Operational carbon dioxide emissions from a retrofitted social home: assessing the impact of grid carbon intensity factors

JUAN FERNANDEZ GOYCOOLEA BSc(HONS), PHD.
Welsh School of Architecture, Cardiff University
fernandezgoycooleajp@cardiff.ac.uk

EMMANUOUIL PERISOGLOU PHD, BSc(HONS), CENG, MCIBSE
Welsh School of Architecture, Cardiff University
perisogloue@cardiff.ac.uk

PROF **JO PATTERSON** PHD, BSc(HONS)
Welsh School of Architecture, Cardiff University
patterson@cardiff.ac.uk

Abstract

This paper presents the performance evaluation of a semi-detached 1970s social home retrofitted to near-zero energy and assess the impact of using dynamic grid CO_2 intensity factors on its operational emissions outcome. Energy efficiency measures including insulation, an air source heat pump and controls, together with renewable energy supply, battery storage and mechanical ventilation with heat recovery were installed into the home. Half-hourly monitoring of energy balance, grid interaction and indoor environment took place post-retrofit. The typical average energy use for this type of home is approximately 12,500 kWh/year, with emissions of 2.53 tonnes CO_2/year. By taking a whole-house energy system approach to the retrofit of the home, energy import was reduced to approximately 1,700 kWh/year (87% savings). Operational emissions results obtained using the National Energy System Operator's (NESO) local, regional and national dynamic factors, and the UKs official annual grid intensity average factor were compared in the analysis. Results showed that, depending on the implemented factor, operational CO_2 emissions ranged between 0.042 and 0.138 tonne/year (98% to 95% reductions). Battery storage enabled the operational CO_2 emissions reductions to be doubled in all cases. Emissions reductions from battery use were proportionally higher when calculated using dynamic CO_2 intensity factors.

Keywords operational emissions, social housing, retrofit, carbon intensity

1. Introduction

Residential buildings contributed 14.3% of the UK's total CO_2 emissions in 2023 (1). Total emissions from residential buildings in the UK reduced by 16.5% between 2022 and 2024, mainly due to increasing energy prices (1). Nevertheless, emissions need to be reduced even further in compliance with the Climate Change Committee (CCC) Carbon Budgets, which established a legal commitment to achieve a 68% reduction by 2030, and 78% reduction by 2035 compared to 1990 levels, with discussions ongoing about raising the target to 81% (2, 3).

The UK Government has introduced schemes to enhance the delivering of whole-house retrofits in social housing, undertaken with a multiplicity of aims, but most prominently to reduce energy demand, fuel poverty and operational Green House

Gas (GHG) emissions, whilst ensuring healthy and comfortable indoor environments (4-6). Despite GHG emissions reduction being at the core of these schemes and policies, methodologies for reporting operational stage GHG emissions of low-energy buildings are still a matter of discussion. The recent UK's Net Zero Carbon Buildings Standard (NZCBS) aims to enable consensus regarding this, but is still in a pilot version (7). Notably, the standard does not offer clarity regarding the use of time-varying emission intensity factors.

This paper evaluates the performance of a low-carbon retrofitted social house with a focus on operational carbon dioxide (CO_2) emissions. The evaluation uses data from its first year post occupation, and aims to highlight the impact of using dynamic CO_2 emission calculations for the CO_2 emissions reporting. Two research questions are considered:

a. What is the impact of using different CO_2 intensity factor sources, static and dynamic, for operational CO_2 emissions assessment?
b. What is the impact of using an on-site battery storage system for reducing operational CO_2 emissions in a house with PV panels?

The study presents a literature review on existing operational emissions reporting methods and standards. The materials and methods section introduces the case study including benchmarks, performance indicators and monitoring strategy to evaluate the performance. This section also includes the procedure for quantifying CO_2 emissions and savings. The results section introduces the obtained electricity balance and indoor environment data, and presents the operational emissions data obtained by the use of different grid's CO2 intensity factors. Savings are calculated in relation to a comparable gas-heated home (Reference case A), and to an equivalent retrofitted home with no battery (Reference case B). The conclusions highlight the main findings and their significance.

2. Review of operational emissions reporting

Operational CO_2 emissions assessment can be understood as the process of quantifying CO_2 emissions that are originated during the operational stage of a building, in the context of its full lifecycle (8). Life Cycle Analysis divides the life of a building or other product into a series of modules classified between the "product stage" (A) and the "benefits and loads beyond the system boundary" stage (D). Operational emissions involves all the emissions arising from the activities covered by modules B1 to B7 of the LCA framework (8), related to the operational stage of buildings. However, it is most commonly associated to emissions resulting from the module "B7: Operational energy use", as this would usually account for the largest single amount of emissions from within this stage.

Operational CO_2 emissions assessment can also be understood as the process of quantifying the emissions resulting by an organisations' activities during a giving period. The GHG corporate protocol framework addresses this by classifying operational CO_2 emissions in three scopes: scope 1 relates to the direct emissions from an organisations' activities, such as direct combustion of gas or oil; scope 2 relates to the indirect emissions derived from the organisation activities, such as the emissions associated to the generation and distribution of consumed electricity; and scope 3 relates to the emissions that are beyond the boundaries of the organisation.

In both frameworks emissions are calculated by the quantification of used fuel or energy and the application of a CO_2 intensity factor. The IEA defines CO_2 intensity as “A measure of the amount of CO_2 (or other greenhouse gases) emitted during the supply of one unit of an energy product” (9). It highlights that the metric enables the comparison and quantification of environmental impact of different activities, but that the extent of inclusion of scope 1 to 3 emissions in the factors can vary. Instruments that quantify operational CO_2 emissions often use fixed, standardised, emission factors for each energy source, including electricity and gas. These factors can be expressed as carbon dioxide equivalent emissions per unit of energy, such as CO_2e/kWh.

Operational CO_2 emission assessments can be classified into two types: forecasts, performed during the design stage of new build or retrofit projects; and in-use reporting, performed during the operational stage of buildings. Forecasts offer an estimation of the expected operational emissions of a building or component during its lifecycle, based on a series of structured assumptions and projected future use and CO_2 emission factors. Reporting, on the other hand, focus on quantifying actual emissions produced by a building or component’s use during a specific period, using measured data and up-to-date CO_2 emission factors.

- CO_2 intensity factors for Forecasting

The CO_2 intensity factors used in forecasts can be expressed by fixed values, established by specific procedures, such as those used for design and evaluation of buildings in the different versions of the SAP method (3,4). Annual forecasted average grid intensity factors might also be sued, such as those published in the UK by the National Energy System Operator’s (NESO) Future Energy Scenarios (FES) databases (10), and by the HM Treasury’s Green Book, used for policy and public spending appraisal (11).

- CO_2 intensity factors for in-use reporting

Factors forecasted at the design stage of a building do not necessarily match actual factors during its operational stage. For this reason, operational CO_2 reporting procedures do not use the design-stage forecasted factors but instead use updated fixed factors published by official sources. In the UK, the official CO_2 factors are published yearly by the Department for Energy Security and Net Zero (DESNZ) (12). These offer an estimate of the average yearly factors for different fuels and energy sources for the ongoing year. In recent years, NESO has made available a database, accessible through an Application Programming Interface (API), that provides actual values of the UK’s electricity grid’s CO_2 intensity factors at 30-minute intervals for both national and regional levels (13). This dataset shows that large variations in the CO_2 intensity of the grids’ electricity can occur in a matter of hours.

