Preparation for an Energy Positive Community in the UK

Modelling-led innovative housing practice in Wales

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ABSTRACT: This paper presents a modelling-led approach to low carbon innovative housing, including a new build and five retrofits located in Wales. The research aims to investigate the implementation of combinations of existing and emerging low carbon technologies through a systems based approach to optimise the use of energy at the point of generation. A performance prediction model has been developed to examine the effectiveness of different strategies in relation to energy and carbon reduction. Simulation results for the new build show the potential to limit energy imported from the grid to about 25% with an annual export to import ratio of 1.55, providing an energy positive performance. For the retrofit properties, the application of Photovoltaics (PV) and LED lighting can reduce the total electricity demand from the grid by up to 90%, and the combination of reduced energy demand, renewable energy supply and battery storage has been shown to reduce net carbon emissions by up to 110%, with total financial savings of 90%-190% through reduced operating energy cost and earnings from renewable energy generation and export. Gas heating energy for the retrofits has been reduced by 20% to 80%. The new build 'energy positive', and retrofit 'nearly-zero energy', performances can be achieved through an integrative 'systems' based approach. This includes attention to affordability and replicability. A grid connection is still needed to balance across seasonal demand and renewable supply, however, the pressure on the grid to provide energy is reduced.

Keywords: energy positive, near-zero energy, energy simulation, housing

INTRODUCTION

To meet the target for an 80% reduction in the UK's carbon emissions by 2050 (HM Government, 2008), it is crucial to reduce the CO_2 emissions associated with residential buildings, which account for some 29% of the UK's total energy consumption (DECC, 2014). In the UK the target for CO_2 emissions for new housing is to be nearly-zero energy by 2021 (European Union, 2010). There are also European 2030 CO_2 emission reduction targets, which include improvements in energy efficiency, with a target 27% energy savings and 27% renewables (European Council, 2014). The built environment, and housing in particular, is likely to be a major focus to achieve these targets. The housing stock in the UK is replaced at around 1% a year (TRCCG, 2008), and it is estimated that 75% of the UK's housing stock that will exist in 2050 has already been built (Wright, 2008). Therefore, the CO_2 emission target reductions will not be achieved through new build alone, and it will be necessary to retrofit existing housing.

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), and more recently to energy positive design. Case studies worldwide have demonstrated the potential for zero carbon and energy positive performance, for both new build and retrofit towards. For example, the three-bedroom 'Habitat for Humanity' net-zero energy home in Colorado, USA, generated 24% more energy than it consumed in the first year of operation (Norton et al, 2008). In Portland USA (Boleyn, 2012), the integration of energy efficient features and high energy-yield solar features, approached a net-zero energy house. A reversible heat pump coupled with passive house design was shown experimentally to achieve a net-zero energy performance in Liege Belgium (Dumont et al., 2015). Retrofitting an older house in Serbia, by upgrading the fabric and adding solar PV (photovoltaic) indicated net-zero energy performance (Stefanoviˊ et al., 2014). Between 2010 and 2012 a series of 'deep' energy retrofits, commissioned by the UK government, indicated CO_2 emission reductions between 40% and 85%, albeit at a high cost, ranging from £50,000 to £168,000 (Baeli, 2013).

The general aim is to minimize energy use and CO_2 emissions through energy-efficiency strategies, together with adopting renewable energy technologies, to achieve a nearly-zero or net-zero energy performance. An annual 'energy positive' performance may be achieved when more energy is exported to the supply grid than is imported. Energy autonomy is when there is no import from the grid, for example, where there is no connection to the grid. However, if the grid is available, this may be not appropriate, other than to secure against grid failure. It is generally easier for new build to achieve energy positive performance, compared to retrofit. So a combination of 'energy positive' new build and 'nearly-zero' energy retrofit could lead to an overall energy positive community.

This paper presents a series of housing case studies, located in Wales, UK, which includes one new build and five retrofits, carried out as part of the SOLCER (Smart Operation for a Low Carbon Energy Region) project. This was funded through the Wales European Regional Development Fund (ERDF) Programme, which formed part of the Low Carbon Research Institute (LCRI) research programme (Jones et al., 2015). A 'systems' based approach, combined reduced energy demand, renewable energy supply and energy storage, all based at a building level. This approach focuses on optimising the integration of technologies and design as a whole, rather than a taking the more traditional 'bolt on' approach for individual components. The aim is to achieve the required performance at an affordable cost, and easily replicated.

