Deep retrofitting: carbon vs cost payback

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Abstract
This paper provides a methodology for calculating carbon and cost payback for deep retrofits with known capital cost and embodied carbon. Cost payback was calculated by subtracting operational cost savings from the capital cost whereas carbon payback was calculated by subtracting operational carbon savings from the embodied carbon. Two future energy cost scenarios combining national UK and global projections were used for the cost payback predictions. Three future grid carbon intensity scenarios based on the UK 2030 clean power target were utilised to calculate carbon payback.

The methodology was applied to a social housing case study that underwent a deep low carbon retrofit. The homes were monitored and modelled before and after the works. Projected data illustrate that carbon payback is 5.9 to 7.9 times faster than cost payback. Embodied carbon associated with imported PV panels is the most dominant carbon contributor to the system and boiler fossil fuel avoidance is the most significant cost and carbon saving.

Keywords Embodied carbon, operational carbon, retrofit, cost payback, carbon payback

1.0 Introduction
The Climate Change Act of 2008 mandated an 80% reduction in greenhouse gas emissions by 2050, compared to 1990s level (1). This target was made more ambitious in 2019 requiring the UK to bring all greenhouse gas emissions to Net-Zero by 2050 (2). The UK built environment is responsible for 25% of total UK greenhouse gas emissions and the 29 million homes in the UK account for approximately 14% of UK greenhouse gas emissions (2). Low-carbon housing retrofit is critical for addressing the nation's climate targets, contributing to reduced carbon emissions but also has the potential to alleviate fuel poverty and stimulate economic growth (3). Decarbonisation of existing homes is one of the main strategies to move toward a Net-Zero future in the UK.

Building retrofit strategies aim to reduce operational energy consumption but capital costs and embodied carbon emissions are an ongoing challenge that needs to be overcome (4).

A significant barrier to retrofitting homes is the capital cost of the solutions and the perceived cost payback period (4, 5). Cost payback refers to the time needed for energy bill savings to match the capital cost of the retrofit solutions considering their lifetime. Carbon payback refers to the time it takes for the operational carbon emissions saved by the retrofit solutions to offset the embodied carbon emissions associated with materials, construction and installation processes throughout the whole lifecycle of the retrofit solutions. Cost payback period can be used to support the decision-making process of owners, whether social or private landlords or occupiers, when deciding what retrofit measures to invest in. Cost payback does not refer to Net-Zero carbon targets.

Carbon payback reflects the potential carbon reductions and should be a priority when making decisions related to Net-Zero targets. Embodied carbon includes all carbon emissions emitted in the production and construction stage which includes the transportation and installation of the solutions (6, 7). Operational carbon is associated with post-occupancy emissions from the use of energy for heating, domestic hot water, ventilation, lighting and the use of appliances and other equipment (6, 7). Reducing operational energy and associated emissions has been included within UK Building Regulations, such as Part L (8), whereas Building Regulations do not clearly designate embodied carbon reductions.

According to Bienert (6), 30-40 gigatons of CO_2e[1] will be emitted by existing buildings around the world by 2050 which accounts for 8.5% of the global greenhouse gas budget[2]. By providing carbon payback calculations for low-carbon retrofits, a comparison of the embodied 'carbon investment' associated with the upgrade of homes can be made with reduced emissions from operational energy. This provides a more holistic view of whether the retrofit contributes towards climate targets.

The quantification of cost and carbon payback requires the quantification of the capital and operational cost and embodied and operational carbon between pre- and post-retrofit. The capital cost of a retrofit investment can be calculated using market prices and/or from retrofit procurement. Embodied carbon can be calculated by estimating carbon emissions generated from the production and the construction stages (7). The operational cost and carbon reduction require monitoring or/and modelling of the pre- and post-retrofit operational energy consumption. Operational cost and carbon are calculated by converting operational energy to energy cost and

[1] Carbon dioxide equivalent (CO_2e) is a unit of measurement that compares the impact of different greenhouse gases on global warming.
[2] Remaining global anthropogenic greenhouse gas budget for a 1.5-degree Celsius compliant world (COP28).

equivalent carbon emissions. Accurate payback would require this conversion to happen for the duration of the payback period. Therefore, cost and carbon conversion factors have been established, determined by grid energy cost and carbon intensity, calculated for the historical grid status. For future calculations, projection scenarios has been considered be considered.

2.0 Energy and carbon performance indicators

2.1 Energy performance indicators for retrofits

Building Regulations, Standards and Guides provide energy targets for new builds and retrofits. UK Building Regulations set operational energy targets through the Standard Assessment Performance (SAP) rating (9). The operational energy is regulated by establishing fabric and systems targets (8, 10). Energy and carbon performance indicators and targets are provided through Technical standards such as the PAS2035-Retrofitting dwelling for improved energy efficiency (11), the LETI Climate Emergency Retrofit Guide (12) and the UK Net-Zero carbon Buildings (13) as well as Certification Standards such as AECB CarbonLite Retrofit (14), EnerPHit Passivhaus (15) and Energiesprong (16). The dominant indicator across these Regulations, Standards and Guides is operational energy suggesting that retrofit strategies and technologies should reduce demand whilst increasing onsite renewable generation and self-sufficiency without compromising comfort levels.

Energy demand can be modelled (predicted), whereas energy consumption can be measured in kWh by using import meters for grid gas and electricity or tank meters for locally stored boiler fuels (oil, LPG). When renewable generation is integrated on-site, energy import and export are important indicators allowing calculation of electricity that residents pay for. Energy cost can be calculated by the metered charges of the imported and exported (net) kWh which may include standing charges and taxes. Import and export prices can vary and are dependent on offers from energy providers and the ability of the resident to be able to understand and be flexible to take these up (17, 18). Electricity storage on site increases self-sufficiency with reductions in both import and export while battery losses should be taken into consideration. Measured energy can be aggregated monthly, seasonally or annually and normalised per m^2 or by other construction and residency parameters (19).

Operational energy at the building level refers to the end-user energy whereas primary energy describes the energy used to generate energy at power stations and transport energy to buildings at the grid level. Operational energy can be compared against existing benchmarks for low carbon housing retrofit in the UK including primary energy demand expressed in Energy Use Intensity (EUI) which is energy use per square meter per year. Benchmarks that include operational energy targets are EnerPHit which is the retrofit standard for Passivhaus (15), the AECB CarbonLite retrofit standard (14) and the LETI Climate Emergency Retrofit Guide.

2.2 Embodied and operational carbon in deep retrofitting

Carbon emissions are associated with every stage of the house's life (20). According to the EN15978 British Standard (7), whole life carbon includes four stages: 1) Product (A1-A3), 2) Construction (A4-A5), 3) In-use (B1-B7) and 4) End of life (C1 - C4). The first two stages are upfront embodied carbon or cradle to practical completion. Operational carbon is incurred during the in-use stage (B6-B7) (7). Circular economy refers to stage D where reuse, recovery and recycling processes beyond a building life cycle and extend the process to Cradle to Cradle.

Low carbon housing retrofit impacts operational and embodied carbon emissions. Embodied carbon account for between 40% - 60% of the total lifecycle energy in low-energy housing (21). Once a home is occupied carbon emissions are caused by operational energy consumed. During a low carbon retrofit, when a component is replaced or added, embodied carbon increases as the new component has been manufactured, transported and installed. However, a reduction in carbon emissions is expected from operational energy reduction and decarbonisation.