This higher-resolution data becomes especially relevant for the evaluation of low or nearly net zero energy buildings (14, 15), where on-site renewable energy systems interact with the electricity grid (16, 17). The unpredictability of the demand, the intermittency of solar energy generation and the storage interactions with the generation and demand contribute to the variability of operational CO_2 emissions. This highlights the relevance of time variations in operational CO_2 emissions reporting procedures, and call for assessing the alignment between calculations performed using fixed factors and using actual, dynamic, CO_2 emission intensities of the grid. Dynamic CO_2 emission calculations use time-varying CO_2 intensity factors to calculate specific emissions at each moment. This approach is particularly useful for assessing cases with battery storage systems, as it helps accurately quantify avoided emissions and determine the CO_2 emissions payback of the storage technology.

- Buildings' operational CO_2 reporting guidance

Guidance documents have been presented by industry in recent years offering standardised methods for operational CO_2 emissions reporting during the operational stage of buildings including:

- GHG protocol scope-2 emissions for organisation-level reporting (2015)
- UKGBC Net Zero Carbon Buildings Framework (2019) (18)
- EUs Carbon Risk Real Estate Monitor (CRREM) (2021) (19)
- PCAF/ CRREM/ GRESB Technical guidance on accounting and reporting GHG emissions from real estate operations (2023) (20)
- Science Based Targets Initiative (SBTi) Buildings sector science-based target-setting criteria for organisations (21)
- RICS Professional Standard on Whole-life Carbon assessment (2023) (22)
- UK Net Zero Carbon Standard (NZCBS), pilot version (2024) (7)

The UK's NZCBS (7) addresses the problem of buildings' operational emissions reporting during the operational stage, by adopting detailed calculation procedures from the RICS whole lifecycle carbon emissions assessment professional standard (22). NZCBS defines key performance indicators and limits per building type. The standard aims to align the three accounting scopes of the GHG protocol with the modular structure provided in the series of standards to assess the environmental impacts of buildings during their lifecycle framed by EN 15978 (23).

However, the RICS standard does not yet address the problem of dynamic emission factors selection for operational stage emissions reporting. In this regard, the fact that the tendency in housing decarbonisation projects has been to electrify heating and services provision (10), implies that actual CO_2 emissions are not necessarily directly linked to energy consumption, but rather dependent on aspects such as the specific building's renewable energy self-consumption and self-sufficiency.

3. Materials and methods

3.1 A demonstration retrofit in South Wales

A collaboration between the Welsh School of Architecture at Cardiff University and a Registered Social Landlord (RSL) provider in South Wales enabled the retrofit of a vacant 1970s end-of-terrace home. The retrofit took place during the last quarter of 2022, and after a brief showcasing period, the home was occupied by new residents in April 2023.

The aim of the retrofit was to be representative of what can be effectively delivered at scale, in a short delivery period, using existing supply chains and skills. The RSL aimed to use this retrofit as a case-study to explore possibilities of domestic retrofitting within the organisation and partners, whilst at the same time understand the long-term outcomes. The home was used a demonstration for the month of January and February 2023, with more than 100 visitors from the social housing, local and national government, community groups, the supply chain and industry and academia attending. Table 1 details the retrofitted home's characteristics, and table 2 shows its main components before and after the retrofit.

Construction year	1970s
House type	End of terrace
Wall construction	Cavity wall masonry (brick and block)
Area (GIA)	88 m^2
Storeys	2
Bedrooms	2 double and 1 single
Bathrooms	1 full on first floor, 1 WC on ground floor
Roof type	Ventilated, cold roof

Table 1 – Pre-retrofit home characteristics

Component/ system	Pre-retrofit	Post-retrofit
Wall	Brick and block	External wall insulation (EPS) 0.18W/m^2K
Plinth	No insulation	External insulation (PIR) 0.18W/m^2K extended below ground
Windows and doors	Standard double glass, PVC frame	Higher spec uPVC 1.4W/m2K without trickle vents.
Floor	Concrete slab, no insulation	No change
Loft	Mineral wool	Mineral wool top-up, final u-value 0.13W/m^2K insulated loft hatch replacement.
Heating system	Gas combi boiler central heating and radiators	8kW air source heat pump, nominal COP 4.14
DHW	Gas combi boiler and electric shower	Heat pump-fed immersion heating unit
Ventilation	Extractor fans and passive ventilation	MVHR, SFP <= 0.59W/s/l
Renewable energies	None	4.92kWp Bolted-on rooftop PV (monocrystalline, 21% efficiency), GivEnergy Gen 2 Li-Ion 9.5kWh battery, and GivEnergy Gen 2 5.0kW hybrid inverter.

Table 2 – Retrofit home components/systems pre and post retrofit

Implemented works enabled permeability to reduce from pre-retrofit value of 13.18 $m^3h^{-1}m^{-2}$@50Pa to 10.50 $m^3h^{-1}m^{-2}$@50Pa post-retrofit. This improvement is due to the installation of EWI, closure of permanent vents, windows and doors replacement and sealing, topping up of loft insulation, and the loft hatch replacement and sealing. A lower permeability was not achieved due to the difficulty to implement specific airtightness measures.

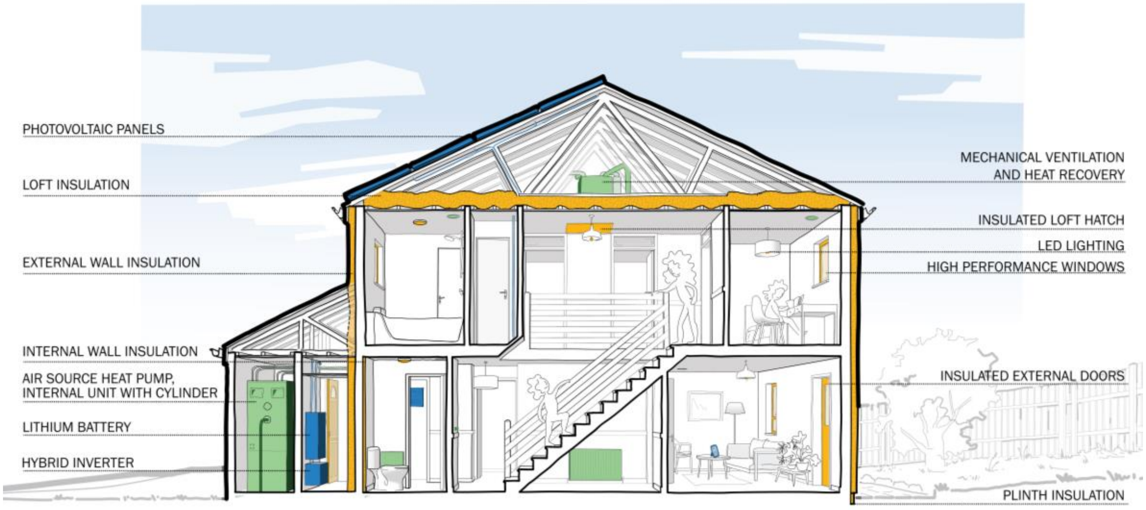

Figure 1 – Implemented measures schematic. Passive measures represented in yellow, active systems in green and renewable energy in blue.