The single new build 'SOLCER House' was designed and constructed to be energy positive, whilst the five retrofits were designed and constructed to have a low to nearly-zero energy performance. For the new-build, there was a level of design freedom to use a range of new technologies, albeit within cost and replication accountability, whilst the five retrofits were more constrained by house type, location and occupation.

For all the cases, thermal simulation and energy modelling was carried out to predict building energy performance within the design and build process. The main focus in this paper is to demonstrate how modelling can be used to identify the most appropriate replicable and affordable combination of measures in relation to the target energy performances.

SOLCER NEW BUILD

The design of the SOLCER House (Figure 1) used a range of technologies and design approaches developed through the LCRI Low Carbon Building Environment Programme (Jones et al, 2015). It was designed and constructed by the Welsh School of Architecture, Cardiff University, to achieve a near PassiveHaus standard. It used a Structural Insulated Panel system (SIPS), which can achieve both high levels of thermal insulation and air tightness, and can facilitate rapid on-site construction. Wall, roof, floor and window U-values were 0.12, 0.1, 0.15 and 1.21 to 1.51 W/°C/m^2 respectively, and the air leakage was measured to be 2.91 m^3/h^{-1}m^2 at 50Pa, on completion of construction. The house has a floor area of 100m^2 and is designed to meet social Welsh Housing Quality Standards (WHQS).

Figure 1: SOLCER House

The 'all electric' SOLCER house provides space heating and domestic hot water (DHW) by combining an air source heat pump, MVHR (mechanical ventilation heat recovery), and thermal water storage (GENVEX Combi-unit). Heating is provided solely through the ventilation system, with an average air supply rate of 0.35h^{-1} (air changes per hour) during the heating season. The total ventilation rate of 0.50h^{-1} includes 0.35h^{-1} from the system, and 0.15h^{-1} from infiltration. A dark coloured Transpired Solar Collector (TSC) located on the upper floor of the south-facing wall (Figure 1) preheats the outdoor air supply prior to the MVHR. A heat pump takes its heat from the exhaust air, after it has passed through the MVHR and transfers this heat to space heating and DHW. Because the heat pump operates on warm exhaust air throughout the year, the COP (co-efficient of performance) is relatively high and stable at around 3.2. An integrated thermal water store is used to provide DHW. The heat pump provides space heating unless DHW is needed, at which time it reverts to top-up the thermal water store.

An integrated solar PV roof (4kW) provides electricity and is linked to a VICTRON ENERGY lithium battery store (6.9kWh). The internal electrical appliance loads were reduced through the use of LED lighting. In the modelling exercise it was assumed that energy efficient appliances were used throughout the house. Grid electricity is used when there is no PV generation, and the battery has discharged. The technologies are integrated into the house design; with the PV panels providing the roof material and the TSC providing the first floor southerly external wall finish (Figure 1). The house was constructed in 16 weeks and is being monitored to measure its performance. The estimated cost for replication is around £1,200 per m^2.

SOLCER RETROFITS

A ‘whole house’ deep retrofit approach is required to achieve government CO_2 emission reduction targets through integrating a package of measures appropriate for the house type. However, deep retrofits have in the past proved difficult to replicate due to their high capital costs (Baeli, 2013). The aim of the five SOLCER retrofit case studies was to provide an affordable and replicable package of measures, applied to typical houses of different construction and age located across South Wales (Figure 2), these are being monitored over a two-year period.

The retrofit cases also adopted the ‘systems’ approach used for the SOLCER new build, combining reduced energy demand with renewable energy supply and storage. Table 1 presents the measures applied in terms of demand reduction and renewable energy supply and energy storage alongside the overall costs. The first houses used lead acid batteries, whereas the last two used Lithium batteries as their cost and performance became acceptable over the time of the project. Table 2 presents air leakage rates measured before and after the retrofit installation. Market available technologies have been used, employing local suppliers to give relatively low cost, high impact solutions to housing retrofit. The costs are in the range £23,000 to £30,000, which is generally less than 50% lower than the earlier UK government programme of retrofits (Baeli, 2013).

