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Exploring the potential of scaling up Smart Local Energy Systems to transform clusters of housing: Insights from a case study in Wales, UK

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Abstract. The research investigates the potential of Smart Local Energy Systems (SLES) to transform existing small clusters of housing into aggregates of prosumers capable of sharing locally generated renewable energy in SLES located in the Swansea area, South Wales, UK. The performance of 3 SLES retrofit scenarios is compared and evaluated at a household and cluster scale. The EnergyPlus software within the DesignBuilder interface is used to carry out the modelling. Results show that SLES retrofit measures at a cluster scale are advantageous in terms of economic and environmental Key Performance Indicators (KPIs). The modelling also showed that replacing photovoltaic panels with a wind turbine in a small cluster of homes in rural Wales, UK offers no benefit in terms of renewable energy generation, carbon emissions or income. Overall, this research offers insights into the potential of SLES in retrofitting small housing clusters into low-carbon aggregates, emphasising the role of PV panels as a renewable electricity source.

1. Introduction

The urgent need to address climate change has led to a global shift towards renewable energy sources [1]. To effectively manage this transition, it is crucial to upgrade existing conventional power systems and explore innovative solutions that can provide cleaner energy at an affordable price while ensuring acceptable energy security [2]. Smart Local Energy Systems (SLES) offer a new paradigm for renewable energy generation, management and use that takes a holistic view on all energy vectors, integrating smart grids and energy storage systems to overcome the energy trilemma [3]. Retrofitting the built environment to accommodate SLES measures can maximize on-site energy generation and self-consumption. This is particularly important for settings like the UK, which has the oldest and worst-performing building stock in the EU [1], as it can tackle the issues of inefficient housing and energy systems through enabling a framework for SLES.

This research aims to compare and evaluate the performance of SLES retrofit scenarios for housing at household and cluster scales. The findings of this study provide valuable insights for decision-making on different technologies applied in SLES. They can thus inform policymakers, urban planners, and energy companies on the benefits of scaling up SLES and provide guidance towards the most effective solutions for achieving net-zero carbon targets in the built environment.

2. Literature Review

According to the recent Climate Emergency Retrofit Guide [4], a recommended approach for achieving carbon savings and supporting the transition to SLES is to integrate energy demand reduction (DR), renewable energy supply (RES), and energy storage systems (ESS) through a whole-house energy systems retrofit. RES and ESS support SLES feasibility, while DR can contribute to the reduction of the overall energy demand and consumption. Recent research projects have focused on applying SLES on a cluster scale, where the energy infrastructure is shared to enable distribution of the locally generated renewable energy. It is argued that scaling up SLES carries the potential for democratisation, disseminating technological innovation and accelerating the adoption of low-carbon measures [6]. SLES clusters can benefit from increased participation in the electricity market [2], lower energy costs, better quality of supply, increased reliability, and reduced carbon dioxide (CO_2) emissions [6]. Despite the benefits, forming a SLES cluster of homes involves many challenges. Creating an effective SLES cluster requires an intersectional approach combining socio-economic territorial planning with technological systems [2]. Not all retrofit technologies are universally successful, as their effectiveness varies according to context and scale [7]. Contextual factors, in particular location, resource availability, culture, and local agents, require identification and consolidation creating a challenge in setting up SLES [2,7]. Thus, to effectively implement SLES, a technological framework could assist in the identification of the most suitable approach for a specific building archetype within a given context.

Li et al. [5] compared household and cluster scale SLES. Their modelling study showed that the scaled-up system caused a decrease in CO_2 emissions and shortening of return on investment; however, the self-sufficiency of the system decreased, and an average annual energy bill increased [5]. Solar power, applied by Li et al. [5] and wind power are both practical options for RES at a cluster scale SLES [8]. The installation of wind turbines (WT) typically occurs in rural, coastal, and offshore areas due to power production capabilities [9]. Predescu [8] has shown that wind power can be more beneficial economically than PV panels in off-grid residential systems, where the wind speed exceeds 5.5 m/s [8]. Wind turbines can generate large amounts of electricity [9], which can increase the income from exported surplus electricity and increase self-sufficiency of the system. This research aims to compare the feasibility of wind and solar powered SLES in a rural context, examining if changing the source of renewable electricity can benefit the system analysed by Li et al**.** [5].