It was not possible to obtain monitored pre-retrofit data for assessment purposes as the house had been vacant preceding the retrofit. The reference yearly demand of a gas-heated home was obtained from the reported average consumption of houses of equivalent typology and age in Wales, using the most updated version of the National Energy Efficiency Data-Framework (NEED) multiple attribute tables, which covers year 2022 (24). Equivalent typology was defined as semi-detached and end-of-terrace homes built between 1965 and 1982 which use gas as the main heating fuel. Table 3 shows the obtained values and number of cases.

Property type	Number in sample	Electricity (kWh/y)			Gas (kWh/y)		
		Lower quartile	Mean	Upper quartile	Lower quartile	Mean	Upper quartile
End terrace	10,940	1,700	2,900	3,600	6,400	9,400	11,800
Semi detached	42,840	1,700	2,700	3,400	6,700	9,800	12,200
Weighted average		1,700	2,741	3,441	6,639	9,719	12,119
Reference case A		12,459					

Table 3 – Average Electricity and Gas consumption of equivalent typology homes in Wales (24)

3.2 Data sources

The analysis presented in this paper used four data sources to analyse the first-year post-occupation of the house:

- Electricity balance: measured, introduced in 3.2.1
- Indoor environment: measured, introduced in 3.2.2
- Grid's CO_2 intensity: 3rd party, introduced in 3.2.3
- Operational CO_2 emissions: calculated, introduced in 3.2.4

The home was occupied from April 2023. However, the first three months were not considered for the analysis to avoid initial non-regular energy use patterns and to account for the occupants' adaptation to the new systems. Therefore, the reported study period is from 1/7/2023 to 30/6/2024.

3.2.1 Electricity balance

The home's energy balance indicators were obtained using the PV inverter's monitoring system. The system registers the home's import/export data using a CT-clamp in the consumer unit at 60 seconds intervals; whilst PV generation, battery charge, and battery discharge are registered directly within the inverter unit (Table 4).

Variable	Nomenclature	Unit	Sampling interval	Description
PV array generation	PV	kWh/i	<60s	Energy generated by the solar panels array during each interval
Battery charge	BC	kWh/i	<60s	Energy charged to the battery during each interval
Battery discharge	BD	kWh/i	<60s	Energy Discharged from the battery during each interval
Export	E	kWh/i	60s	Energy exported to the grid during each interval
Import	I	kWh/i	60s	Energy imported from the grid during each interval

Table 4 – Monitored electricity system variables

Total load and directly consumed energy were calculated by the system in real time (Table 5). Load was calculated for all intervals (i) using the energy balance equation of the house (Equation 1). Direct consumption was calculated by the onsite renewable generation energy flow equation (Equation 2), indicating that generated energy is prioritised for direct consumption, then storage and finally any remaining excess, for export. The renewable system's output was calculated using Equation 3.

$$L_{(i)} = I_{(i)} + RS_{(i)} - E_{(i)} \quad (1)$$

$$DC_{(i)} = PV_{(i)} - BC_{(i)} - E_{(i)} \quad (2)$$

$$RS_{(i)} = PV_{(i)} - BC_{(i)} + BD_{(i)} \quad (3)$$

Variable	Nomenclature	Unit	Formula	Description
Load	L	kWh/i	(1)	Total energy consumed by the home electric system during each interval.
Direct Consumption	DC	kWh/i	(2)	Total energy consumed on-site directly from the PV panels
Renewable system output	RS	kWh/i	(3)	Renewable energy system output to the house load and electricity grid during each interval

Table 5 – Derived electricity system variables

The data was aggregated into half-hourly intervals for the study period for analysis. Sub-metering of the home's heating loads was carried out for the heating season

November 2023 and June 2024. This data was obtained from hard-wired din-rail mounted meters in the house's consumer unit. The data was then collected and transmitted at hourly intervals using iMonnit wireless pulse-counter sensors. Table 6 introduces the obtained variables.

Variable	Unit	Sampling interval	Description
ASHP	kWh	60 minutes	Total energy consumed by the external heat pump unit
Immersion heater	kWh	60 minutes	Total energy consumed by the immersion heater
MVHR	kWh	60 minutes	Total energy consumed by the mechanical ventilation and heat recovery system

Table 6 – Monitored individual circuits electricity variables

Diagram 1 shows a schematic of the home's electrical system power flows and its main components.

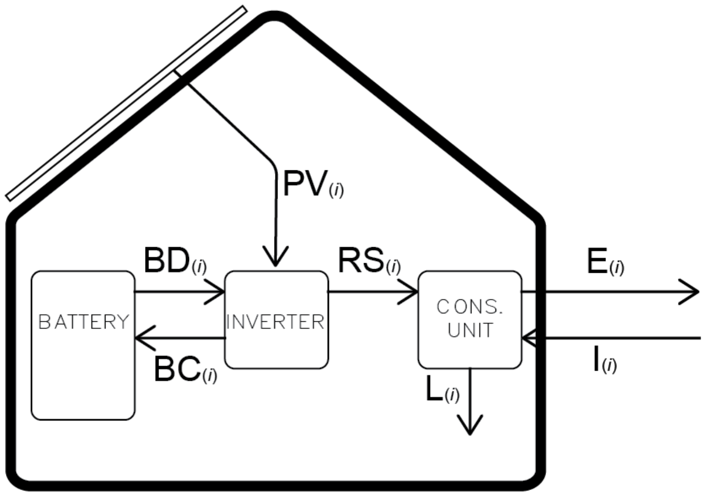

Figure 2 – Schematic of energy flows, nomenclature according to Table 4 and Table 5

3.2.2 Indoor environment

Temperature and Relative Humidity (RH) was collected from all living spaces to monitor comfort. Imonnit remote monitoring sensors were used with an accuracy of ±0.5C for temperature and ±3% for RH. Monitoring of comfort is necessary to assess if the consumed energy met the heating energy demand and to ensure comparability of the obtained values.

3.2.3 Grid CO_2 emissions intensity

Two sources of CO_2 intensity factors have been consulted:

1. NESOs carbon intensity API service (13):

Half-hourly actual GB, and calculated Wales and South Wales emission factor values were retrieved for the study period from the NESO data service. These values account for CO_2 emissions intensity of the electricity consumed from the national grid on the specific region at each specific interval. These factors take into account the generation mix, transmission losses and import/export balance with neighbouring systems (25, 26). The values correspond to operational CO_2 emissions only, and do not consider lifecycle emissions of the electricity generation and transmission infrastructure nor CO_2 equivalent emissions (25, 26).

2. The “UK Government GHG Conversion Factors for Company Reporting”, published yearly by the DESNZ (12):

Yearly “official figures for scope-2 emissions” have been obtained from the DESNZ. These values are presented as CO_2e/kWh, and CO_2/kWh, which does not consider the role of GHGs such as CH_4 and N_2O in the final value. For this paper, only the CO_2/kWh values have been consulted, to ensure comparability with the unit offered by the NESO data service. The UK’s standard mains natural gas conversion factor has also been obtained from this dataset, for calculating the annual emissions of the Reference Case A (equivalent gas-heated home), as detailed in 3.2.4.

Table 7 shows then main descriptives of electricity CO_2 factors from each dataset for the studied period. Values correspond to half-hourly intervals. Figure 3 displays the average profiles per season and factor.