Operational carbon can be calculated from the operational energy demand or consumption by using conversion factors indicating the carbon intensity of the fuel used at the grid level. Carbon and cost are based on varying grid carbon intensity and energy markets but long-term values may be used for simplicity; such factors are used in SAP (9). The UK government publishes annual greenhouse gas conversion factors including carbon intensity of fuels (22) whereas the National Energy System Operator (NESO) publishes 30min grid real-time carbon intensity of fuels (23).

Guidelines for calculating embodied carbon has been developed, however, they focus on new buildings, for example, LETI's Climate Emergency Design Guide suggests 300kg CO_2e/m^2 for residential buildings (12). Research indicates that embodied carbon associated with retrofit solutions can vary widely. Research of 36 low-carbon retrofit projects from around the world indicated an average carbon payback period from 1 to 8 years depending on building type and retrofitting depth with embodied carbon varying from 20 to 140kg CO_2e/m^2 (6).

3.0 Developing energy cost and carbon intensity projections

3.1 Energy cost; historic data and future projections

Data show a steep increase in energy prices from 2020 to 2023 due to international conflicts and a lack of UK gas security (17, 24, 25). The UK Government responded to the crisis by setting caps and providing grants to protect customers (18, 26). Future price projections are precarious as UK and global economy and energy factors are unpredictable. UK Government plans to increase energy security and decrease dependence on imported LPG fossil fuels whilst decreasing inflation may result in a stabilisation in energy prices (27). The Cornwall report on the 2030 power market projections highlights short-term European resilience due to plentiful gas storage and an increasing integration of renewables (28). Beyond 2030, forecast is risky as indications are that natural gas prices will start to rise affecting energy prices (29). Domestic gas will be phased out, but the timeline is not clear moving from 2025 target towards 2040 (30). Wind energy is likely to get cheaper as decarbonisation demands funds to further develop green technologies. Thus, further price reduction beyond 2030 is not a foreseeable scenario (31).

Exporting energy back to the grid can financially benefit the resident (32). To support the export market and optimise the use of renewable energy generation and storage, the Smart Export Guarantee scheme was designed by the UK Government through Ofgem to develop a competitive export market (32). The scheme was introduced in 2020 with energy suppliers providing bundled and unbundled tariffs with increasing an annual average tariff from 4.34 pence/kWh in 2020 to 9.90 pence/kWh in 2024 with the tariff forecasted to stabilise (33).

Figure 1 illustrates UK energy prices from 2019 to 2024 (17) with projections from 2024 to 2050 considering the analysis above. The electricity (black) and gas (blue) prices projections are based on two scenarios, baseline scenario (dashed line) and a variable decreasing scenario (dotted line). In the baseline scenario, energy prices remain the same whereas for the variable decreasing scenario, prices fall at 4.1% from 2024 to 2030 and then remain the same reflecting market projections (28, 31). Electricity export price indication is based on combined historic average bundled and unbundled tariffs from across the SEG scheme (33). Future projections for export are unclear but the market seem to reach a plateau (33) thus the baseline scenario was preferred.

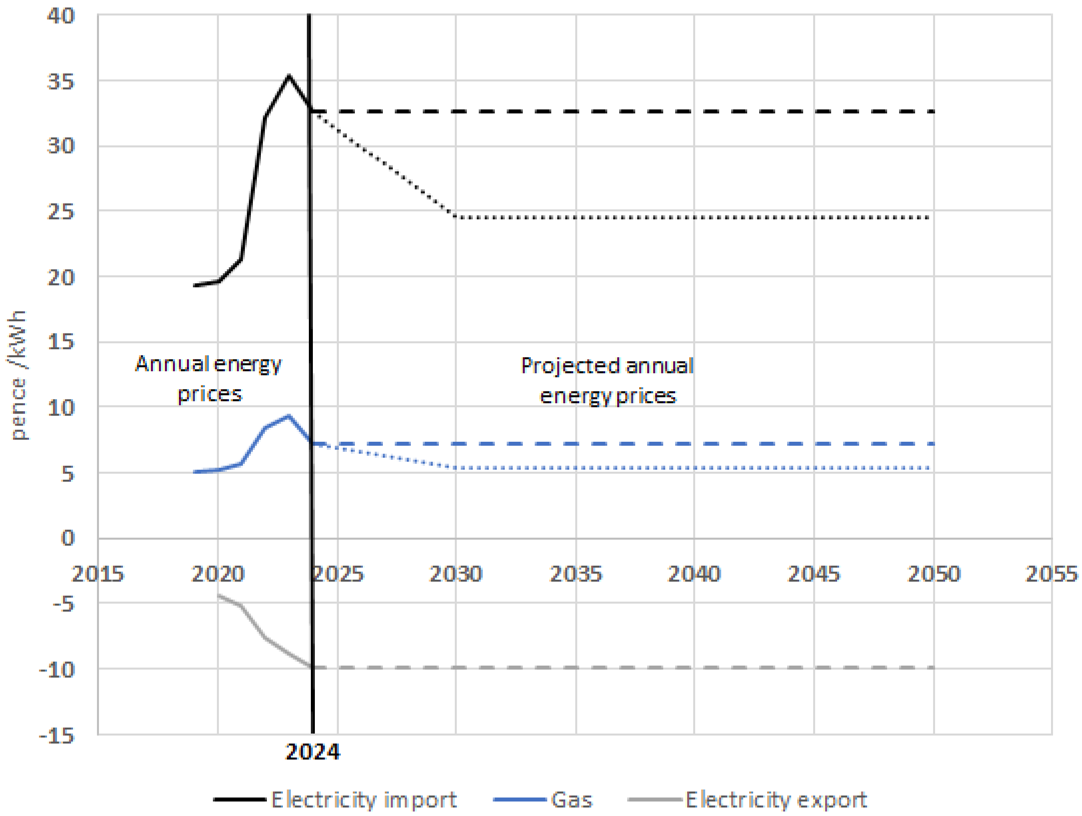

Figure 1 Projection of gas and electricity prices under different scenarios to 2050; authors based on literature (17, 28, 31, 33).

3.2 Grid carbon intensity; historic data and future projection

The UK Government has committed to reducing carbon emissions by 68% by 2030 with Net-Zero targeted by 2050 (34). The Climate Change Committee (CCC) developed a Sixth Carbon budget to guide the UK in pursuing this zero-carbon goal (34). In 2022, the UK achieved its Third Carbon budget and CCC indicated the energy supply sector contributed more than half of emissions reductions (35).

In Spring 2021, renewable energy sources alongside nuclear power and low-carbon power contributed 59% of the electricity generation (36) and the last coal powered energy plant closed in October 2024 (37). The UK electricity generation mix in October 2024 consisted of gas (21.3%), imported electricity (20.8%), wind (19.7%), nuclear (14.5%), solar (11.7%), biomass (10.6%), and hydropower (1.4%) (23). The UK Government set an ambition of clean power by 2030 (38) and NESO stated that they are confident of operating the UK electricity sector at zero carbon in the near future (36).

The Grid Carbon Intensity defines the kilograms of carbon dioxide (CO_2) equivalent emitted per kilowatt-hour of electricity generated (39). The national grid carbon intensity in 2024 ranged from 74-242 gCO_2/kWh daily average depending on the availability of renewable energy sources (23). Renewable energy contributions vary across regions of the UK, leading to significant differences in regional grid carbon intensity. NESO categorises grid carbon intensity into 5 indices: very low, low, moderate, high, and very high (23). South Wales, the geographical location of the case study homes, had the highest annual average Grid Carbon Intensity in the UK with 249.5 gCO_2/kWh in 2024, as 89.2% of electricity was generated from gas (23).

