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Abstract. This paper presents an evaluation of the economic and technical feasibility of a renewable-led low carbon house in the UK. A holistic systems-based approach to achieve energy positive house has been taken. Long-term economic and technical feasibility analysis have been carried out based on a validated thermal and energy model of the house. The economic analysis employs the Return on Investment (ROI) method and considers changes to government financial support and technology progress over time. Results show that the extra investment on the house, compared with that for building a standard social house of similar size, can be paid back within the system lifespan under both the old Feed-in Tariff and its proposed replacement with reduced financial support. Variants examined in the technical feasibility analysis include housing type, orientation and location. Results show that the house can be replicated to achieve an energy positive performance for all variant combinations. Among the variants, location has the highest impact on building performance including annual electricity import, CO_2 emission and electricity self-sufficient ratio, with South UK performing better than North UK. This implies that more efficient or advanced technologies would be needed to achieve similar building or system performance in areas of unfavourable climate. The outcome of the research has demonstrated the affordability of the energy positive house, and the technical feasibility of its replication with different housing types, orientations and locations in the UK. This study supports the wide scale replication of this affordable systems-based approach in domestic building design and construction when incorporating appropriate technologies.

1. Introduction

There have been worldwide efforts to employ renewable energy systems for tackling the fuel poverty issue, either at a community scale [1] or for single domestic building [2]. Around 291,000 households, equivalent to 23% of all households in Wales, still live in fuel poverty [3], and for England the estimated proportion is 11%, approximately 2.5 million [4]. In the UK, renewable technologies have been employed since the 1980s at community scale, for example in the Linford Solar Court (1979), the Rainbow Housing project (1980), the Giffard Park Housing (1984), the BedZed Development (2001), the Hockerton Housing (2002) or the Lammas Community (2009). Also at the single building scale, with innovative house projects such as the Bradville Solar House (1972), the projects presented in the Homeworld 81 exhibition, the House for the future (2000) or the Ty Unnos (2011). There have been UK government supported schemes to provide financial support for small scale renewable energy generation, such as the Feed-in-tariff (FIT) and its potential replacement, the new supply-led 'Smart Export Guarantee' (SEG) scheme [5], and the Renewable Heat Incentive (RHI). Driven by government

incentive mechanisms and the demand on minimizing fuel poverty, low carbon domestic retrofit in the UK has been moving towards a systems-based approach with regards to renewable energy integration. There have also been attempts to integrate a systems-based approach in new houses. The SOLCER house, built in Bridgend (South Wales) in 2015, was designed and constructed by the Welsh School of Architecture (WSA) at Cardiff University to be an energy positive house [6]. The SOLCER house is a new build house that employs a whole house systems approach, integrating high performance building fabric, an efficient service system, renewable energy generation and energy storage [7]. Unlike most renewable energy applications in domestic buildings, where renewable energy generation only serves as an auxiliary energy source, the 'all electric' SOLCER house can meet around 70% of its total energy needs and produce more power export than import over an annual period [8]. The total floor area of the building is 100m^2 and is designed to meet social Welsh Housing Quality Standard (WHQS).

Figure 1. The SOLCER house by WSA.

The design of SOLCER house incorporates existing and emerging technologies and design approaches developed through the LCRI Low Carbon Buildings Programme [6]. The technologies have been integrated and optimized through a systems-based approach to meet the house's reduced energy demand using renewable energy supply and energy storage. The house is built with high performance Structural Insulated Panels (SIPs) for walls and roof (U-values = 0.12 W/K/m^2), a highly insulated floor slab (U-values = 0.10 W/K/m^2) and composite windows (U-values = 1.12 to 1.51 W/K/m^2). The measured air leakage after completion was 2.91 m^3/h/m^2 at 50 Pa. Space heating and domestic hot water (DHW) are provided through Integrating Transpired Solar Collector (TSC) and a GENVEX Combi-unit which combines Mechanical Ventilation Heat Recovery (MVHR), an Exhaust Air Heat Pump (EAHP) and thermal water storage. The dark coloured TSC is located on the upper floor of the south-facing facade (Figure 1), which preheats the outdoor air supply prior to the MVHR, but also reduces heat losses through the wall by providing an additional external layer on the south facing external wall. A 4.3kWp integrated solar photovoltaic roof and a 6.9kWh lithium battery storage are assisted by grid import to meet the electricity demands. The system is designed to import electricity from grid only when there is no PV generation and the battery is fully discharged.