Dataset	Minimum	Average	Median	Maximum	Avg. daily variation	Max. daily variation
SW*	4	251.3	276.0	391.0	194.2	368.0 (08/07/2023)
W*	2	181.2	174.0	387.0	169.1	378.0 (08/07/2023)
GB*	14	136.4	132.0	309.0	91.8	206 (15/11/2023)
UK*	204.9				0.0	

Table 7 – Electricity grid’s CO_2 intensity factors datasets for the study period, where SW: South Wales – Dynamic; W: Wales – Dynamic; GB: Great Britain – Dynamic; UK: United Kingdom – Static. All values reported in gCO_2/kWh.

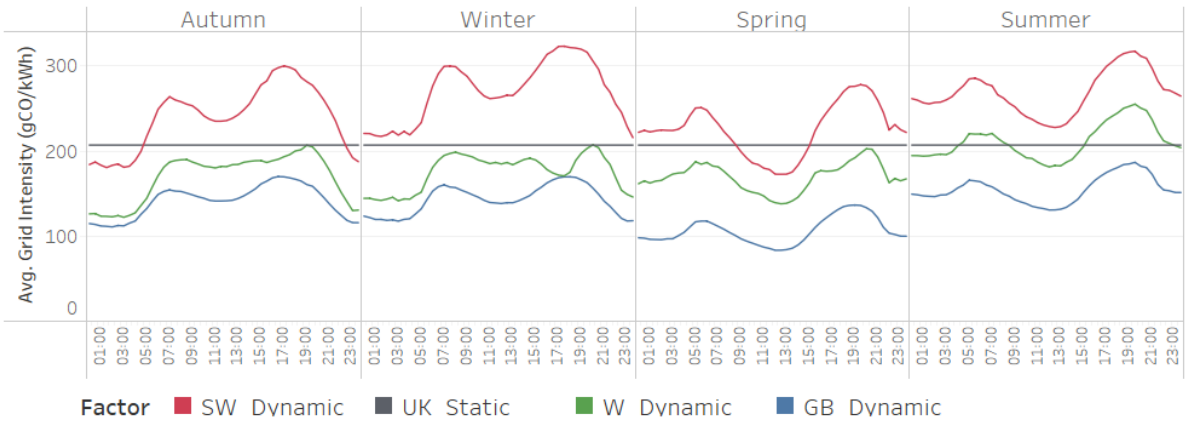

Figure 3 – CO_2 intensity factors’ average hourly values by season for the studied period

In the following sections, CO_2 factors are referred to as $CF_{N(i)}$, indicating CO_2 factor according to dataset N, during interval (i), where datasets correspond to SW, W, GB and UK.

3.2.4 Operational CO_2 emissions

Operational CO_2 emissions were calculated following the guidance from the RICS Professional Standard, version 3 (22), as adopted by the NZCBS: excluding upstream embodied CO_2 emissions in infrastructure used to source, distribute and store energy in the grid (7). Therefore, it was considered that:

- energy generated on-site that is consumed on-site (RS) had operational emissions of 0gCO_2/kWh, and
- exported energy was considered to account for emission reductions at the grid's CO_2 intensity factor rate, up to the yearly threshold of the imported energy.

This means that electricity that was exported to the grid and reimported from the grid at a different time in the year contributed towards the emissions neutrality of the building. However, if yearly energy exports exceed the yearly import of the home, this would not be accounted as negative CO_2 emissions.

It was not possible to obtain a dynamic dataset of the energy consumption of an equivalent home, emissions from a gas-heated reference case was obtained, with yearly total values and yearly fixed CO_2 factors per energy source.

- Emissions of Reference Case A: Average consumption of an equivalent type gas-heated home:

$$REA_{N(y)} = \left(Ref\ Gas \times CF_{G(y)}\right) + \ (Ref\ Elect \times Avg.CF_{N(y)}) \quad (4)$$

Where $RE_{G(i)}$: Reference emissions during year (y), Ref Gas: Typical gas consumption for the year, typology and place according to NEED values, in kWh; $CF_{(G)}$: DESNZ Natural Gas CO_2 Factor for the year (y) in gCO_2/kWh, Ref Elect: Typical electricity consumption for the year, typology and place according to NEED values, in kWh; Avg. $CF_{N(i)}$: Avg. CO_2 Factor according to dataset N during year (y) in gCO_2/kWh.

For all other variables, CO_2 emissions were calculated dynamically using specific energy flow and CO_2 intensity factors for each half hour interval (i). The calculated metrics are:

- Reference emissions Case B: Equivalent retrofitted home without PV and battery:

$$REB_{N(i)} = \ \mathrm{L}_{(i)} \times \mathrm{CF}_{\mathrm{N}(i)} \quad (5)$$

Where $REA_{N(i)}$: Reference emissions during interval (i) according to factor N, $L_{(i)}$: Load during interval (i) in kWh; and $CF_{N(i)}$: CO_2 Factor according to factor N during interval (i) in gCO_2/kWh.

- Gross operational emissions (produced off-site due to on-site grid imports):

$$GE_{N(i)} = \ I_{(i)} \times CF_{N(i)} \quad (6)$$

Where $GE_{N(i)}$: Emissions during interval (i) according to factor N, $I_{(i)}$: Electricity imports during interval (i) in kWh; and $CF_{N(i)}$: CO_2 Factor according to dataset N during interval (i) in gCO_2/kWh.

- Emissions saved through direct consumption:

$$SDC_{N(i)} = \ DC_{(i)} \times CF_{N(i)} \quad (7)$$

Where $SDC_{N(i)}$: Saved emissions through direct consumption during interval (i) according to factor N, $L_{(i)}$: Load during interval (i) in kWh; and $CF_{N(i)}$: CO_2 Factor according to dataset N during interval (i) in gCO_2/kWh.

- Emissions saved through battery discharge:

$$SBD_{N(i)} = BD_{(i)} \times CF_{N(i)} \tag{8}$$

Where $SBD_{N(i)}$: Saved emissions through battery discharge during interval (i) according to factor N, $BD_{(i)}$: Battery discharge during interval (i) in kWh; and $CF_{N(i)}$: CO_2 Factor according to dataset N during interval (i) in gCO_2/kWh.

- Emissions saved through grid export:

$$SEE_{N(i)} = \begin{cases} E_{(i)} \times CF_{N(i)}\ , if\ \sum_{i=1}^{k} I_{Y,i} > \sum_{i=1}^{k} E_{Y,i} \\ 0\ , if\ \sum_{i=1}^{k} I_{Y,i} < \sum_{i=1}^{k} E_{Y,i} \end{cases} \tag{9}$$

Where $SEE_{N(i)}$: Saved emissions through exports during interval (i) according to factor N, $E_{(i)}$: Exports during interval (i) in kWh; $CF_{N(i)}$: CO_2 Factor according to dataset N during interval (i) in gCO_2/kWh; and *k* is the number of the interval. Therefore, $\sum_{i=1}^{k} I_{Y,i}$ represents the cumulative summation of Imports up to interval k.

- Total saved operational emissions:

$$TS_{N(i)} = RE_{N(i)} - GE_{N(i)} = SDC_{N(i)} + SBC_{N(i)} + SEE_{N(i)} \tag{10}$$

Where $TS_{N(i)}$: Total saved emissions during interval (i), in gCO_2/kWh. $CE_{(i)}$ and $RE_{N(i)}$ respond to Reference case emission $RE_{A(i)}$ or $RE_{B(i)}$; else responds to the preceding formulas.