3. Method

Using a case study approach, this research models 3 retrofit scenarios on 6 single-storey social housing bungalows in Swansea, Wales (Figure 1), to explore different paths towards the scalability of SLES. The 6 homes form a social housing cluster owned and managed by the Swansea Council and were chosen for replicability and archetypal relevance and as they were in need of repair.

Figure 1. Case study – 6 single-storey bungalows located in Swansea, South Wales. Courtesy of the LCBE team, WSA.

The bungalows were built in the 1970s and pre-retrofit were very expensive to heat. The Low Carbon Built Environment (LCBE) research team at the Welsh School of Architecture (WSA), Cardiff University carried out a whole energy system retrofit in all 6 bungalows during 2019-2021. For this research, a baseline and 3 retrofit scenarios (presented in Table 1) will be tested. The DR measures in all scenarios remain the same: external wall insulation (100mm graphite EPS boards, U value <= 0.25 $W/m^2/K$), loft insulation (insulation roll, U value 0.13 $W/m^2/K$), Mechanical Ventilation and Heat Recovery system, LED lighting and new windows and doors (U value <= 1.5 $W/m^2/K$).

Table 1. Retrofit scenarios modelled in DesignBuilder.

Scenario Name	Abbreviation	Purpose of the scenario
Baseline House Pre-retrofit	BHP	Dwellings in their original pre-retrofit state, used as a baseline for the assessment of other scenarios.
LCBE Household Retrofit	LHR	LCBE retrofit applied individually to the bungalows.
LCBE Cluster Retrofit	LCR	LCBE-retrofitted dwellings sharing RES, ESS, and a ground source heat pump (GSHP) at a cluster scale to test how scaling applied technologies impacts the system.
Alternative Cluster Retrofit	ACR	WT as a source of renewable energy in place of PV panels applied in LHR and LCR to test whether wind power can successfully substitute solar power in rural SLES clusters.

3.1. Key Performance Indicators (KPIs) of SLES

Setting KPIs is fundamental for a quantitative comparison of the retrofit scenarios. At the time of conducting this research, there are no universally accepted standards for assessing the performance of SLES [10]. The KPIs chosen to assess the modelled scenarios (Table 2) are supported by literature [5, 10]. They are set to form a framework focusing on the technical aspects and feasibility of the system at a cluster scale, assessing technical, environmental and economic domains.

Table 2. KPIs used in modelling of the scenarios.

KPI domain	KPI	Unit	Source of data
Technical Domain	Electricity Import	kWh/ year	Modelling Output
	Electricity Export	kWh / year	Modelling Output
	Self-Sufficiency	%	Modelling Output
Environmental Domain	Total CO_2 emissions	kg / year	Emissions from exported oil, LPG and electricity based on UK Government GHG Conversion Factors 2022 [11]
Economic Domain	Bills	£ / year	Cost of imported electricity, oil and LPG under the standard variable tariff [12]
	Income	£ / year	Income from exported kWh of electricity priced under the Smart Export Guarantee [13]
	Technology Investment Cost	£	The sum of investment cost of all technologies [5] [14-15]

3.2. Modelling and Validation

3.2.1 Modelling tool applied

EnergyPlus was used via the DesignBuilder interface to model the interactions of all investigated buildings, their components and systems across the scenarios. This software supports whole-building simulations, including external weather conditions, heat gains and losses, internal loads, and occupants' activity, enabling a comprehensive evaluation of a building's energy systems [16]. Weather data was obtained from the Met Office weather station at Mumbles Head [17], located about 13 miles from the site.