The performance of the SOLCER House has been fully monitored since its construction and has proved to perform as expected, however, evidence is required to prove its cost-effectiveness compared with new build social houses, and whether the systems-based approach works for different housing types, orientations and locations in the UK. This research studies the economic and technical feasibility for the SOLCER House's replication across the UK. Work is carried out from the following aspects, 1) a long-term economic analysis to produce a Return on Invest (ROI) graph of the system compared to a best practice new build social house; 2) a technical feasibility analysis to apply the system to different housing types, orientations and locations in the UK.

The UK government has reduced its financial support for renewable energy generation. FIT closed on 31st March 2019 and the alternative SEG scheme proposes to pay only for power export. RHI is not applicable for the SOLCER house as it uses an exhaust air heat pump. The economic analysis in this paper will discuss impacts resulting from changing financial support over time. By examining a worst-case economic scenario with limited income from power export and no RHI gain, it will provide an unbiased and referable case for international researchers living in countries where there is limited or no financial support for domestic renewable system application.

2. Methodology

In preparation for the economic and technical feasibility analysis, a thermal and energy model was developed in the dynamic tool HTB2 [9], to predict energy performance of the as-built SOLCER house. The model has undergone several calibration processes based on survey and monitoring data collected from the SOLCER House over a two years period, proving to be reliable for scenario modelling [10]. HTB2 is typical of the more advanced numerical models, using input data including hourly climate for the location, detailed building materials and construction, spatial attributes, system and occupancy profiles, to calculate the energy required to maintain specified internal thermal conditions. It can also deal with most thermal related systems such as Mechanical Ventilation Heat Recovery (MVHR) and Transpired Solar Collectors (TSC) when relevant technical parameters are available. As a result, HTB2 provides more complete and dynamic prediction of the performance of individual system components. Its results can be further processed to calculate the resulting energy supply, CO_2 emission, operating cost and electricity self-sufficiency.

2.1. A long-term economic analysis

The long-term economic analysis is carried out using the Return on Investment (ROI) method. ROI measures the amount of return on a particular investment, relative to the investment's cost. A simple formula is presented in Equation (1). The ROI varies over time, along with the increasing of gain or loss from investment and the adding of extra investments if applicable.

$$ROI = (gain\ from\ investment - cost\ of\ investment)\ /cost\ of\ investment \qquad (1)$$

For this research, the investment's cost will be the extra money needed to build the SOLCER house compared with building a best practice social house of the same size, which complies with Welsh Building Regulations [3]. Differences between the two houses in terms of fabric, system element and total cost are presented in table 1. MVHR is employed in the social house to achieve similar indoor air quality as that of the SOLCER house. The total cost of the social house refers to the published cost statistics for Welsh new build dwellings, mainly social houses [11].

Table 1. A summary of the differences between the SOLCER house and a best practice new build social house of the same size in Wales, UK.

	SOLCER house	A best practice new build social house
Building fabric element	Wall U-value: 0.12 W/K/m^2 Roof U-value: 0.12 W/K/m^2 Floor U-value: 0.10 W/K/m^2 Window U-value: 1.12-1.51 W/K/m^2 Air permeability: 2.91 m^3/h/m^2	Wall U-value: 0.18 W/K/m^2 Roof U-value: 0.13 W/K/m^2 Floor U-value: 0.13 W/K/m^2 Window U-value: 1.40 W/K/m^2 Air permeability: 5.0 m^3/h/m^2
Service and renewable system	TSC area: 14.0m^2; GENVEX Combi-unit, including MVHR, ASHP (COP 3.21) and hot water tank; 4.3kW$_p$ building integrated solar PV; 6.9kWh lithium battery.	No TSC; Gas fired system boiler with hot water tank, radiators; With MVHR; No solar PV; No battery storage.
Total cost	£1380 /m^2	£ 1240 /m^2 [11]