- Net operational emissions:

$$NE_{N(i)} = GE_{N(i)} - TS_{N(i)} = SE_{DC(i)} + SE_{BC(i)} + SEE_{N(i)} \tag{11}$$

Where $NE_{N(i)}$: Net operational emissions during interval (i), in gCO_2/kWh; else responds to the preceding formulas.

- Aggregations:

$$x_T = \sum_{n=i}^{i+N} x_n \tag{12}$$

For variables introduced in formulas (5) to (11), aggregations were obtained as standard summations, where *x* corresponds to the value being aggregated and *T* corresponds to the analysis period for which values are being aggregated (e.g. 30 minutes, 1 hour, 1 day, etc.).

3.3 Analysis methods

Section 4.1 provides an overview of the monitored electricity data main KPIs and section 4.2 introduces the monitored indoor environment data. Operational CO_2 emissions results obtained from applying the formulas presented in the previous section are presented in section 4.3. Two comparative analyses were conducted, aligned to the two proposed research questions.

For the first analysis, Reference case A was used to calculate total savings achieved through the retrofit, and results are presented in section 4.3.1.

For the second analysis, Reference case B was used to calculate savings achieved by using the battery system as compared to not using it.

In both cases the results obtained by using the different dynamic and static factors were compared.

4. Results

4.1 Electricity balance and grid interaction

The measured yearly totals for each of the electricity balance variables are shown in Table 8. As the house operated using only electric energy sources, these values reflect the energy balance of the whole house system for the reported period.

Variable	Total measured energy (kWh/year)	Energy intensity (EUI) per m^2 GIA (kWh/m^2 GIA/year)
Consumption (L)	4,451	50.58
Generation (PV)	4,312	49.00
Renewable system output (RS)	4,240	48.18
PV direct consumption	1,378	15.66
Export I(E)	1,431	16.26
Battery charge (BC)	1,503	17.08
Battery discharge (BD)	1,388	15.77
Import (I)	1,686	19.16

Table 8 – Yearly energy balance totals in kWh.

These totals show that the house achieved a self-consumption of 66.80%, of which a 52.18% (1,388 kWh) was achieved by shifting the PV-generated energy consumption time to the battery. This is consistent with the 66% self-consumption suggested by the MCS self-consumption tables for households who are in half-day, for the generation and storage capacity of the house (12). The self-sufficiency of the house during the same period was 64.76%, meaning that only a 35.24% of the house's yearly energy needs (1,686 kWh) came from grid electricity imports.

The difference between the total generation and the renewable energy system output is given by the losses of the battery storage system. Throughout the year losses added up to 115.2 kWh, representing a 7.6% of the total energy charged into the battery.

The ASHP, Immersion tank and MVHR systems consumption was metered for the period between December 2023 and June 2024, registering a consumption of 1,041 kWh, of which 747.9 kWh corresponded to the ASHP and 196.8 kWh to the Immersion tank. Based on these measurements and the monthly degree days, a projection was performed to estimate the consumption values of the remaining months, obtaining the yearly totals displayed in Figure 4.

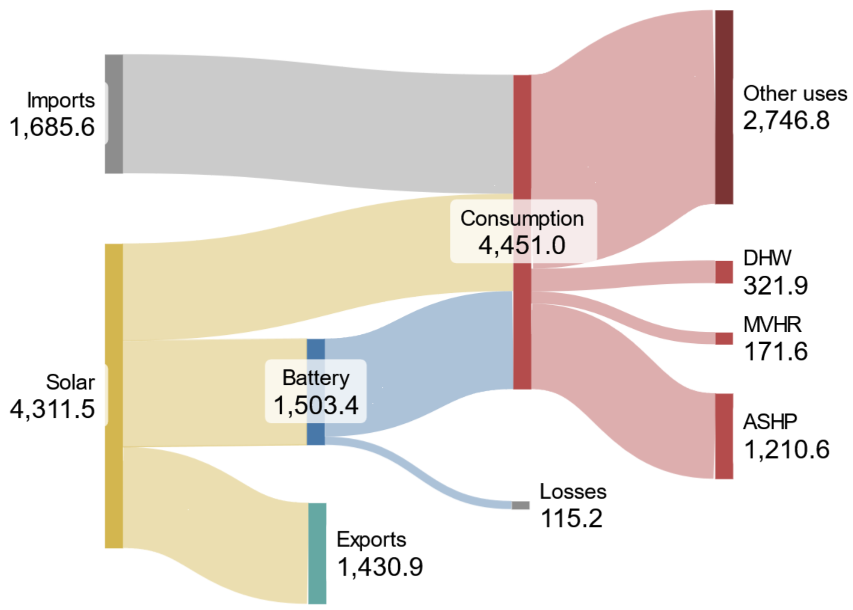

Figure 4 – Energy flows in the house during the studied period

Overall, it could be said that the home was close to achieving a net energy balance based on yearly figures, given that the difference between RS and L was of only 4.70% (209 kWh). Nevertheless, meeting the house energy needs involved 1,686kWh of grid imports, which occurred mainly during the winter season, as shown in the next section.

Figure 5 below shows the average electricity consumption and generation profile per season. It is noticeable that almost all energy imports occurred during the cold seasons, with low imports in the Spring and none during the Summer. The opposite pattern is observed regarding the exports, which concentrate almost exclusively in the warmer seasons.

