Building and Community Energy Retrofit Housing in Wales

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ABSTRACT

This paper presents a modelling-led approach applied to low carbon innovative housing retrofit practice in Wales, UK. The research has investigated the implementation of combinations of existing and emerging low carbon technologies through a system based approach to optimise the use of energy at the point of generation at both building and community scales. A performance prediction model has been developed to examine the effectiveness of different strategies in relation to energy and carbon reduction. Simulation results of individual building have shown, the retrofits with a net carbon reduction by up to 110% indicating a zero-energy or energy positive performance. Based on this, further investigation is carried out in retrofitting the whole community towards a 'zero-energy' or 'energy positive' community through a micro-grid connection and storage. The simulation results show an energy positive performance can be achieved for community 1 under the proposed retrofit scenarios.

Keywords: *building energy simulation, energy positive community, renewable energy supply*

1. INTRODUCTION

To meet the target of an 80% reduction in the UK's carbon emissions by 2050 (HM Government, 2008), it is crucial to reduce the carbon emission associated with the domestic sector, which accounts for some 29% of the UK's total energy consumption (DECC, 2014a). The housing stock in the UK is replaced with a proportion of only around 1% a year (TRCCG, 2008), it is estimated that 70% of the UK's housing stock that will exist in 2050 has already been built (Wright, 2008). Therefore, it will be necessary to retrofit existing housing, as the CO2 emission target reductions will not be achieved through new build alone. A growing interest in nearly zero energy or zero energy housing (NZEH or ZEH) has been shown in the past decade, where a number of cases studies worldwide have demonstrated the feasibility. Norton et al. present the design, construction and performance of a three-bedroom Habitat for Humanity net-zero energy home in a cold climate, which generate 24% more energy than it consumed in the first year of operation (Norton et al., 2008). Musall et al. summarizes the research of the International Energy Agency's Annex 52 "Towards Net Zero Energy Buildings", including a comprehensive collection of more than 280 zero energy buildings worldwide, with both existing and new build (Musall et al., 2010). Serghides et al. report that the refurbishment of an old Single Family House in Cyprus into a nearly Zero Energy Building is financially viable (Serghides et al., 2015). In general, the idea is to minimize the need for building energy use through effective energy-efficient strategies before adopting renewable energy technologies to meet the reduced energy requirement, to achieve a nearly zero or zero energy balance between demand and supply, import and export. Energy positive performance could be achieved when more energy is exported compared with that imported over a whole year.

However most near-zero or zero performance has been investigated for new build housing. This paper presents an energy modelling-led approach to investigate energy retrofit housing in Wales, UK, for individual buildings, and community scale with the integration of a micro-grid connection and battery storage. The investigation considers combinations of existing and emerging low carbon technologies through a system based approach, combining reduced energy demand, renewable-energy supply and energy storage.

2. LOW CARBON RETROFIT TECHNOLOGIES

Through proper retrofit strategies, energy use and the resulting carbon emissions of the houses can be reduced significantly. Energy retrofit technologies are designed to reduce energy demand, especially space heating, which comprises around 66% of the domestic energy usage in the UK (DECC, 2014b). Fabric insulation is generally considered to be the most effective strategy. A large number of domestic houses in the UK were built with cavity walls, 60% of which did not have thermal insulation by 2004 (EHCS, 2004). Cavity wall insulation can reduce up to 40% heat loss through the walls (EST EEBPH, 2003). Older houses have solid walls and require external or internal wall insulation to improve their performance. It is estimated that upgrading an old poorly insulated house to post-1990 standards through roof and wall insulation can 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 (Shorrock et al. 2005). Loft insulation is generally easy to apply as a cost-effective measure. Although many lofts already have some level of insulation, loft 'top-ups' can cost effective, bringing them to a minimum of 270mm loft insulation, the level required to meet the current Building Regulations in the UK for new build (DECC, 2014c). 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 improving the heating system, either downsizing the current system, or switching to a more energy-efficient system, with modern boilers achieving over 90% efficiency (Everett, 2007).

Other popular technologies to reduce energy demand include LED lighting, energy-efficient appliances, and Mechanical Ventilation Heat Recovery (MVHR). Most LED light lamps can save over 80% electricity compared to conventional incandescent lamps do (DoE, 2014), and last longer with less maintenance. A notable improvement of energy efficiency has been shown in the appliance market due to technical progress. For example, the average electricity use of an A+++ Panasonic fridge freezer is only 175kWh/yr, while that of an A+ fridge freezer of the same size is 313 kWh/yr. However, the energy use of appliances can vary greatly with occupant behaviour. Mechanical Ventilation Heat Recovery (MVHR) has the potential to reduce heating losses by pre-heating supply air using heat recovered from stale air leaving the property, and improve indoor air quality by providing constant fresh filtered 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 increase heating and auxiliary energy demand (White, 2016).