Financial benefits from the extra investment on the SOLCER house, compared with the best practice social house, are mainly associated with the operating energy cost savings from the systems based approach of integrating reduced energy demand, renewable energy supply and energy storage. Income from government schemes such as the old Feed-in Tariff or the potential new SEG scheme are considered, together with costs for maintaining the two properties. The total gain from investment can be obtained using equation (2). Expenses for maintaining the components in SOLCER house are added, and taken as a negative gain. While any maintenance cost of the social house is taken as a return of the investment. Replacement expenses are included in the maintenance costs for components with lifespans shorter than the designed system lifespan, which is assumed to be 25 years for this case study. A summary of the lifespans, maintenance and replacement costs of individual components is presented in Table 2. The costs for maintenance and replacement were obtained from market searches and suppliers.

Table 2. A summary of the low carbon technologies.

Components	Specifications	Maintenance (£/yr)	Replacement (£)	Lifespan
External wall insulation	SIPs Panels	0	0	>= 50
TSC	An area of 14.0 m^2	0	0	>= 30 [12]
Combi-unit	HP: COP 3.21; MVHR; DHW tank: 185L.	40 (filters)	0	20-25 [13,14]
PV	4.3kWp BIPV, module efficiency 15.0%.	20 (cleaning)	Inverter replacement every 15 years for £300 per kWp PV.	25-30 [13,15,16]
Battery	Lithium, 6.9kWh	0	6,500	10-20 [17,18, 19]
MVHR	SPF 0.56W/l/s, 91% efficiency	40 (filters)	2,500	15 [20]
Gas boiler	System boiler with tank (90% efficiency)	100 (inspection)	4,000	15-20 [20, 21]

The research also considers the degradation of component performance over time, such as annual degradation rates of 0.7% for PV capacity [22], 2-3% for lithium battery capacity if well managed [23]and for every 10 year, 6-10% for boilers efficiency and 10-24% for air cooled chillers COP [24]. A standard UK discount rate of 3.5% [25] is used to calculate the present value of future cash flows, therefore enable a comparison of investments and benefits in the long term. This discount rate indicates how rapidly the value today of a future real pound decreases by time, and it applies to real values with the anticipated effects of inflation already removed. In this research, it is assumed that inflation will affect all prices equally, in which case the real values of future cash flows will equal to the current prices, so the inflation rate is not needed for the calculation.

$$C_{gain} = \Sigma_1^t \left(C_{si}/(1+r)^{i-1} \right) + \Sigma_1^t \left(C_{pvi}/(1+r)^{i-1} \right) - \Sigma_1^t \left(C_{mi}/(1+r)^{i-1} \right) \qquad (2)$$

$$C_{si} = \Sigma_1^h \left(E_{zi}P_z \right) - \Sigma_1^m \left(E_{yi}P_y \right) \qquad (3)$$

$$C_{pvi} = C_{pv}(1-\alpha)^{i-1} \quad or \quad C_{pvi} = C_{pvEi} \qquad (4)$$

$$C_{mi} = \Sigma_1^n M_x - \Sigma_1^a M_b \qquad (5)$$

C_{gain} − total gain from the extra investment on SOLCER house, compared with that for building the social house;

r −discount rate;

C_{si} − operating energy cost savings on year i;

C_{pvi} −income from Solar PV of year i when i is within the tariff timescale, 20 years;

C_{mi} − net expense from maintenance on year i;

t – the last year of the selected time period, for example the designed system lifespan;

h – total number of fuels used in the social house;

E_{zi} – use of fuel z in the social house on year i, obtained from the calibrated model with consideration to system performance degradation over time;

P_z – price of fuel z;

z – fuel No., ranging from 1 to h;

m – the total number of fuels used in the SOLCER house;

E_{yi} – use of fuel y in the SOLCER house on year i, obtained from the calibrated model with consideration to system performance degradation by time;

P_y – price of fuel y;

y – fuel No., ranging from 1 to m;

C_{pv} – 1st year generation and export incomes from PV according to the old Feed-in Tariff;

α – performance degradation rates for PV;

C_{pvEi} – income from power export based on the potential SEG scheme (only metered power export would be paid, so would vary with PV and battery degradation over time, and can be obtained from the calibrated energy model);

M_x, M_b – maintenance fees of SOLCER house component x and the social house component b, respectively (components here and after include only those presented in Table 1);

n, a – the total number of components in the SOLCER house and the social house, respectively.