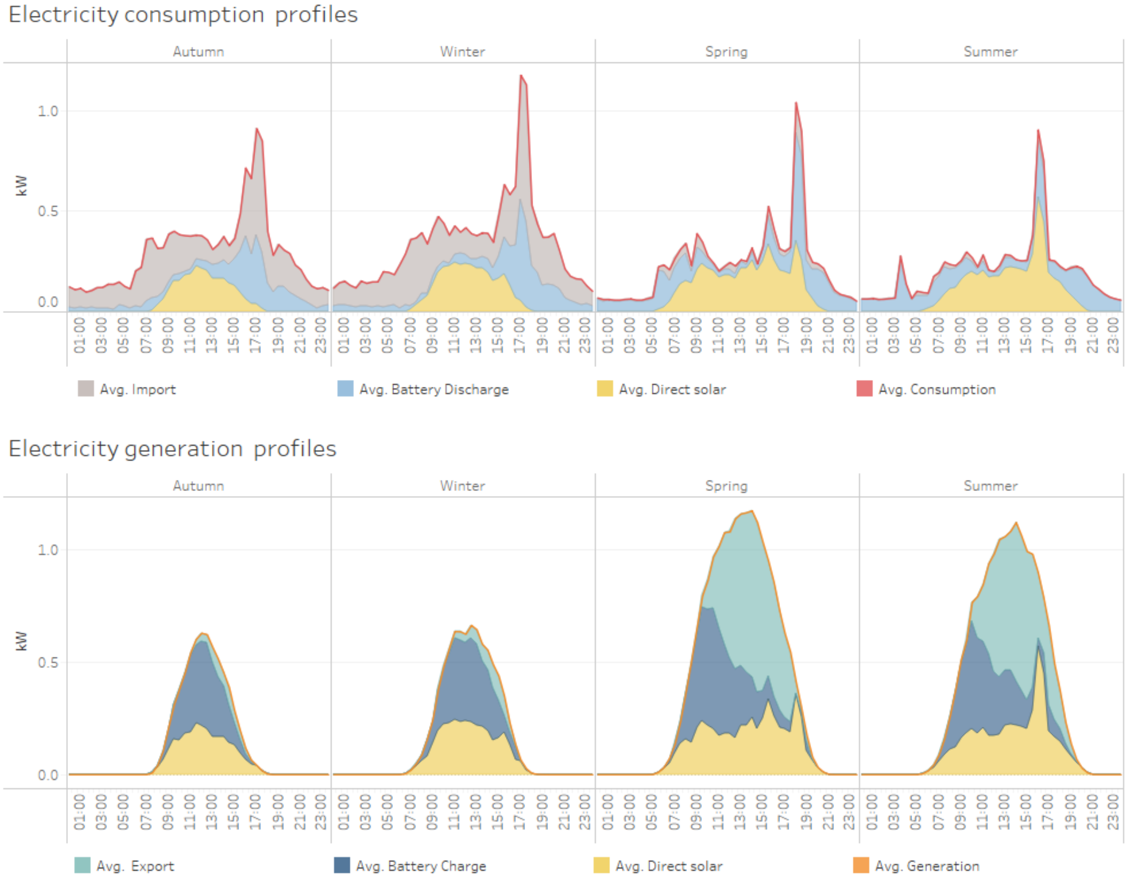

Figure 5 – Electricity consumption and generation profiles per season, showing source and uses of the energy respectively

4.2 Indoor environment

Table 9 shows the temperatures recorded during the heating season (November 2023 to March 2024) at hourly intervals. These figures suggest a slight indoor environment underheating. This, however, has been identified to reflect the resident's setpoint for the system. Average humidity during the monitored period reached 65.4%.

Area	Min	Average	Max
External	-3.88	6.77	12.07
Bathroom	13.11	16.81	20.16
Kitchen	16.17	18.20	20.41
Living Room	15.56	17.40	19.16
Main Bedroom	16.56	17.90	19.58
Second Bedroom	16.49	18.12	20.23
Third Bedroom	16.40	18.02	19.45

Table 9 – Monitored heating season (November-March) temperatures per room.

Figure 6 shows the average daily temperature per room for the full monitored period, July 2023 to June 2024. Although average temperatures remain over 18C most of the time, these can be considered low by standards expected from a retrofitted home.

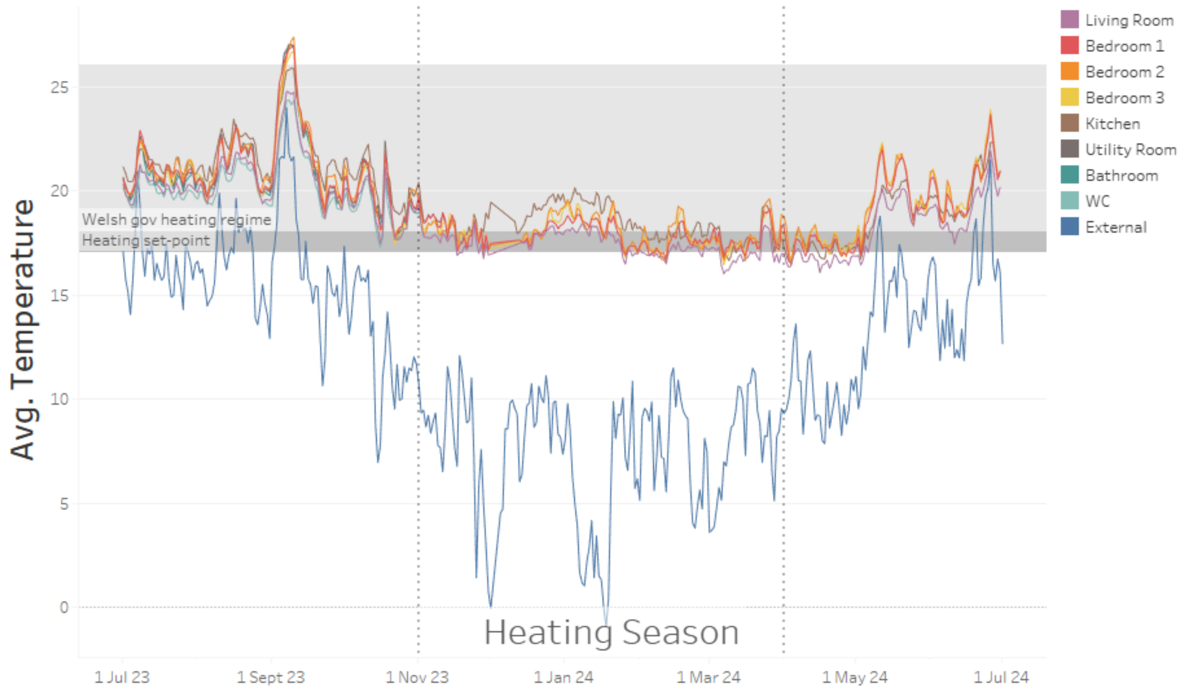

Figure 6 – Average daily temperatures per room. External values in blue

4.3 Operational CO_2 emissions

The obtained values of yearly operational CO_2 emissions are introduced in Table 10.

Emissions	Factor (kgCO2)			
	SW (Dynamic)	UK (Static)	W (Dynamic)	GB (Dynamic)
Gross emissions (GE) ($kgCO_2$)	448.8	348.6	299.3	248.1
Gross emissions / ($kgCO_2/m^2$)	5.1	4.0	3.4	2.8
Net emissions (NE) ($kgCO_2$)	137.7	52.3	42.4	73.1
Net emissions / GIA ($kgCO_2/m^2$)	1.6	0.6	0.5	0.8

Table 10 – Yearly emissions totals for the reported period using each CO_2 factor.

These figures show substantial differences in resulting emissions depending on the CO_2 factor used. Although the absolute values might be considered similar, the relative differences are considerable.
Using the monitored data and the official UK government yearly static factor for GHG reporting, it was obtained that the house operation was responsible for 348.6 $kgCO_2$/year of gross emissions, that is 39% higher than the gross emissions obtained

using the GB dynamic factor, and 29% lower than the same value calculated using the SW dynamic factor.
Net emissions obtained using the UK government yearly static factor was 52.3 $kgCO_2$/year. Using NESO's GB dynamic factor, the obtained value was 39.8% higher. The greatest difference in net emissions came from the use of regional-specific factors. Particularly, net emissions obtained using the South Wales dynamic factor were a 163% higher than using the UK static factor and 88.4% higher than using the dynamic UK factor.
Figure 7 introduces a comparison of these values, where net emissions are represented in grey, and gross emissions (GE) by the sum of net and displaced emissions.