NESO has developed four future energy scenarios that project future electricity generation structures and corresponding grid carbon emissions, including holistic transition scenario (HT), electric engagement scenario (EE), hydrogen evolution scenario (HE) and counterfactual scenario (miss Net-Zero by 2050) (40). The future Grid Carbon Intensity is 41 gCO_2/kWh for HT, 73 gCO2/kWh for EE, 74 gCO_2/kWh for HE and 134 gCO_2/kWh for the counterfactual scenario by 2030 (40).These Grid Carbon Intensity projections are for the whole of the UK.

By combining the projection for South Wales, three future regional grid carbon intensity scenarios can be generated including Net-Zero carbon, moderate, and high based on these indices, NESO's 2025 zero carbon target and clean power 2030 (23, 34, 36) as shown in Table 1. The historical hourly grid carbon intensity from Sep 2019 to Nov 2024 was obtained from the NESO website (41). Linear interpolation was employed to calculate annual Grid Carbon intensity based on the future grid carbon intensity scenarios to indicate the decline of Grid Carbon Intensity as an annual linear trend (42), as shown in Figure 2.

Table 1 The future Grid Carbon Intensity scenario for South Wales by 2030; authors based on literature (23, 34, 36).

Future Grid Carbon intensity scenario	2030 Grid Carbon intensity (gCO_2/kWh)	Description
Net Zero carbon	16	Rapid zero carbon transition: achieve the Net-zero carbon grid to the same level as the areas in the UK where the grid carbon intensity is already very low
Moderate	106	Moderate zero carbon transition: achieving moderate grid carbon intensity indices by 2030
High	203	In alignment with the counterfactual scenario. Slow Net-Zero carbon transition for South Wales achieving the same level as the 2024 England grid carbon intensity by 2030

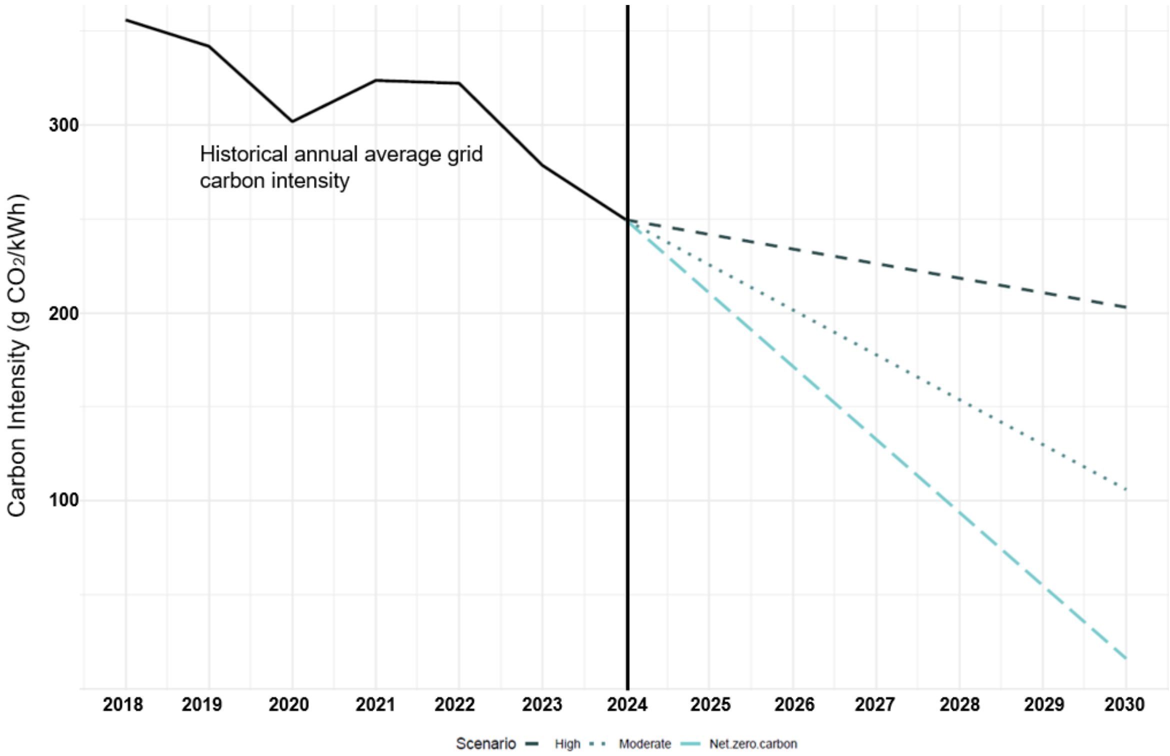

Figure 2 projection of annual grid carbon intensity under different scenarios for South Wales by 2030; authors based on literature 2030 (23, 34, 36, 41).

4.0 Methodology

This study examines the cost and carbon payback of a case study deep retrofit project designed and delivered by the Centre for a Low Carbon Built Environment (CLCBE) team and Swansea Council. The methodology used is shown in Figure 3. The six retrofitted homes were monitored and modelled before and after the retrofit and average annual values were calculated to represent the homes' energy performance. Operational energy was used as an indicator calculate annual operational cost and carbon by using annual conversion factors discussed in section 3.0 (Figure 1 & Figure 2). Average retrofit capital cost and embodied carbon of the solutions were also calculated. Cost payback was calculated in years by balancing capital cost and annual operational energy cost savings. Carbon payback was calculated in years by balancing embodied carbon and operational carbon savings.