With consideration to the discount rate which account for the devaluation of pound over time, a more reliable discounted ROI is developed and presented in Equation (6). The year when the total gain from investment is equal to the total cost of investment is taken as the payback time. The payback time illustrates the amount of time needed to recover the investment. A positive value of ROI indicates a good investment, while a negative value indicates a bad one. And the steeper the ROI line the faster the return.

$$ROI_i = [\Sigma_1^t (C_{pvi}/(1+r)^{i-1}) + \Sigma_1^t (C_{si}/(1+r)^{i-1}) - C_{in} - \Sigma_1^t (C_{mi}/(1+r)^{i-1}] / [C_{in} + \Sigma_1^t (C_{mi}/(1+r)^{i-1})] \quad (6)$$

ROI_i – the ROI of the investment on year i; C_{in} – the extra investment on SOLCER house, compared with cost for building the social house.

2.2. A technical feasibility analysis

To have a complete examination of the adaptability and replicability of the SOLCER house, the following variants have been selected and studied in the technical feasibility analysis:

- housing type (detached, semi-detached and terrace),
- orientation of the main roof (west, southwest, south, southeast and east) assuming that PV is installed on the main roof only,
- location (Cardiff, Glasgow, Manchester and Southampton).

Four typical cities are selected to include the majority of climate conditions in the UK, with one in the north, one in the south and two in the middle. CIBSE test reference year (TRY) weather data of individual cities were employed for the simulation.

The technologies installed at the SOLCER house were reviewed to accommodate any performance improvement since the SOLCER house was built. The major potential improvements include the increased module efficiency of the Building Integrated PV (BIPV) according to the latest market data, and the employment of a big TESLA battery with a capacity of 13.5kWh and a round trip efficiency of 90%. The adapted PV module efficiency is assumed to be 19.75% for this case study, much higher than that of the SOLCER house, which is 15%.

A single-variant analysis and a multi-variant analysis were used to understand how the SOLCER house performs in different scenarios, including examining house performances after adaptation to the efficiency of PV module, and comparing sensitivities of different variants in relation to energy consumption, CO_2 emission, operating cost, electricity self-sufficiency. The sensitivity of each variant in relation to a specific performance is determined by the performance range achieved to include the average performances of individual case groups employing the same variant value.

3. Results and discussion

3.1. The long-term economic analysis
Three scenarios are examined in the economic analysis, including:
- Scenario 1: As-built SOLCER house with the Feed-in Tariff from 2015;
- Scenario 2: As-built SOLCER house with only power export income under the SEG scheme;
- Scenario 3: Adapted SOLCER house with only power export income.

The first two scenarios are to enable the consideration of changing of external financial support over time, while the last one is to account for technology performance improvements over time, such as an increased PV efficiency.

Results from the ROI analysis are summarized and compared in Figure 2. It indicates, compared with a best practice new built social house,

1) the extra investment on the SOLCER house can be paid back in 12 years under the 2015 Feed-in Tariff when it was built;

2) the extra investment on the SOLCER house cannot be paid back within the designed system lifespan of 25 years under the new SEG Scheme with income only from power export;

3) with consideration to the relevant technology improvements over time, extra investment on the adapted SOLCER house can be paid back in 17 years at the first time, thereafter 25 years with replacement costs over time taken into account;

4) in all the scenarios, the steeper increase at year 16 is because of a higher replacement cost of the social house compared with that of the SOLCER house, while the drop at year 21 is due to the big investment on replacing the battery of the SOLCER house;