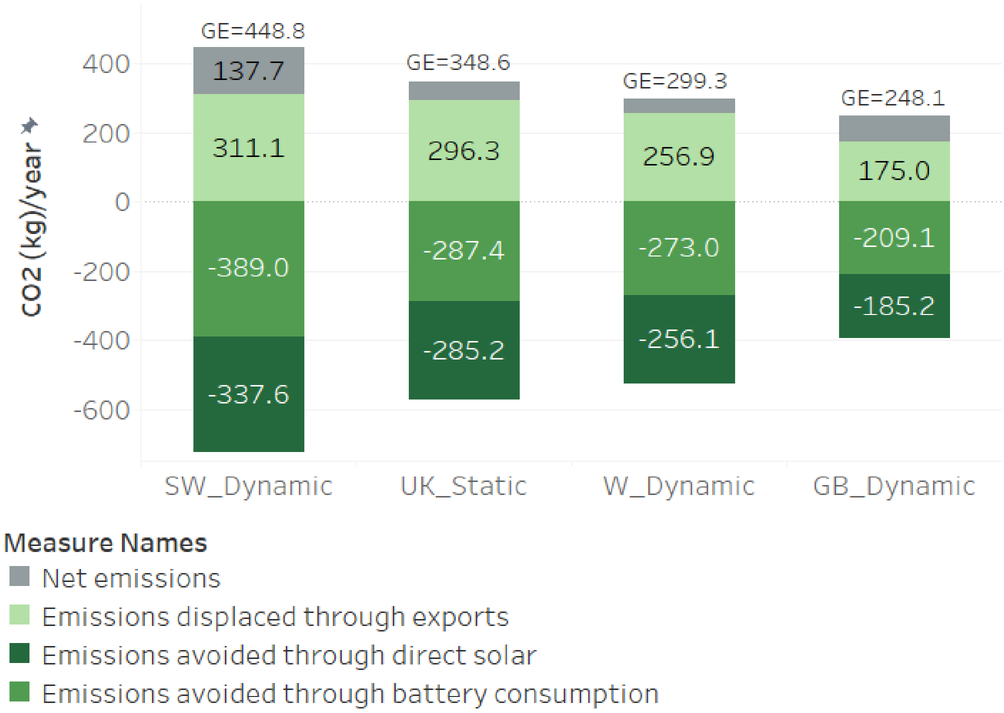

Figure 7 – Totals for the reported period using each CO_2 factor, where GE: total over 0; NE: in grey.

Figure 8 (next page) shows the differences in average daily emissions per season and implemented grid intensity factors. As the house operated mostly self-sufficiently during spring and summer, no significant differences in gross emissions (dark grey) were recorded in these periods. However, differences during autumn and winter were more pronounced, specially around peak demand times.

A second interesting insight from this chart is that despite a clear gradient in gross emissions profiles can be seen, the CO_2 emissions displacements (light grey) do not follow the same pattern. Particularly, the spring profile obtained using the UK static factor has a different shape than the same profile obtained using the dynamic factors, apparently overestimating the savings achieved from morning and early afternoon exports.

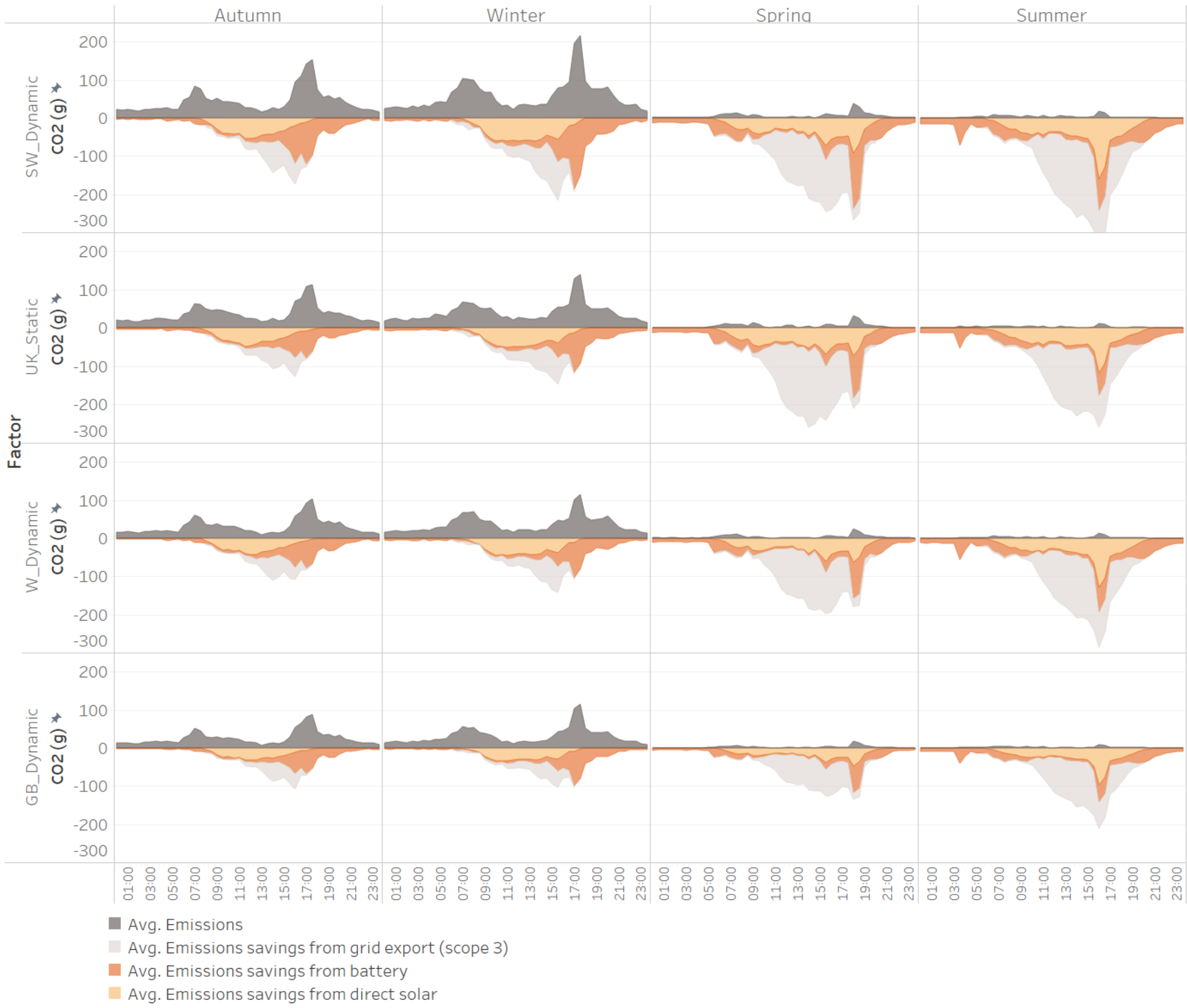

Figure 8 – operational CO_2 emissions profiles obtained using each of the factors per season

4.3.1 Savings from the whole-house retrofit

Using the Reference Case A energy consumption values introduced in Table 3 and the DESNZ 2024 CO_2 emission factors, it was possible to determine that the annual total CO_2 emissions for a gas-heated equivalent typology home ranged between an average of 1.69 to 3.16 TCO_2e/year for the lower and upper quartiles respectively. The mean value for the identified representative group was 2,530.4 TCO_2e/year. This value has been used to calculate CO_2 emissions reductions from the Reference Case A in the UK static factor application.

Since the Reference Case A data is provided as yearly totals and not disaggregated by hours, the emissions from electricity were calculated using the yearly average intensity for the electricity grid according to each CO_2 intensity factor during the studied period, as previously presented in (Equation 4), thus obtaining corrected Reference case A emissions for each grid emission factor application. Results are presented in Table 11.

