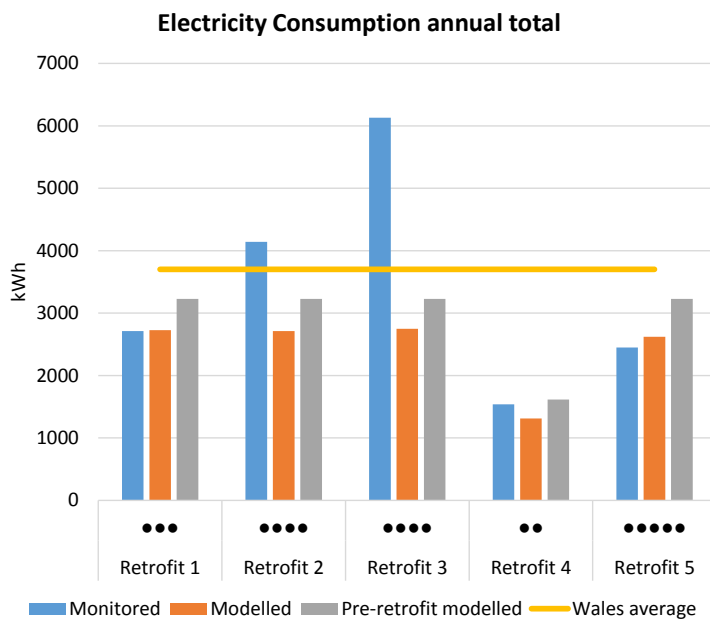
Retrofit houses				Retrofit1	Retrofit2	Retrofit3	Retrofit4	Retrofit5
Number Occupants:				2 adults & 1 child	2 adults & 2 children	2 adults & 2 children	1 adults & 1 children	3 adults and 2 children
Performance Indicator	Data Type	Unit						
I	External temperature heating season average	Monitoring	°C	7.8	8.7	8.4	7.8	8.2
		Modelling	°C	7.5	7.5	7.5	7.5	7.5
II	Internal temperature heating season average	Monitoring	°C	18.1	19.5	18.5	16.6	19.5
		Modelling	°C	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
VII I	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

343

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

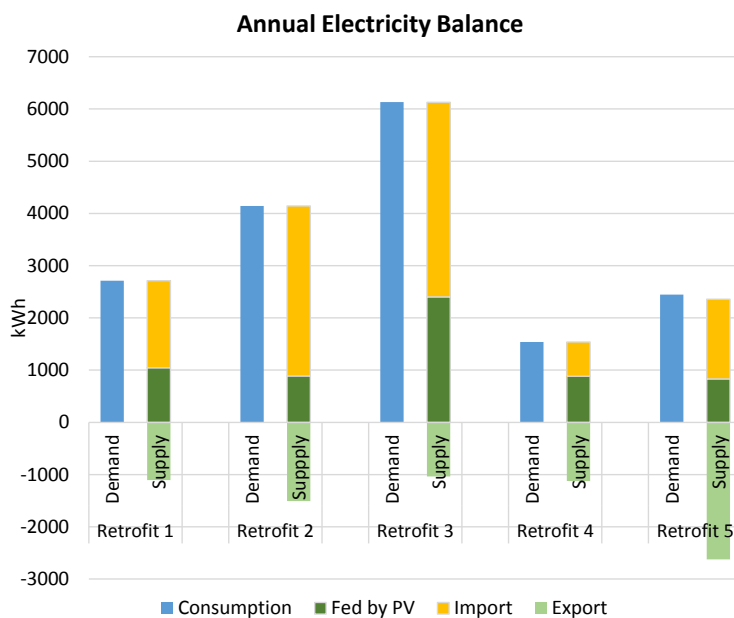
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354