Renewable energy supply can be used to meet the reduced energy demand. The current average annual solar resource in the UK is estimated to be 101W/m^2 (Burnett et al. 2014), or 2.4 kWh/m^2/day. The electricity generated from Solar PV can be stored using batteries, maximising its use onsite, and only surplus power exported to the grid.

3. METHOD

A series of energy retrofits have been studied in Wales (Jones et al. 2016). At the start of each retrofit, a survey was carried out to investigate the current conditions of the property. A combination of energy saving measures were then proposed, combining fabric measures, renewable energy and energy storage, through a systems based approach. A low carbon design approach will firstly reduce internal heat and power loads, followed by passive design, and finally applying efficient heating, lighting and ventilation services, combined with the integration renewable energy supply and storage. Energy simulation models were developed for three houses in order to predict the optimised performance of the houses with appropriate packages of energy saving measures. The best option for each house was identified, in terms of energy consumption, carbon emission and operating cost savings.

These models were then expanded to a community scale, in order to examine their performance in relation to further reducing energy use through micro-grid connection and community scale energy storage. At a community scale, the average household energy performance could be better or worse than that of single build due to a combination of different building types (terrace, semi-detached, detached) and orientations according to the layout. However, there are 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. Installing PV on both sides of a pitched roof with east-west orientation may even lead to increased energy generation due to the larger PV area.

The simulation tools employed in the research include HTB2 and VirVil SketchUp (Jones et al., 2013). Both HTB2 and VirVil SketchUp were developed at the Welsh School of Architecture, Cardiff University. HTB2 is typical of the more advanced numerical models, using as input data, hourly climate for the location, building materials and construction, spatial attributes, system and occupancy profiles, to calculate the energy required to maintain specified internal thermal conditions (P.T. Lewis, D.K. Alexander, 1990). Due to its advantages of flexibility and ease of modification, it is well suited for use in the field of energy efficiency and sustainable design of buildings, which is rapidly evolving. The software has been developed over thirty years, and 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). VirVil SketchUp is an extension development of HTB2 for urban scale modelling. By linking SketchUp with HTB2, it can carry out dynamic thermal simulation for multiple buildings in a community or urban scale, with consideration to overshadowing impacts from the neighbourhood. Based on the output from thermal simulation, hourly energy models were developed to integrate energy demand, supply and storage at both building and community scales.

4. SIMULATION RESULTS

The retrofits are all located in South Wales, UK. Table 1 summarizes the energy saving technologies employed in the retrofits of three houses (Retrofits 1, 2 and 3), which formed part of the Low Carbon Research Institute (LCRI) SOLCER Retrofit project (funded by the European Regional Development Fund (ERDF)). Table 2 summarizes the proposed optimisation strategies for the three communities. The three communities are based on existing layouts for Retrofit House types 1, 2 and 3.

	Retrofit 1	Retrofit 2	Retrofit 3
			
Basic information	2000's, 3-bed filled cavity wall 86m^2 semi-detached, southeast facing, with gas heating.	Pre-1919, 2-bed 74m^2 solid wall, mid-terrace south facing, with gas heating.	1950's, 3-bed 80m^2 cavity wall semi-detached southeast facing, with gas heating.
Energy-efficient strategies	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. LED lighting.	a. external wall insulation; b. loft insulation; c. LED lighting.
PV	4.5 kW_p PV roof.	2.6 kW_p PV roof.	3.97 kW_p PV roof.
Energy storage	Lead acid battery with 18kWh storage.	Lithium battery with 2.0 kWh storage.	Lithium battery with 10kWh storage.