The retrofit case studies 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. 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 systems and renewables.
2) A range of strategies was *modelled*. Modifications to the heating, ventilation and lighting systems, including LED lighting, heating MVHR, and controls were included. Renewable energy options comprised solar PV and battery storage. Modelling allowed the exploration of the impact on energy consumption, CO_2 emissions, and operating cost savings of each combination of measures.
3) The optimum package for each house was *confirmed and agreed*, considering budget limit and work timetables, and the installation took place.

Two of the cases (Figure 2: cases 1 and 5) were empty houses, so measures could be applied without any occupant disruption. The remaining three cases were carried out with the occupants in residence. Energy retrofitting may be linked to carrying out other general ‘refresh’ improvements to raise housing standards.

ENERGY SIMULATIONS

Energy simulation modelling was used during the planning and design stage of the new build and retrofits, based on the computer simulation framework VirVil SketchUp (Jones et al., 2013a). This was developed at the Welsh School of Architecture, Cardiff University, and is based around the dynamic building energy model, HTB2 (Lewis and Alexander, 1990). Input data includes: 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, the total net CO_2 emissions, and costs. It used current CO_2 emission factors (BRE, 2014) in relation to electricity and gas supply. The operating energy costs were estimated from current fuel prices (British Gas, 2014). Income from solar PV was estimated from the current UK Government's Feed-in Tariffs scheme (Ofgem, 2014).