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

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



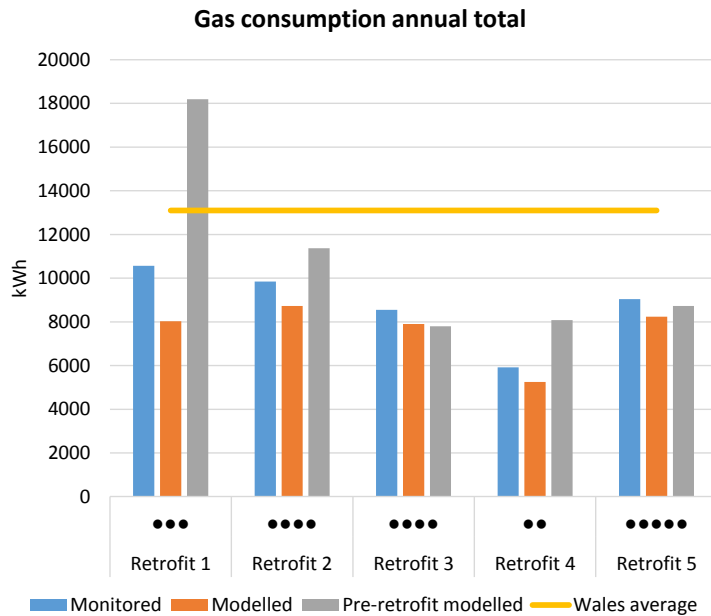
364

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

366 Figure 6 compares the annual gas consumption for the modelled and monitored results
 367 together with the UK average domestic annual gas consumption for reference. Interestingly,
 368 all cases except Retrofit 1 are below the UK average consumption values for both pre- and
 369 post-retrofit results. This may be due to the variation of building age, previous energy
 370 efficiency measures carried out, number of occupants and associated occupant behaviours.
 371 The modelled and monitoring results compare quite well and the modelling indicates

372 significant energy savings from the application of thermal insulation to the external envelope
373 as summarised in Table 3.

374



375

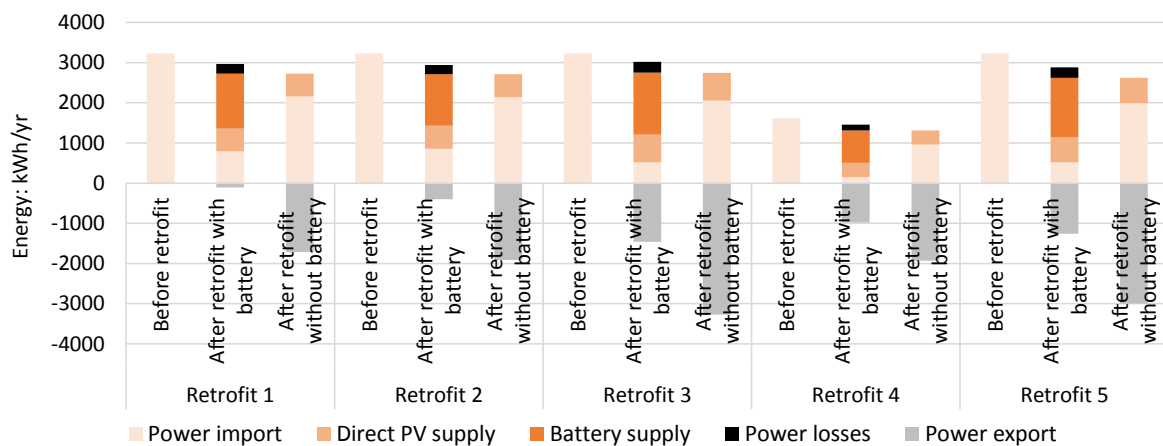
376 **Figure 6: Comparison of annual modelled and monitored gas consumption.**

377

378 3.3 Analysis of battery storage

379 The first 3 houses had lead acid battery storage, whilst Retrofits 4 and 5 had lithium Ion
380 batteries. The lead acid batteries had concerns. Firstly, they need to retain 50% charge to
381 maximise their operating lifetime, which resulted in energy drawn from the grid when there
382 was no solar PV available. The monitoring also projected a drop off in performance of around
383 5% per year. It was decided to model the benefits of installing a 10 kWh lithium battery
384 system to all five retrofit houses, with battery power available to all electricity usage in the
385 houses. Figure 7 compares the retrofit electricity consumption for three cases: before retrofit,
386 after retrofit with battery storage (10 kWh Li) and after retrofit without battery storage. The