Table 1: Information summary of the retrofits

	Community 1 (retrofit 1)	Community 2 (retrofit 2)	Community 3 (retrofit 3)
House age and building type	2000s, Semi-detached Detached Mid-terrace	Pre-1919, Middle terrace End terrace	1950s, Semi-detached Detached Mid-terrace
Total floor area	4969 m^2	9200 m^2	10064 m^2
The energy efficient components	The performance of all properties upgraded to that of retrofit 1: Wall U-value (0.26 W/m^2.K), Window U-value (2.0 W/m^2.K), 300mm loft insulation, LED lighting, Efficient system boiler.	The performance of all properties upgraded to that of retrofit 2: Wall U-value (0.38 W/m^2.K), Window U-value (2.0 W/m^2.K), 300mm loft insulation, LED lighting, Efficient combi-boiler.	The performance of all properties upgraded to that of retrofit 3: Wall U-value (0.20 W/m^2.K), Window U-value (2.0 W/m^2.K), 300mm loft insulation, LED lighting, Efficient combi-boiler.
PV	312 kW_p PV roof.	389 kW_p PV roof.	452 kW_p PV roof.
Battery (Community scale)	Lithium battery: 290 kWh	Lithium battery: 220 kWh	Lithium battery: 360 kWh
Further optimisation strategies	PV applied on both roofs for east-west oriented houses.	PV area tailored according to roof size, to reduce roof losses due to standardised module sizes as shown in Table 1.	PV applied on both roofs for east-west oriented houses.

Table 2: Information summary of the communities

4.1. Retrofits 1, 2 and 3 results

Figure 1 presents the overall annual savings of the three retrofits. The electricity savings are between 55% and 90% with the higher saving associated with more electricity demand met by PV supply. Gas savings are highest for retrofit 2, where insulation has been applied to solid wall pre-1919 houses. CO2 emission reductions are in excess of 70% for all three retrofits, and exceeding 100% for retrofit 3, indicating an energy positive performance. All retrofits have high cost savings indicating an income generation from exporting electricity to the grid. 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 for retrofit 1 which has a hot water tank, further gas savings of 17% are predicted (the other two retrofits have combi-boilers with no hot water storage). Table 3 summarizes the predicted annual performance of the retrofitted properties. An electricity self-sufficient ratio of more than 85% can be achieved by retrofit 1 and 3, indicating their majority of electricity use can be met by PV energy supply and storage.

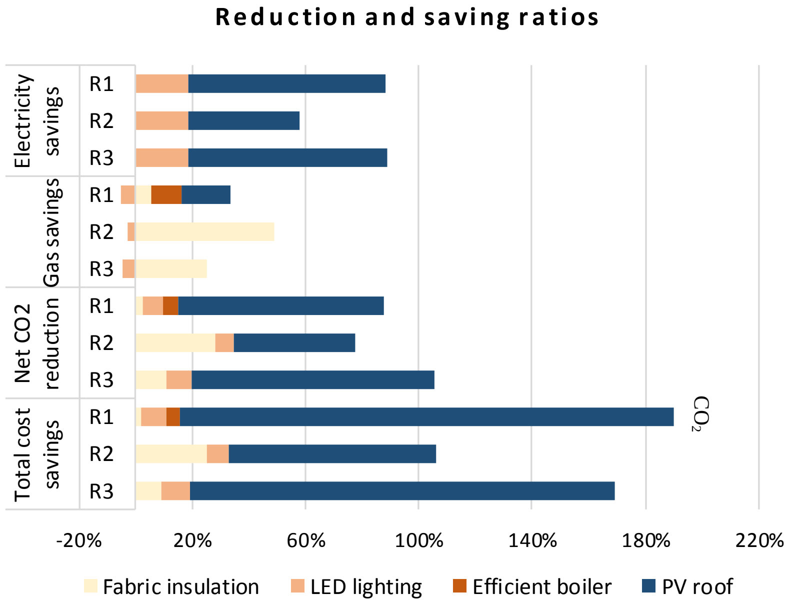

Figure 1: Summary of the predicted performance optimisation of the three retrofits

	Retrofit 1	Retrofit 2	Retrofit 3
Total electricity generation by PV	4493 kWh/yr (52 kWh/m²/yr)	2572 kWh/yr (35 kWh/m²/yr)	3916 kWh/yr (49 kWh/m²/yr)
Electricity generation by PV per kW_p	998 $kWh/kW_p/yr$	989 $kWh/kW_p/yr$	986 $kWh/kW_p/yr$
Electricity from grid	281 kWh/yr (3 kWh/m²/yr)	1021 kWh/yr (14 kWh/m²/yr)	268 kWh/yr (3 kWh/m²/yr)
Electricity to grid	1279 kWh/yr (15 kWh/m²/yr)	1519 kWh/yr (21 kWh/m²/yr)	1992 kWh/yr (25 kWh/m²/yr)
Electricity export to import ratio	4.55	1.49	7.43
Electricity self-sufficient ratio	90%	49 %	86%
Electricity demand	1983 kWh/yr (23 kWh/m²/yr)	1983 kWh/yr (27 kWh/m²/yr)	1983 kWh/yr (25 kWh/m²/yr)
Heating demand	4245 kWh/yr (49 kWh/m²/yr)	3856 kWh/yr (52 kWh/m²/yr)	3201 kWh/yr (40 kWh/m²/yr)
Gas supply	3798 kWh/yr (44 kWh/m²/yr)	4284 kWh/yr (58 kWh/m²/yr)	3557 kWh/yr (45 kWh/m²/yr)
Net operating carbon emission	302 kg/yr (4 kg/m²/yr)	667 kg/yr (9 kg/m²/yr)	-126 kg/yr (-2 kg/m²/yr)