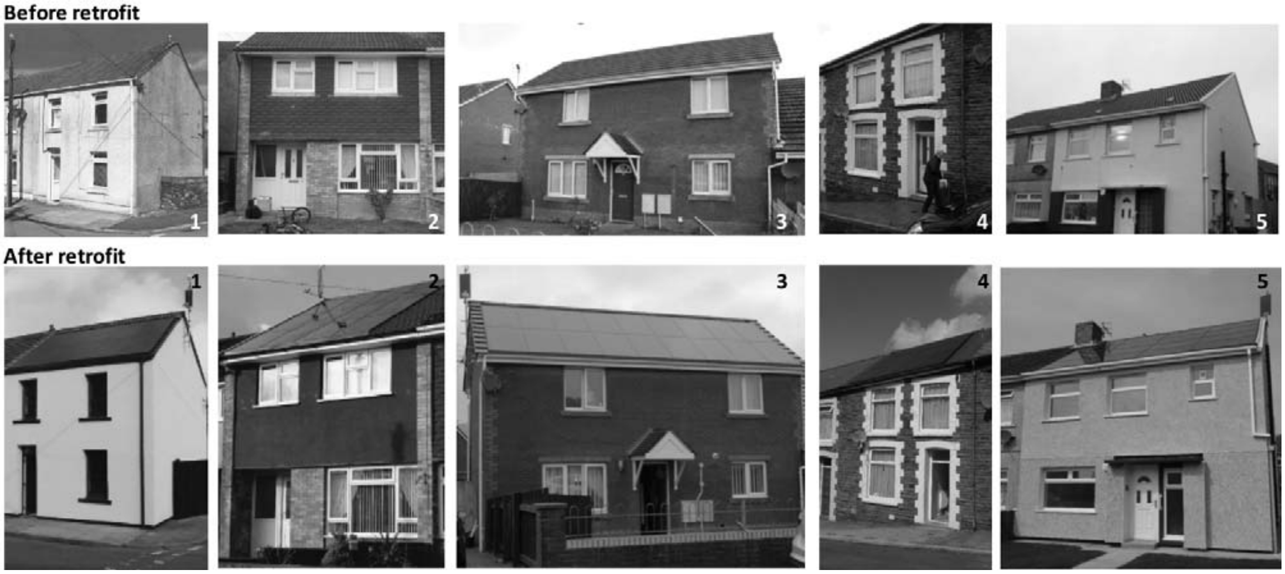

Figure 2: Properties before and after retrofitting

Table 1: Information summary of the retrofits and new build

	Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5
Basic information	Pre-1919 2- bed, solid wall, end-terrace of 67m^2, gas boiler.	1960s, 3-bed cavity wall, semi-detached, 70m^2, gas combi-boiler	2000s, 3-bed filled cavity wall semi-detached of 86m^2, gas boiler	Pre-1919 solid wall, 2-bed solid wall, mid-terrace of 74m^2, gas combi-boiler	1950s, 3-bed filled cavity wall semi-detached of 80m^2, gas combi-boiler
Energy-efficient strategies	a. solid external wall insulation; b. loft insulation and flat roof insulation to rear extension; c. low-E double glazing; d. MVHR; e. LED lighting; f. new system boiler with hot water tank.	a. gable cavity wall insulation and front external wall insulation; b. loft insulation; c. MVHR; d. LED lighting.	a. loft insulation; b. LED lighting; c. new gas boiler and hot water tank.	a. rear external wall insulation, front internal wall insulation; b. loft insulation; c. floor and roof insulation of the utility room; d. LED lighting.	a. external wall insulation; b. loft insulation; c. 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: 4.8kWh feed LEDs and hot water.	Lead acid battery: 8.5kWh feed LEDs and fridge.	Lead acid battery: 18kWh feed all electrical appliances.	Lithium battery: 2.0 kWh feed all electrical appliances	Lithium battery: 10kWh feed all electrical appliances.
Retrofit Cost	£30,452	£27,438	£30,446	£23,852	£30,510

Table 2: Presents air leakage rates measured before and after the retrofit installation

	Retrofit 1		Retrofit 2		Retrofit 3		Retrofit 4		Retrofit 5	
	h^{-1}	m^3.h^{-1}.m^2 @50Pa	h^{-1}	m^3.h^{-1}.m^2 @50Pa	h^{-1}	m^3.h^{-1}.m^2 @50Pa	h^{-1}	m^3.h^{-1}.m^2 @50Pa	h^{-1}	m^3.h^{-1}.m^2 @50Pa
Before retrofit	0.75	13.5	0.54	9.6	0.36	7.4	0.48	8.9	0.41	7.9
After retrofit	0.39	7.0	0.43	7.6	Not available		0.55	10.1	Not available	

RESULTS: NEW BUILD SOLCER HOUSE

Figure 3 presents the monthly simulated energy performance over a year. The results show the amount of energy exported to the grid during summer (from March to October), and imported from the grid during the winter (October to February). Table 3 presents the annual energy demand for space heating, DHW and appliance load. It also presents the annual performance of the system components, with the PV, batteries, TSC and MVHR providing a predicted 36%, 17%, 15%, and 15% of the annual energy contribution to the house, compared with 17% from the electricity grid. From the analysis it is estimated that the annual self-sufficiency is 75%, which means 75% of the energy demand can be directly met onsite by the renewable energy system and battery storage. The house has an annual energy import to export ratio of 1.55, indicating that an energy positive performance can be achieved. Figure 4 shows the monthly contribution performance of the TSC, MVHR and heat pump over the year to space heating.

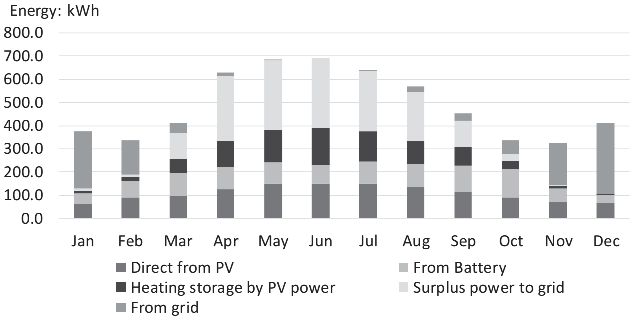

Figure 3: Monthly energy demand, supply and export

Table 3: annual energy demand and component performance

		kWh	%
Demand	Space heating	369	9%
	DHW	1479	35%
	Appliance load	2377	56%
System performance	PV	2156	36%
	Batteries	1014	17%
	TSC	906	15%
	MVHR	932	15%

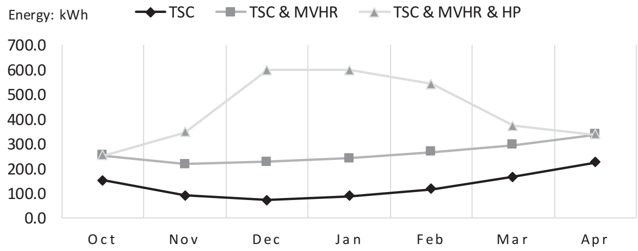

Figure 4: Monthly inlet air heating from TSC, MVHR and Heat Pump over heating season