387 battery storage provides a greater proportion of PV electricity to the house than would be
 388 used directly from the PV panels. Without the batteries there is greater export to the grid.
 389 There are losses associated with battery storage, but these are predicted to be relatively small.
 390 The imported electricity cost and the generation and export electricity incomes are calculated
 391 using the existing feed-in tariff arrangements for generation and export (13.19 P/kWh import;
 392 4.11 P/kWh generation; 4.91 P/ kWh export), in order to estimate the annual electricity cost
 393 benefits of using batteries. The cost savings from adding the batteries were calculated by
 394 comparing the electricity import costs of the post-retrofit cases with batteries and those cases
 395 without batteries. The results from the modelling are compared in Figure 8 and presented in
 396 Table 5 for the five retrofit houses. The analysis indicates that the inclusion of a battery has a
 397 cost benefit of between around £100 -to £200 per year. Lithium batteries have a lifetime of
 398 12–15 years and so the investment cost is still high (500–700 £/kWh), for example, for a 10
 399 kWh battery a minimum of £5000 investment is needed (Naumann et al., 2015, & market
 400 data for 2017: Wind&Sun Ltd, PowerTech Systems, SimpliPhil Power). However,
 401 maximising the use of renewable energy within the house can take pressure of the electricity
 402 grid, and as battery costs come down and potentially grid energy costs rise, the financial
 403 balance is likely to become more favourable in future.

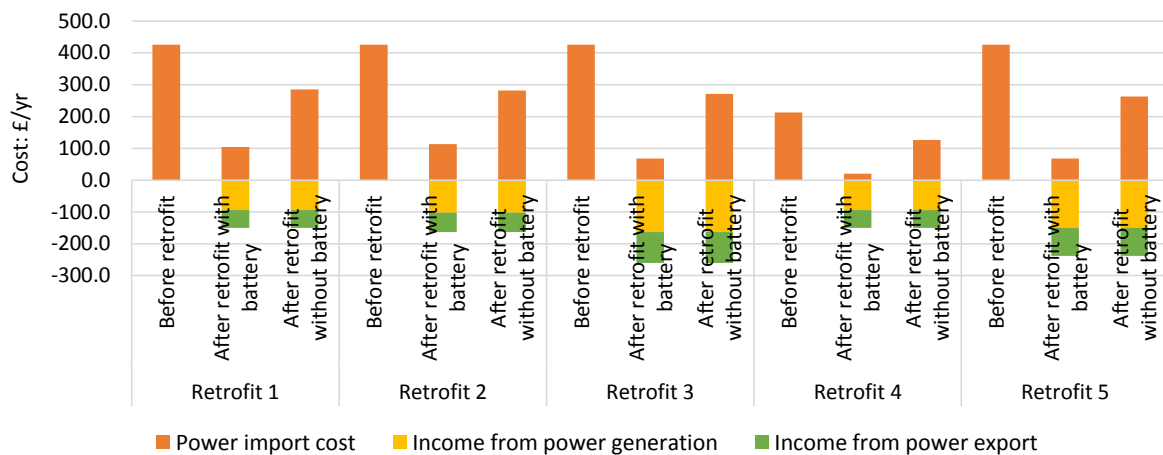


405 **Figure 7: Comparing energy performance, before retrofit and after retrofit, with and**
 406 **without battery storage (10kWh Li).**

407 **Table 5: A summary of electricity import and cost for different scenarios (before retrofit,**
 408 **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

409



410

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

413

414 **4 Conclusion**

415 The analysis of the five retrofit houses has indicated the potential for significant reductions in
 416 energy use, CO₂ emissions and energy costs. This is achieved using a whole house approach,
 417 combining energy efficiency with building integrated renewable energy generation and
 418 energy storage. CO₂ emission reductions are shown to be in the range of 50–75%, with cost

419 savings of £402 to £621 per year. The cost of retrofits ranges from £23,852 to £30,510, so
420 justifying an energy retrofit on a simple payback from annual energy cost savings is difficult.
421 However, there is a range of other factors that might influence the decision for a whole house
422 approach. For example, the building fabric itself may need refurbishment, including re-
423 rendering and re-roofing, in which case the additional costs for applying energy measures
424 will be easier to justify. Energy retrofitting will also reduce fuel poverty, which will in turn
425 improve the health and well-being of occupants, and potentially reduce the load on the health
426 and social services.

427 The combination of energy modelling and monitoring has improved understanding the energy
428 savings achieved, with up to 56% reduction in heating and up to 84% reduction in electricity
429 imported from the grid. The use of battery storage can provide annual cost savings of around
430 £200. Using batteries with solar PV can reduce electricity grid stress, through more
431 renewable electricity being used at source. In future as controls get ‘smarter’, grid import and
432 export can be managed for the most efficient operation, and as battery costs continue to be
433 reduced, they will become economically viable.

434 As whole-house retrofit scales up in numbers, the costs will be further reduced. Already we
435 are experiencing considerable cost reductions (by at least 50%) in comparison with earlier
436 whole house retrofit studies. If the UK is to achieve its CO₂ emission reduction targets, then
437 housing retrofit must play a major role.

438

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444

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