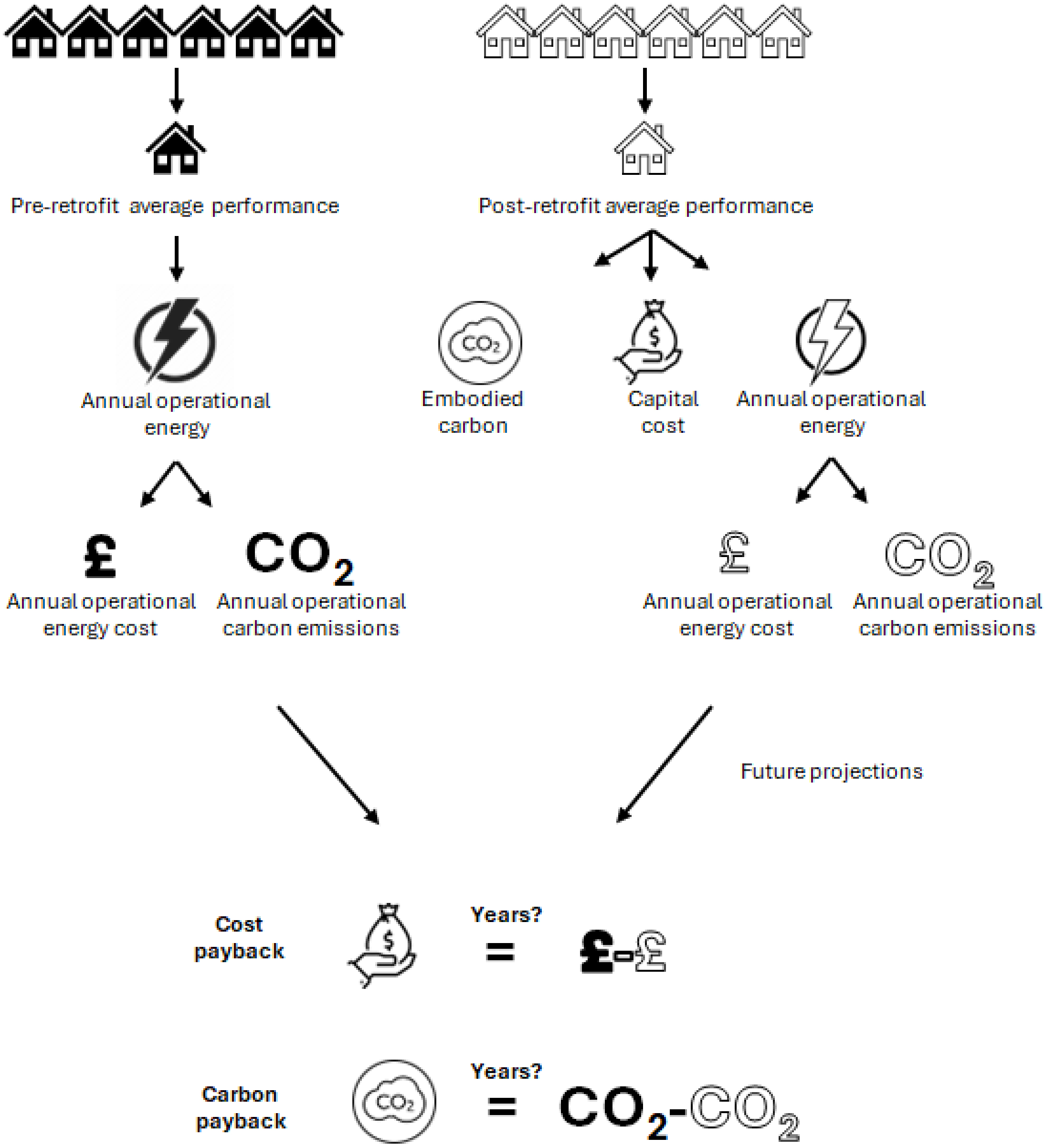

Figure 3 Diagram of methodology used to calculate cost and carbon payback.

4.1 Case Study Introduction

The case study involved a deep retrofit following a whole building energy systems approach to reduce energy demand, integrate renewable energy supply and enable energy storage at an individual home level. The L-shaped, terraced homes are situated in a semi-rural area of Swansea County in South Wales. They each have a floor area of 64m², with two bedrooms, a living room, a kitchen and a bathroom, along with front and rear gardens Figure 4. The roofs have four aspects, including southwest and southeast directions.

Pre-retrofit, residents experienced high utility bills and reported comfort issues including damp, draughts and cold temperatures. Cavity wall and roof insulation was removed and PVC panels under the windows was replaced by block walls with external wall insulation. High performance external wall and roof insulation

(0.25W/m2K and 0.13 W/m2K respectively) was installed. Windows were replaced with low-emissivity double glazing at 1.5 W/m2K. Fabric was sealed, and air permeability was reduced from 9.8 to 5.5 m3/h/m2 @ 50Pa. A Mechanical Ventilation Heat Recovery (MVHR) system was installed. A 3kW Ground Source Heat Pump (GSHP), low-temperature TRVs radiators together with a 150l hot water tank were installed to replace old fossil fuel off-grid boilers. Two integrated photovoltaic (PV) arrays were installed in the southwest and southeast roofs with a total of 5.8kWp accompanied by a 13.5kWh AC-coupled battery (43). All six homes were therefore all electric post retrofit.

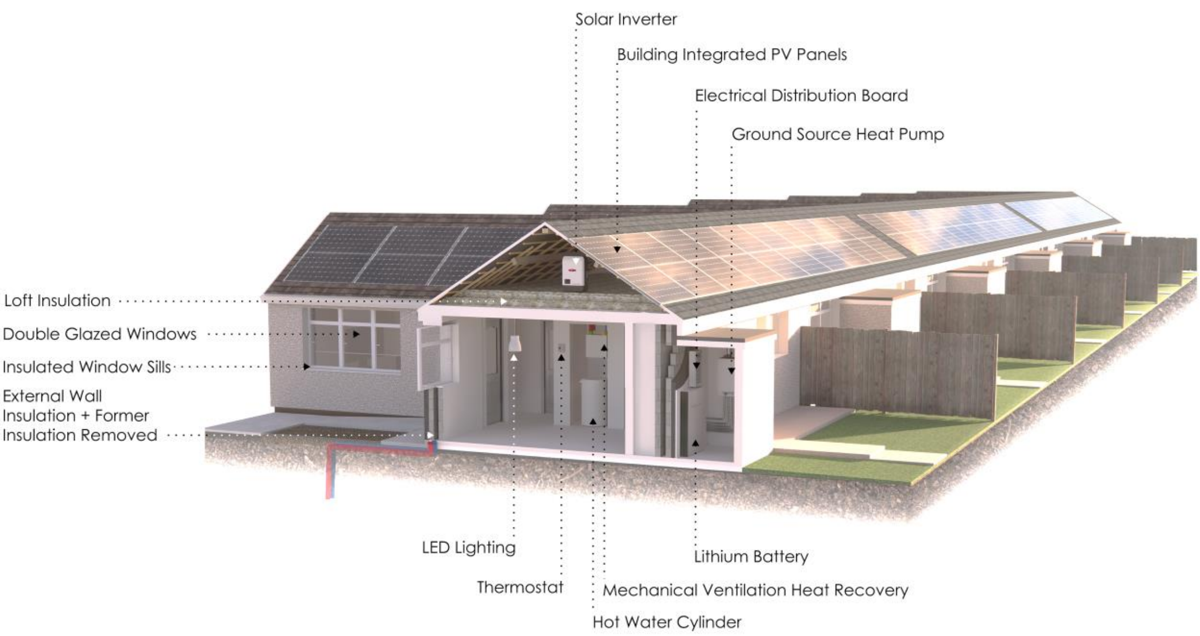

Figure 4. Six South Wales deep retrofitted homes illustrating low carbon solutions authors based on CLCBE outputs (43).

4.2 Measured Operational Energy and Calculated Embodied Carbon

Operational energy use before and after the retrofit was modelled by using HTB2 (44) and DesignBuilder (45) and monitored on-site using appropriate equipment. Modelling and monitoring information are included in the performance evaluation publication of the case study (43).

Pre-retrofit monitoring included current clamps and voltmeters to measure electricity consumption whereas heating fuel was quantified using historic bills. During the retrofit, remote monitoring equipment to measure weather, comfort and energy were installed. Post-retrofit, energy consumption and energy used directly from the PV were calculated by using Equation 1, Equation 2 and Equation 3. Monitoring process and data analysis to remove the performance gap associated with residents variation is explained in (43).

$$E_{Imported} + E_{Generated} = E_{Exported} + E_{Consumed} + E_{BatteryLosses}$$

Equation 1

$$E_{BatteryLosses} = E_{Charged} - E_{Discharged}$$

Equation 2

$$E_{Generated} = E_{PVDirect} + E_{Charged} + E_{Exported}$$

Equation 3

$E_{Imported}$ is the electricity imported from the grid in kWh,
$E_{Generated}$ is the electricity generated from the photovoltaic panels in kWh
$E_{Exported}$ is the excess generated energy exported to the grid in kWh
$E_{Consumed}$ is the energy consumed in the house in kWh
$E_{BatteryLosses}$ is the energy lost by the battery system equals to the energy used to charge the battery ($E_{Charged}$) minus the energy discharged from the battery and used in the house ($E_{Discharged}$), all in kWh.
$E_{PVDirect}$ is the generated energy that was directly used in the house in kWh.