RESULTS: SOLCER RETROFITS

Figure 5 shows the predicted annual heat gains and losses before and after retrofit. Figure 6 presents the overall annual savings. The electricity savings are between 30% and 90% with the higher saving associated with more electricity demand met by PV supply. Gas savings are highest for cases 1 and 4, where insulation has been applied to solid wall pre-1919 houses. CO2 emission reductions are in excess of 70% for all cases, and exceeding 100% for case 5, where there is an overall net electricity energy positive performance. All cases have high cost savings with three cases (3,4 and 5) indicating income generation due to exporting electricity to the grid. The performance of the MVHR systems in cases 1 and 2 indicates an increased energy use (including fan power) due to the relatively high air leakage rates (see table 2), which when combined with the MVHR ventilation rate, results in an overall excessive ventilation compared to occupancy requirements (0.5h^{-1}). The results also indicate the reduced contribution to (gas) heating from lighting following the application of LEDs. Where the PV is used to contribute to DHW (immersion) heating, further gas savings of 8%-17% are predicted.

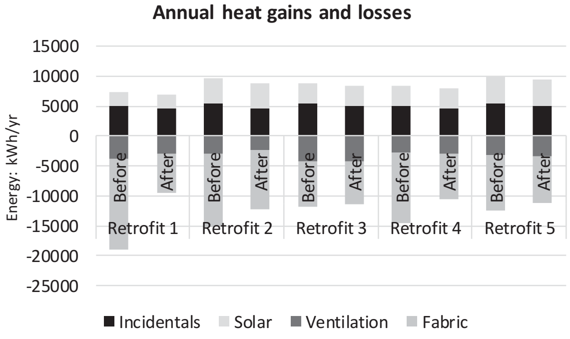

Figure 5 heat gains and losses for the retrofit (before and after)

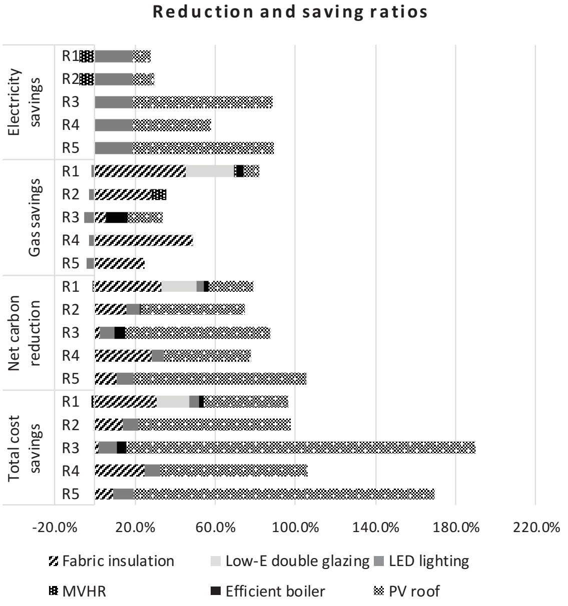

Figure 6: Summary of the predicted performance optimisation of the retrofit properties

CONCLUSION

The paper has described case studies of a systems approach to low carbon innovative housing, including a new build and 5 retrofits in Wales, UK. The low carbon strategies employed in the systems approach have been discussed, including reducing energy demand, renewable energy system and storage. The reported energy simulations indicate an energy positive performance for the new build and approaching nearly-zero energy performance for the retrofits. All the buildings described are being monitored from 2015 to 2017 to assess their performance in use.

The replication cost for the new build is similar to standard UK costs for social housing and higher quality private sector housing. For retrofit, the cost of 'deep' retrofit has been reduced considerable compared to previous UK programmes. It is now approaching affordability, especially if combined with other 'refresh' improvements. For both new build and retrofit the measures applied were generally available through local supply chains and the work was carried out by local building contractors.

At a community scale there may be advantages of sharing renewable energy supply and storage systems compared to individual building integrated systems, especially where some building may not have an optimal orientation in relation to solar energy systems. So a combination of 'energy positive' new build and 'near-zero' energy retrofit, together with some distributed localized zero carbon energy supply would lead to an energy positive community. At the next step, further exploration will be carried out with regards to this to expand the current systems based approach and integrative building energy model into community scale.

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