Factor ($kgCO_2$)	SW (Dynamic)		UK (Static)		W (Dynamic)		GB (Dynamic)	
	Abs	%	Abs	%	Abs	%	Abs	%
Reference case A (RE_A)	2,658.1	100	2,530.4	100	2,465.9	100	2,343.2	100
Gross savings from retrofit	2,209.3	83.1	2,181.8	86.2	2,166.6	87.9	2,095.1	89.4
Gross operational emissions (GE)	448.8	16.9	348.6	13.8	299.3	12.1	248.1	10.6
Savings from grid exports (SEE)	311.1	11.7	296.3	11.7	256.9	10.4	175.0	7.5
Net operational emissions (NE)	137.7	5.2	52.3	2.1	42.4	1.7	73.1	3.1
Total savings (TS) from retrofit	2,520.4	94.8	2,478.1	97.9	2,423.5	98.3	2,270.1	96.9

Table 11 – Operational CO_2 emissions and savings results obtained using reference case A (gas-heated) for each CO_2 factor ($kgCO_2$)

The results show that through the retrofit the house achieved gross savings higher than 83%, and total savings higher than 94% in all cases. Nevertheless, the difference in relative savings obtained between the different factors is considerable, with up to 6.3% difference in gross emissions savings, between SW and GB dynamic; and up to 4.5% in total savings (between W dynamic and SW dynamic).

4.3.2 Savings from PV and Battery

The operational CO_2 emission savings obtained from the implementation of the PV and battery system were calculated by comparing the actual emissions of the house to those that would have been obtained if the PV and battery system had not been installed (Reference Case B). By doing this, the contribution of the PV direct consumption and the batteries was quantified for CO_2 emission factor application case. Table 12 summarises the obtained results by comparing absolute and relative savings.

Factor ($kgCO_2$)	SW (Dynamic)		UK (Static)		W (Dynamic)		GB (Dynamic)	
	Abs	%	Abs	%	Abs	%	Abs	%
Reference case B (RE_B)	1,175	100	921.2	100	828.4	100	642.4	100
Savings from direct solar consumption (SDC)	337.6	28.7	285.2	31.0	256.1	30.9	185.2	28.8
Savings from battery consumption (SBD)	389.0	33.1	287.4	31.2	273.0	33.0	209.1	32.5
Gross savings (SDC+SBD)	726.6	61.8	572.6	62.2	529.1	63.9	394.3	61.4
Savings from grid exports (SEE)	311.1	26.5	296.3	32.2	256.9	31.0	175.0	27.2
Total savings (TS) from PV and battery	1037.7	88.3	868.9	94.3	786.0	94.9	569.3	88.6

Table 12 – Operational CO_2 emissions and savings results ($kgCO_2$) obtained using reference case B for each CO_2 factor

The CO_2 factor selection had an impact on the final gross emission savings value that was as high as a 82.96%. This difference was observed between the GB dynamic dataset (394.3 $kgCO_2$) and the SW dynamic dataset (726.6 $kgCO_2$).

The contribution of savings from direct solar were higher when calculated using the static factor, although the average difference between the static factor and the dynamic ones was of only 1.5%. The contribution of savings from battery consumption were in all cases higher when calculated using the dynamic factors, by an average of 1.7%. The contribution of savings from grid exports were higher when calculated using the static factor, by an average of 3.9%. The average difference in total savings when between the static and the dynamic factors was 3.72%. Figure 9 shows a comparison of the carbon emissions savings contributions of the direct PV and the battery for all four scenarios.

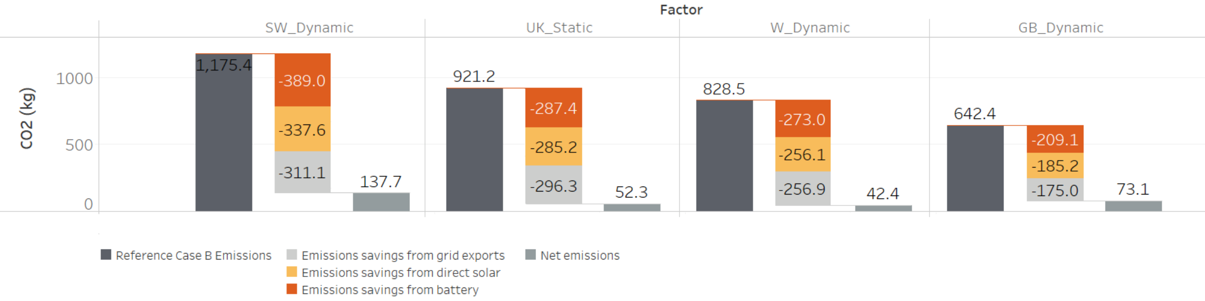

Figure 9 – Gross operational CO_2 emissions and savings results obtained using each factor

If the UK static dataset is used as a baseline case, the GB dynamic dataset registers the largest relative differences: the reference case was 28.8% lower, and the savings were 31.1% lower than if calculated using the UK static factor. Table 13 shows a comparison of the relative differences between each obtained savings values and the one obtained using the official static CO_2 factor $CF_{(UK)}$.

Difference to same value obtained using the UK static emission factor (%)	Factor			
	SW (Dynamic)	UK (Static)	W (Dynamic)	GB (Dynamic)
Reference case B (RE_B)	28.7	0.0	-14.1	-28.8
Savings from direct solar consumption (SDC)	18.4	0.0	-10.2	-35.1
Savings from battery consumption (SBD)	35.3	0.0	-5.0	-27.2
Savings from grid exports (SEE)	5.0	0.0	-13.3	-40.9
Total savings ($SE_{(i)}$)	19.4	0.0	-9.5	-34.5
Gross emissions (GE)	27.6	0.0	-10.1	-30.3
Net emissions (NE)	163.3	0.0	-18.9	39.8

Table 13 – Operational CO_2 emissions and savings results differences between each of the dynamic and UK official static factor

5 Conclusions

The analysed social home case study was delivered and inhabited under real market conditions in South Wales. The outcomes of the housing retrofit were monitored over one year. CO_2 emissions savings were analysed and reported using four different sets of grid CO_2 intensity factors.

The study had a number of limitations:

- Change in tenancy meant no pre-retrofit data was available. Therefore, a benchmark derived from equivalent homes in the context has been used.
- It has not been possible to determine the reasons for some rooms' underheating, as a long term post occupancy survey has not been carried out with residents yet.
- Embodied emissions and payback periods have not been considered in this analysis.

In relation to the first research question, the study showed that using different available CO_2 intensity factor sources, static and dynamic, for the operational CO_2 emissions assessment produced substantially different results. The differences were more relevant when the dynamic results were assessed in relation to the fixed UK factor, with savings from Reference A varying from 81 to 89% (Gross) and 94% to 98% (Net), depending on the factor used. Considering that all factors were applicable to the actual analysed location and period, the study suggests that great care needs to be taken in the specifications of dynamic intensity factors selection in future standards and methodologies. Particular attention should be given to geographical inequalities or handicaps arising from differences in the local grid's CO_2 intensity.

The second research question looked at the impact of the PV panels and the on-site battery storage system to reduce operational CO_2 emissions as compared with consuming energy from the grid, using the same factors. It was found that both the PV panels and the batteries had a similar contribution to the overall operational CO_2 emissions reduction. Depending on the implemented factors, the PV panels contribution to the reduction ranged between 28.7 to 31.0%; whilst the batteries contributed between 31.2 and 33.1%. Total operational CO_2 emissions savings ranged between 88.3 and 94.9% depending on the implemented factor.

For future work, a more comprehensive assessment of the benefit of the batteries should consider the system's embodied carbon and projected emissions payback in line with the grid's future decarbonisation scenarios. The observed differences in operational CO_2 savings resulting from implementing different CO_2 factors will have direct impacts in payback calculations.

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