3.2.2. Data applied in modelling

The 6 bungalows are modelled as 6 single zone buildings. 6 occupants' profiles were created (**Table *3***) to reflect realistic energy use. The profiles were created to reflect UK average domestic hot water consumption (DHW) [14], heating setpoint [15], heating hours in winter, and equipment power density [16]. Depending on the heating system, the energy used to provide DHW will be different. The heating is set to be on from 1st October to 1st April.

Table 3. Assumed occupancy profiles for the 6 bungalows on an average day.

	UK average	House A	House B	House C	House D	House E	House F
DHW consumption [l]	29.2-44.8 [18]	35.5	39.3	32.4	30.6	30.2	32.7
Heating setpoint [°C]	17-22 [19]	20	21	22	22	21	21
Heating hours in winter	Dependent on preferences	7- 11 am 7- 9 pm	7- 10 am 6- 9 pm	7 am-10 pm	7 am- 9 pm	5 am-1 pm 5- 9 pm	6-10 am 5- 9:30 pm
Equipment power density [W/m²]	5 – 11 [20]	9	10	8	7.5	8.5	9.5

To validate the energy use resulting from occupancy profiles shown in **Table 4**, annual consumption figures have been compared to UK average values and data from Li et al. [5]. Pre-retrofit, House E relied on electricity for heating and DHW, resulting in much higher electricity use than other houses (**Table 4)**. High electricity use from House E skews the average household electricity use from Li et al. [5]. The amount of oil and LPG consumed by households can vary widely, and estimating their average usage is challenging, as both are purchased in litres from fuel suppliers.

Table 4. DesignBuilder modelled BHP scenario LPG/ oil and electricity consumption compared with UK average and data from Li et al. [5].

	UK average per household	Pre- retrofit average per household **[5]**	House A	House B	House C	House D	House E	House F
Annual LPG/ Oil Use [kWh]	-	8,019 [5]	6,635	7,982.0	9118	11,937	0	12,141
Annual Electricity Use [kWh]	2,474 [21]	4,173 [5]	2,193	2,071	1,990	1,613	12,476	2,506

3.3. Modelling Low Carbon Technologies (LCTs)

Through solar analysis, South-West, and South-East roofs were identified to be best suited for PV installation [5]. The roof area per bungalow was measured to be 20.1 m^2 for SW roof, and 35.8 m^2 for SE roof allowing 2 kWp and 4 kWp respectively. Utilizing shared roof space between bungalows in the LCR scenario provides more area for PV panels, increasing energy generation to 39.5 kWp per system compared to a maximum of 36 kWp in the LHR scenario. Battery sizing for each system has been compared for self-sufficiency and battery capacity using DesignBuilder, as shown in **Figure 2** below.

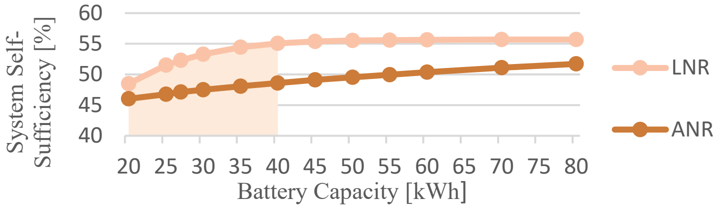

Figure 2. Battery optimisation in DesignBuilder for ACR and LCR scenarios.

The battery capacity should fit within the stabilising zone, where self-sufficiency hasn't plateaued. In LCR, it is between 20 and 40 kWh. The proposed system was 2 units of 13.5 kWh Tesla Powerwall [5], providing 27 kWh, the minimum Powerwall capacity within the stabilising zone. For ACR, the self-sufficiency does not plateau within the range of 20-80 kWh. In place of a Powerwall, which doesn't support WTs, a TESVOLT Li-ion battery [14] was modelled for the ACR of similar size to 27 kWh for consistency. For LCR and ACR, the GSHP peak output was estimated at 18.5 kW. **Table 5** summarizes the modelled low carbon technologies applied in each of the scenarios.