5) for each scenario, the payback speeds can be ranked as, year 1-15 >=year16-20>year 21-25, and the big decrease from year 21 results from the finalisation of the Feed-in Tariff which lasts only for 20 years for each application.
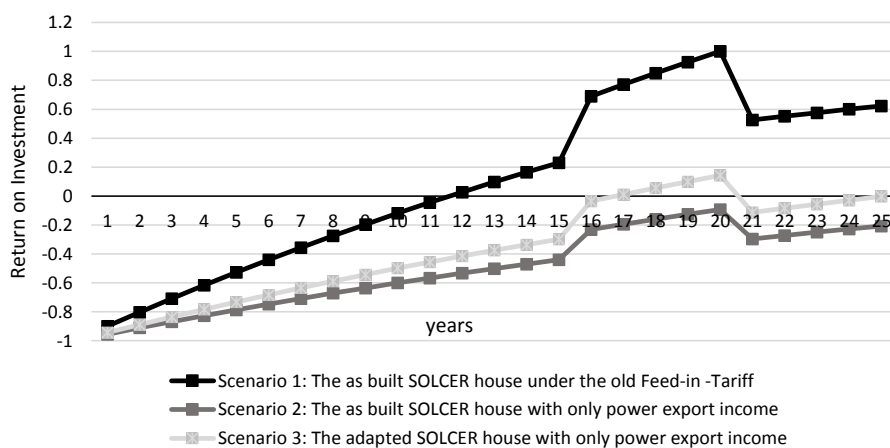
Figure 2. A comparison of ROIs for different scenarios.

3.2. The technical feasibility analysis
Simulation results from HTB2 for the technical feasibility analysis are summarized below in Table 3 and Figures 3 and 4. Table 3 presents the electricity export to import rates, with values above 1 being energy positive, and values close or below 1 being near-zero energy performance. Figure 3 compares the saving ratios of electricity import from single-variant changes on the basis of SOLCER house in Cardiff, and Figure 4 illustrates the multi-variant's sensitivities in relation to electricity import, CO_2 emission and electricity sufficient ratio.

Table 3 shows the majority of the replication cases are energy positive except the east and the west facing semi-detached houses and the east-facing mid-terrace house in Glasgow, which only achieve near-zero or zero energy performance. However, these can be improved by installing PV on the east and

west facing roof, as the annual solar potentials and electricity yields on both sides of the roof will be similar. This would not increase the total peak PV power as the peak power outputs from both sides of the roof would not occur at the same time, and therefore would not require additional capacity accommodation from the grid, which would be an additional cost. Therefore, an energy positive target can still be met by these houses.

Table 3. A summary of the predicted electricity export to import rates for replication for different housing types, orientations and UK locations.

| | Export to import rates | | | | | | | | | | | |
| | Cardiff | | | Glasgow | | | Manchester | | | Southampton | | |
	Detach	Semi	Mid	Detach	Semi	Mid	Detach	Semi	Mid	Detach	Semi	Mid
W	1.8	2.0	2.2	0.9	1.0	1.1	1.2	1.3	1.4	1.6	1.7	1.9
SW	2.5	2.8	3.1	1.2	1.4	1.5	1.6	1.7	1.9	2.1	2.4	2.6
S	2.9	3.2	3.7	1.4	1.6	1.8	1.8	2.0	2.2	2.5	2.8	3.1
SE	2.4	2.6	3.0	1.2	1.3	1.5	1.5	1.7	1.9	2.1	2.3	2.6
E	1.7	1.8	2.1	0.9	1.0	1.0	1.1	1.2	1.4	1.5	1.6	1.8
Detach--Detached house, Semi--Semi-detached house, Mid--Mid-terrace.												