Table 3: The predicted energy performance of the properties after retrofit

4.2. Community scale results

Table 4 presents the predicted energy performance of the communities. The potential of PV generation is shown through the visualisation of solar radiation on the roofs, with red indicating the most solar radiation, orange the second most, and green the least. Both red and orange roofs have been considered for PV installation. This explains why there is more electricity generation per household in community 1, compared with the single case in table 3, as PV is considered on both sides of the pitched roofs for almost half the number of buildings, i.e. those with an east-west orientation. Community 1 is 90% self-sufficient in electricity use, and with an annual net CO_2 emission of 588kg/household, indicating an energy positive performance over the year. For community 2, there is an increase of PV generation compared to the performance of the individual Retrofit 2, as a result of the increased PV area per household from further optimisation (see Table 2), contributing to a smaller average net carbon emission. For community 3, it generates proportionally less electricity per household, but uses more electricity and gas, compared with the single build Retrofit 3 (see Table 3). This is due to most buildings in community 3 without an optimal orientation as that of the single build, and only a couple of buildings have both sides of roofs considered for PV installation (see red and orange roofs in Table 3).

	Community 1	Community 2	Community 3
Visualisation of solar potential on the roofs  1200 kWh/m^2 900kWh/m^2 700 kWh/m^2			
Total electricity generation by PV	5319 kWh/household/yr (61 kWh/m^2/yr)	3103 kWh/household/yr (42 kWh/m^2/yr)	3377 kWh/household/yr (43 kWh/m^2/yr)
Electricity generation by PV per kW$_p$	980 kWh/kW$_p$/yr	991 kWh/kW$_p$/yr	940 kWh/kW$_p$/yr
Electricity from grid	315 kWh/household/yr (4 kWh/m^2/yr)	1021 kWh/household/yr (14 kWh/m^2/yr)	790 kWh/household/yr (10 kWh/m^2/yr)
Electricity to grid	2444 kWh/household/yr (28 kWh/m^2/yr)	2055 kWh/household/yr (28 kWh/m^2/yr)	2059 kWh/household/yr (26 kWh/m^2/yr)
Electricity export to import ratio	7.76	2.01	2.61
Electricity self-sufficient ratio	90%	49%	60%
Electricity demand	1983 kWh/household/yr (23 kWh/m^2/yr)	1983 kWh/household/yr (27 kWh/m^2/yr)	1983 kWh/household/yr (25 kWh/m^2/yr)
Heating demand	3281 kWh/household/yr (38 kWh/m^2/yr)	4682 kWh/household/yr (63 kWh/m^2/yr)	4162 kWh/household/yr (52 kWh/m^2/yr)
Gas supply	2394 kWh/household/yr (28 kWh/m^2/yr)	5203 kWh/household/yr (70 kWh/m^2/yr)	4625 kWh/household/yr (58 kWh/m^2/yr)
Net operating carbon emission	-588 kg/household/yr (-7 kg/m^2/yr)	587 kg/household/yr (8 kg/m^2/yr)	340 kg/household/yr (4 kg/m^2/yr)

Table 4: The predicted energy performance of the communities

5. CONCLUSION

The paper has described case studies of a systems approach to low carbon innovative housing, including three retrofits in South Wales, UK. The results indicate that, the combination of reduced energy demand, renewable energy supply and battery storage could reduce net carbon emission by 88%, 78% and 110% for the three retrofits, demonstrating that a near-zero energy and for one case energy positive performance, can be achieved.

There can be added benefits from a community performance compared to an individual house performance due to the increased area of PV applied to different orientations and building type variations (detached, semi-detached, terrace). For some east-west oriented houses, PV applied to the whole roof rather than the south facing side can significantly increase the total electricity generation. Community 1 has the potential to achieve an energy positive performance.

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