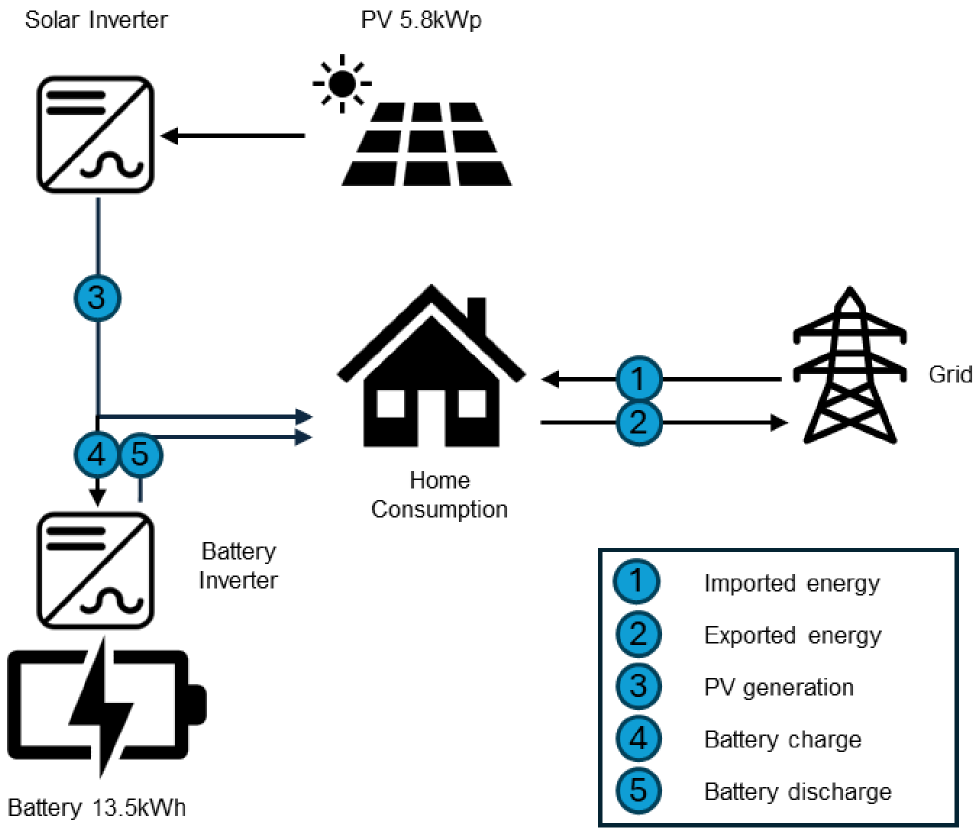

Figure 5 Long-term energy monitoring for the 6 homes.

The annual operational energy pre-retrofit includes the aggregation of the electricity imported, and the fossil fuel use for heating and hot water. The annual operational energy post-retrofit included electricity imported only. Electricity generated, stored and used onsite does not contribute to operational carbon emissions.

Two assessments of embodied carbon were carried out. The first used the FCBS CARBON tool, a commercial tool developed by FCBStudios Ltd (46). A second assessment used a process-based approach covering stages A1–A5, from cradle to site. Calculations relied on carbon factors sourced from the Carbon Inventory, ICE Energy Database (47), and other literature (43) due to the absence of Environmental Product Declaration (EPD) documents.

4.3 Cost payback calculation

Cost payback time ($C_{ost}PT$) refers to the duration of time required to offset the capital cost of the building retrofit solutions through the savings achieved through operational energy cost over time. For constant annual energy price, $C_{ost}PT$ could be calculated from Equation 4.

$$C_{ost}PT = I_{capital\_cost}/EC_{saving,annual}$$

Equation 4

$C_{ost}PT$ is the payback time in years,
$I_{capital\_cost}$ is the capital cost of the low carbon solutions for the retrofit in £,
$EC_{saving,annual}$ is the annual operational energy cost savings (£).

Capital cost is calculated by aggregating costs for each retrofit solution per home. As the case study included 6 homes, economies of scale resulted in a lower cost per property as costs such as mobilisation of the drilling rig for the installation of the GSHP and scaffold were reduced. Annual operational energy cost savings include savings from export and reduced import as well as elimination of fossil fuel use. The total annual cost savings in a chosen year (t) was calculated using Equation 5.

$$EC_{saving,t} = E_{export,t} * EC_{exportgrid,t} + E_{import,t} * EC_{importgrid,t} + E_{Fossil,t} * EC_{Fossil,t}$$

Equation 5

$E_{export,t}$ is the exported energy in kWh,
$EC_{exportgrid,t}$ is the financial benefit from export in £/kWh,
$E_{import,t}$ is the imported energy reduction in kWh,
$EC_{importgrid,t}$ is the financial benefit from reduced import in £/kWh,
$E_{Fossil,t}$ is the fossil fuel avoidance in kWh,
$EC_{Fossil,t}$ is the financial benefit of the avoided fossil fuel in £/kWh and
t in the year of value collected.

Annual energy figures (kWh) and costs (£/kWh) are required to calculate the total annual cost savings. Annual energy figures, including avoided fossil fuel use, export and import reduction, are known from monitoring and modelling process explained in section 4.2. Energy prices and projections are presented in section 3.1 and illustrated in Figure 1. $C_{ost}PT$ can be calculated by subtracting the total annual operational cost saving for each calendar year from the capital cost until the total annual savings equal the capital cost. $C_{ost}PT$ can be represented graphically; however, if the reduction is linear, a cumulative equation including an annual ratio of cost savings can be used.

4.4 Carbon payback calculation

The carbon payback time ($C_{arbon}PT$) refers to the time required for offsetting the total embodied carbon from the retrofit solutions through carbon savings (48-50). $C_{arbon}PT$ can be calculated using Equation 6.

$$C_{arbon}PT = C_{embodied}/C_{saving,annual}$$

Equation 6

$C_{arbon}PT$ is the carbon payback time in years,
$C_{embodied}$ is the total building embodied carbon emissions in kg CO_2,
$C_{saving,annual}$ is the total annual operational carbon saving in kg CO_2.

The annual carbon savings from the retrofit of each home includes 1) avoidance of carbon emissions from the switch from using fossil fuels 2) reducing operational carbon by reducing energy demand and the implementation renewable energy supply and storage 3) carbon offset by exporting excess renewable electricity to the grid (48-50).

The emission reduction from on-site fossil fuel consumption includes emissions from combustion onsite but excludes upstream emissions such as fuel transportation. Electricity may be exported to the grid increasing total annual carbon savings (51). This paper only considers the carbon offset that happens when onsite annual renewable energy generation is greater than annual energy use of the building, i.e. direct emissions from the grid are being displaced by net annual exported electricity, a method used in other guidance (51). Losses are incurred during export distribution and this should considered (51), energy losses of 7.5% are used for these calculation as indicated by UK power networks (52).