According to the single variant analysis in Figure 3, alternative housing types result in a decrease of electricity import by up to 22%, while the changing of orientation or location increases annual electricity import, with the case in Glasgow being the worst, requiring a 54% increase in electricity import from the grid.
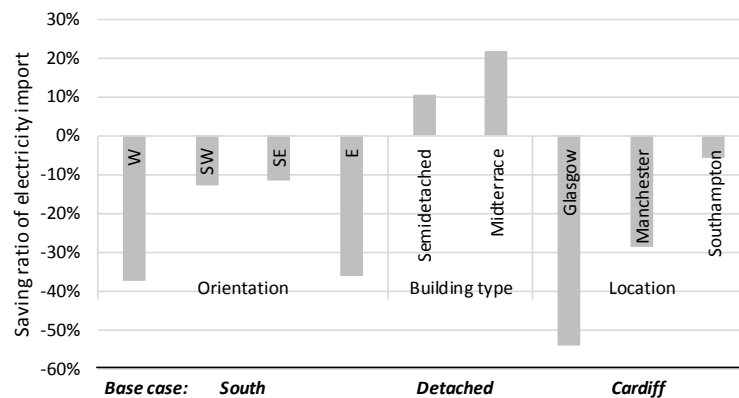
Figure 3. Saving ratios of annual electricity import from single variant changes on the basis of the SOLCER House.
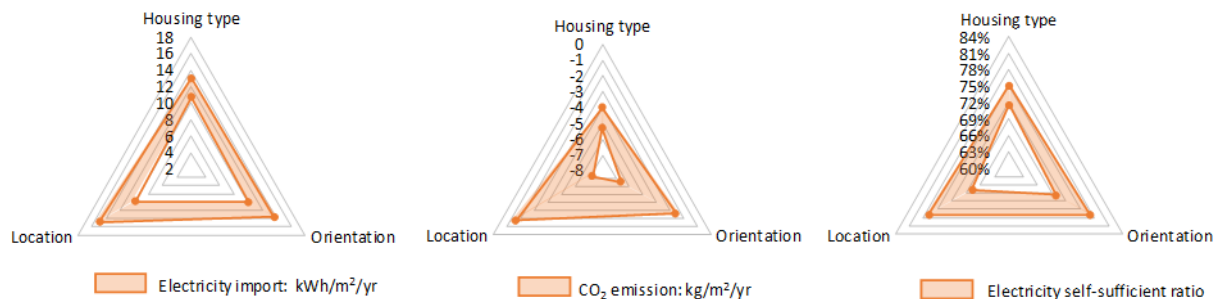
Figure 4. A sensitivity analysis on housing type, orientation and location in relation to electricity import, CO_2 emission and electricity sufficient ratio.

The results of a sensitivity analysis in Figure 4 indicate that the location has the highest impact on annual electricity import, CO_2 emission and electricity self-sufficient ratio, while housing type has the lowest. The results imply that there would be big performance differences between geographical areas

if the SOLCER house was replicated across the country, and the trade-offs between housing type and location, orientation and location will not minimise the differences. Therefore, besides the favourable housing type and orientation, more efficient or advanced technologies would be needed in the less favourable locations, such as cities in the north, to achieve similar performance target.

4. Conclusion

This paper has presented a long-term economic analysis and a technical feasibility analysis of the SOLCER house, a renewable-led energy-positive house in the UK. Analyses have been carried out based on a validated thermal and energy model of the SOLCER house, also taking into account the changing of financial support and technology improvements over time. Results from the economic analysis show that the extra spending on building the SOLCER house can be paid back in 12 years under the old Feed-in Tariff, when compared with a best practice social house of similar size. Under the new SEG scheme, where only power export would be paid, pay back of the extra investment on the adapted SOLCER house can still be achieved during the system's lifespan. Results from the technical feasibility analysis show the replication of the SOLCER house with different housing types and orientations and in different locations across the UK can be energy positive, although east-west facing houses in northern areas might require additional PV installation to boost generation due to low solar potentials. The technical feasibility analysis also indicates location has the highest impact on building performance, such as annual electricity import, CO_2 emission and electricity self-sufficient ratio; implying that more efficient or advanced technologies would be needed to achieve similar building or system performance in the less favourable locations. The outcome of the research has demonstrated that the affordability of the SOLCER house, and the technical feasibility of its replication of different housing types and orientations in different areas in the UK. The payback within lifetime of the system implies that occupants can benefit from improved internal conditions, namely healthier life quality with the same cost they can afford in social houses, therefore will reduce fuel poverty.

The research also highlights the importance of government schemes for promoting renewable energy application in domestic buildings, although at some point, the reducing or withdrawal of this support can be offset by foreseeable technology improvements. As the highest impact on building performance is a result of location, financial support for renewable energy application should be tailored according to location, such as providing more support to less favourable areas to justify expense and increase affordability. Future work could investigate innovative or more advanced technologies for further improving building performance of the SOLCER house, in particular its replication in the less favourable areas in the UK.

Acknowledgments

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