Table 5. BHP, LHR, LCR, ACR scenarios - Electricity source, heating system, DHW; cost per system.

	BHP	LHR	LCR	ACR
On site Electricity source	-	PV 6 kWp per system (36 kW total) @ £2,100 per kWp[a][5]	PV 39.5 kWp per system @ £2,100 per kWp[a] [5]	10 kW wind turbine @ £ 63,950[b] [15]
ESS	N/A	13.5 kWh Li-ion per system @ £6,500[a] [5]	27 kWh Li-ion per system @ £1,400[a] [5]	28.8 kWh Li-ion per system @ 22, 537[b] [14]
DHW & Heating	Oil/ LPG Boiler eff. 70% (electrical heating for House E) DHW from main heating system	6 kW GSHP @ COP 4.0 with a hot water tank@ £15,000[a] Water based radiators [5]	18.5 kW GSHP @ COP 4.0 with a hot water tank @ £25,000[a] Water based radiators [5]	18.5 kW GSHP @ COP 4.0 with hot water tank @ £25,000[a] Water based radiators [5]

[a] Data from literature published in 2019 [5] and reviewed in 2023.
[b] Data from retailers [14-15] accessed in 2023

4. Results and Discussion

The results are presented in **Table 6**. The initial investment cost of the LCTs is much lower in the scaled-up scenarios LCR and ACR, as a result of economies of scale and optimised sizing. The highest system self-sufficiency was achieved by the LHR system (70.2% - 76.3%) due to the larger ESS. Despite the decreased self-sufficiency, the amount of exported energy to the grid significantly increased under the LCR scenario resulting in the highest income from export back to the grid. During periods of peak energy demand, the system cannot meet demand, but high-RES levels allow for export of excess energy which compensates financially for imported energy expenditure at other periods when using appropriate energy supplier tariffs. The ACR scenario, which requires the lowest initial investment cost, results in the lowest self-sufficiency and income. The DesignBuilder simulation has shown that the 10 kW WT generates only 19,462 kWh in this context, compared to 44,889 kWh from PV panels, under the LCR scenario. indicating insufficient wind power potential in this context. Under the ACR scenario, energy export is significantly lower than in other scenarios, demonstrating improved matching of energy demand and generated on-site electricity, which can be beneficial if electricity export is not feasible.

Table 6. Summary of all scenarios in terms of the KPIs, results presented per cluster.

	LCT initial investment cost [£]	Oil/ LPG import [kWh/ year]	Electricity import [kWh/ year]	Electricity export [kWh/ year]	Energy Self-Sufficiency [%]	Annual bills [£/ year]	Income [£/year]	Total CO_2 emissions [kg/ year]
BHP	0	47,814	22,849	0	0	12,511	0.0	14,674
LHR	204,600	0	6,437	21,304	70.2– 76.3	7,073	5,113	-2,875
LCR	120,950	0	6,980	31,626	67.1	2,318	7,590	-4,766
ACR	88,950	0	17,023	4,964	45.0	5,652	1,191	2,332

The results of this research confirm findings of Li et al. [5] that the scaled-up system results in higher carbon savings per annum and increased annual electricity export. Li et al. [5] has noted smaller decrease in self-sufficiency when scaling up the system, likely as a result of including only 5 of the bungalows into the study. The self-sufficiency of the modelled LCR system could be improved by increasing the EES size. Future research should explore hybrid energy systems combining wind and solar power to improve self-sufficiency, load matching and income.

5. Conclusion

The research confirms that scaling up SLES to a cluster offers advantages in terms of decreased total carbon emissions and increased on-site energy generation, while a single household SLES shows increased energy self-sufficiency. The initial investment cost of LCTs varies greatly, favouring the cluster scale scenarios. The modelling showed that replacing PV panels with a WT in a small housing cluster in rural Wales, UK, offers no benefit in terms of renewable energy generation, carbon emissions or income under the Smart Export Guarantee tariff. The potential income from energy export is a subject to local grid constraints and applied tariffs.

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