The total annual carbon savings in a chosen year (t) was calculated by Equation 7.

$$C_{saving,t} = E_{export,t} * (1 - e_{loss}) * CI_{grid,t} + E_{import,t} * CI_{grid,t} + AE_{Fossil,t} * CI_{Fossil}$$

Equation 7

$E_{export,t}$ is the exported energy in kWh,
e_{loss} is the rate of energy losses during the distribution in %,
$E_{import,t}$ is the imported energy reduction in kWh,
$CI_{grid,t}$ stands for the grid carbon intensity in kg CO_2 / kWh
$E_{Fossil,t}$ is the fossil fuel avoidance in kWh,

CI_{Fossil} is the carbon intensity of fossil fuels in kg CO_2 / kWh and
t in the year of value collected.

Using Grid Carbon Intensity per year as described in 3.2, total annual carbon saving can be calculated by Equation 7. CarbonPT can be calculated by subtracting the total annual carbon saving for each year from the total embodied carbon until the total carbon savings equal the embodied carbon.

Carbon savings calculated due to a reduction of electricity consumption and through exporting excess renewable electricity depend on the grid's carbon intensity ($CI_{grid,t}$). With the energy transition taking place in the UK, the Grid Carbon Intensity declines linearly on an annual basis, as presented in section 3.2. As there is uncertainty around the annual Grid Carbon Intensity in the future, 2030 targeted Grid Carbon Intensity were used and linearly interpolated to 2024 values, as shown in Figure 2.

The CarbonPT is the period (T) when cumulative carbon savings ($C_{saving}\ (T)$) equals the total building embodied carbon ($C_{embodied}$). A cumulative equation can be used to calculate the period (T). The cumulative carbon savings in a period (T) is calculated using Equation 8 based on the predicted ratio of annual carbon savings reduction. The full formula derivation is shown in the Appendix.

$$C_{saving}\ (T) = \sum_{k=1}^{t} C_{saving\ ,0} * (1-\alpha)^k$$

Equation 8

$C_{saving}\ (T)$ refers to the amount of carbon savings in t years in Kg CO_2,
$C_{saving\ ,0}$ is the amount of carbon savings in starting years in Kg CO_2,
α stands for the ratio of annual reduction in carbon savings.

The ratio of annual reduction in carbon savings (α) is calculated by the initial carbon savings and the carbon savings in the t year, as shown in Equation 9.

$$\alpha = 1 - e^{\frac{\ln(\frac{C_{saving,t}}{C_{saving,0}})}{t}}$$

Equation 9

$C_{saving,t}$ is the amount of carbon savings in t years in Kg CO_2,
T is the period starting from the initial year can be found when cumulative carbon savings, $C_{saving}(T)$, equal to total building embodied carbon emissions ($C_{embodied}$), as shown in Equation 10.

$$T = \frac{\ln(1 - \frac{C_{embodied} * \alpha}{C_{saving,0}})}{\ln(1-\alpha)} - 1$$

Equation 10

5.0 Results and Discussion – Case study

5.1 Energy performance, Carbon and Cost of the retrofit

The deep retrofit cost per home was £65,000 (UK pounds) including the energy demand reduction, renewable energy supply, energy storage and all incidental costs as illustrated in Figure 4. This excludes Cardiff University research and development time as well as Swansea Council and Cardiff University planning, design, procurement and management of installation.

Figure 6 show the pre-and post-retrofit annual energy consumption for the average home. Annual energy reduction is 12,556kWh because of fossil fuel reductions and a further 1,409kWh reduction due to electricity import savings. The average measured electricity export was 1,963kWh.

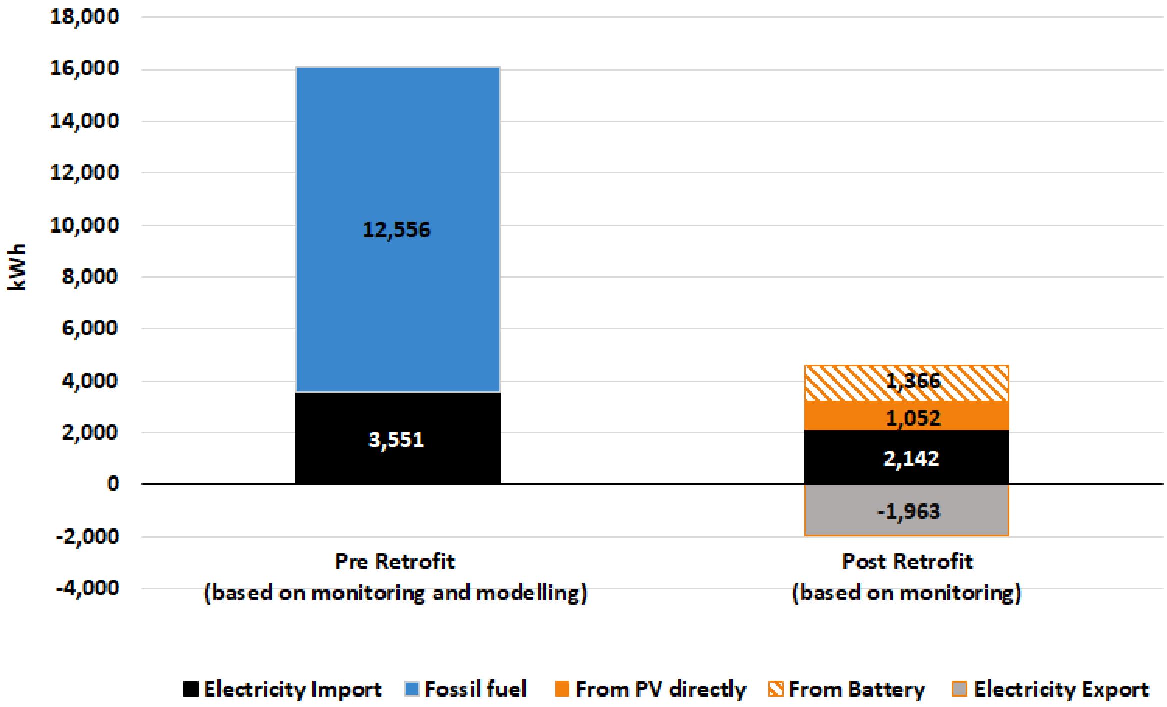

Figure 6 Case study average home - pre- and post-retrofit annual energy consumption and export; authors based on (43).

Figure 7 shows the embodied carbon per home across the case study. The total estimated embodied carbon using the process-based approach for stages A1 to A5 (explained in section 4.1) was calculated at 22,980 KgCO2e +-20%. The contribution of the integrated PV panels to the total embodied carbon was 64%. This contribution was calculated based on 2019 assumptions during the case study procurement phase. More recent research has shown that PV panel embodied carbon has and will be drastically reduced (53).

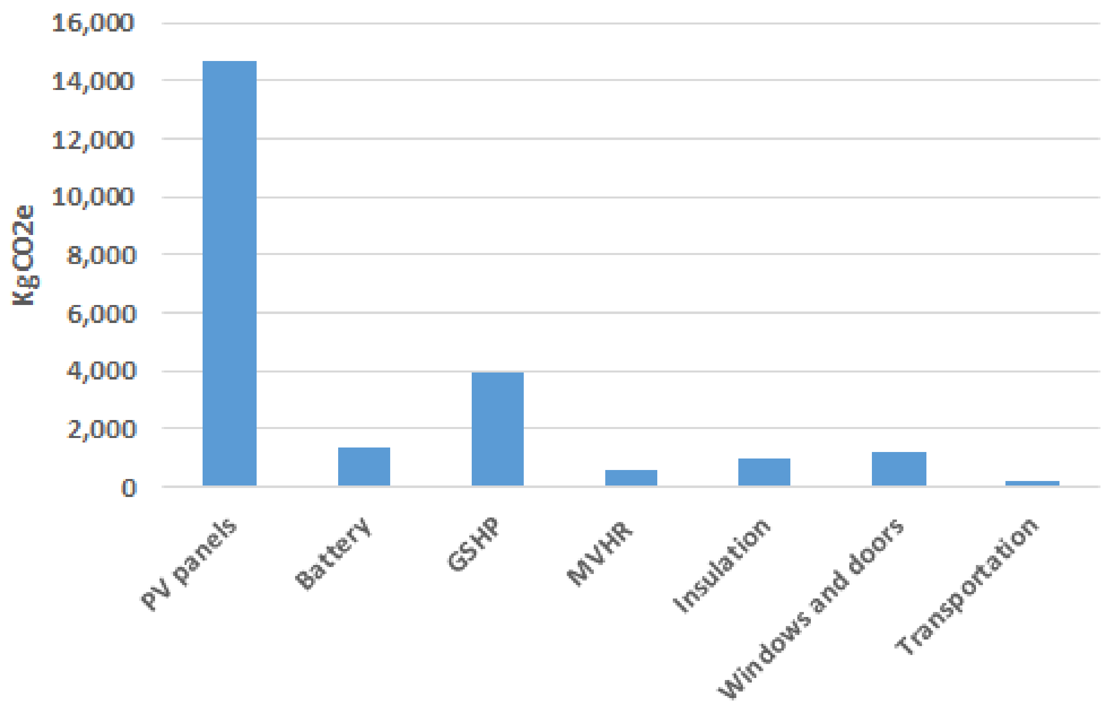

Figure 7 Embodied carbon of low carbon solutions applied in case study homes based on 2019-2020 calculations; authors based on (43).

5.2 Cost payback

Figure 8 shows the average annual energy cost savings for the retrofit homes. The first 4 years (2021-2024) are based on actual monitored data whereas from 2025 onwards the projections follow 2 scenarios 1) baseline standard scenario (S) 2) variable decreasing scenario (D) discussed in section 2.3 and Figure 1. Cost savings are due to electricity import, fossil fuel avoidance and electricity export; calculated using Equation 7 and Figure 1.

For the first post-retrofit years from 2021 to 2025, the savings are measured and follow the energy crisis price increase. From 2025 on (projected), for the 1) baseline scenario - £1,564 annual savings are constant whereas the 2) decreasing scenario - linear savings are predicted until 2030 (Figure 1) when savings stabilise at £1,224.

The values from Figure 8 were then removed from the capital cost of the solutions - £65000 UK pounds that was accumulated on completion in 2020. Figure 9 shows the annual reduction for the two scenarios, S and D. The payback happens at 41.5 years for the Standard scenario and in 51.5 years for the variable Decreasing scenario.

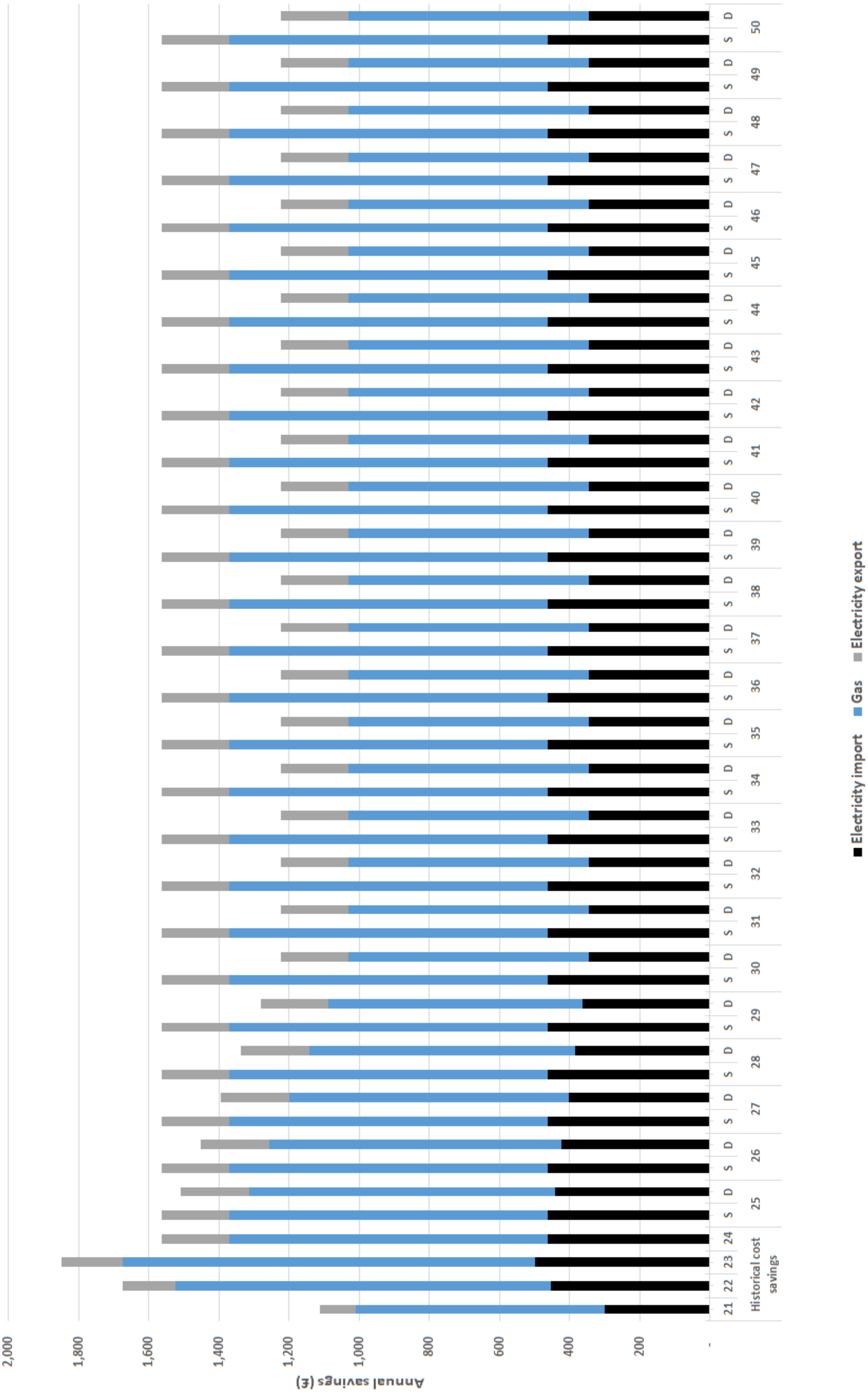

Figure 8 Average annual energy cost savings from fossil fuel avoidance, electricity import reduction and export sale

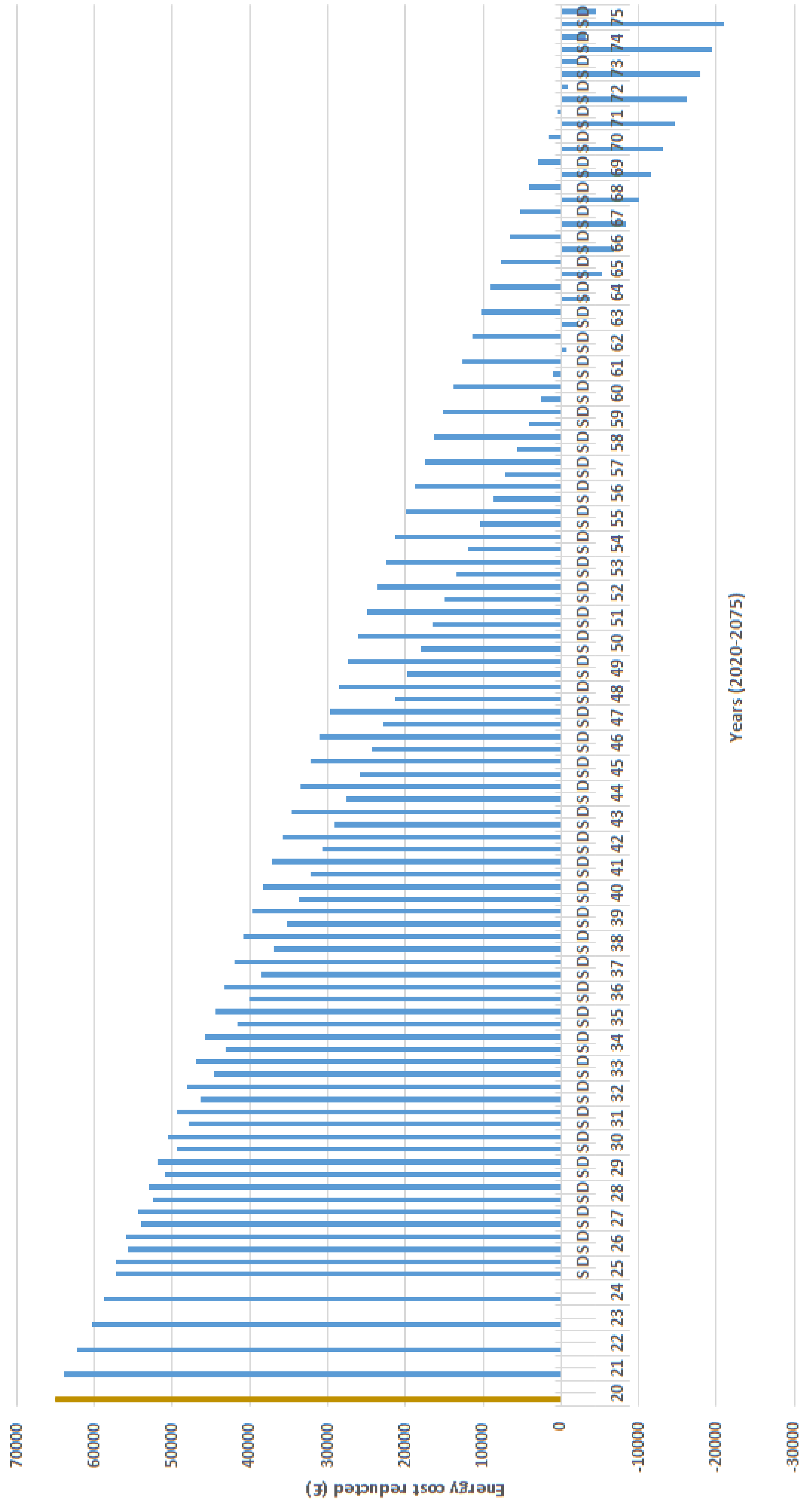

Figure 9 Cumulative cost saving and payback period per retrofit.

The calculations include several limitations in addition to the reliability of the energy price projections. Within 40-50 years' time, the retrofit solutions such as integrated PV panels and MVHR will need replacing which would increase the capital cost. Capital cost was compared against energy savings only; however, an investment in low-carbon solutions such as high-performing windows and doors and improved thermal performance through insulation can improve house value. The additional value could be deducted from the capital cost at the time of completion. As the above parameters are contradictory and difficult to estimate they were not considered in the application of the payback calculation.

Retrofitting homes can benefit residents' health and well-being. In this case study average indoor temperature significantly increased whereas relative humidity and CO2 decreased. Comfort benefits increase the asset value and indirectly decrease national healthcare load and costs.

5.3 Carbon payback

The historical carbon savings and projected potential future carbon savings under three future grid scenarios (high, moderate and Net-Zero carbon) were calculated. Carbon savings included avoiding on-site fossil fuel consumption, electricity import reduction and excess renewable electricity export. Figure 10 illustrates the total annual carbon saving across three grid carbon intensity scenarios explained in section 3.2 and visualised in Figure 2.

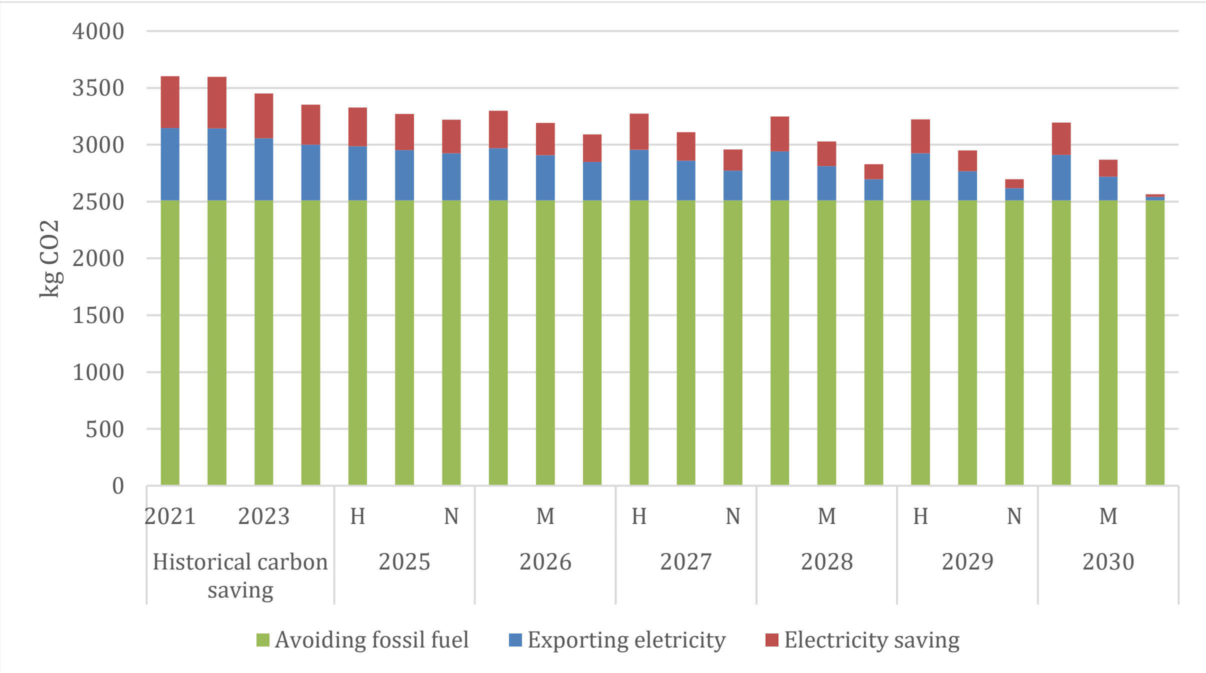

Figure 10 Annual total Carbon Saving by sources under three scenarios (H: high, M: Moderate and N: Net-Zero carbon);

Figure 11 shows the embodied carbon (2020) and the cumulative carbon saving by housing retrofit by years and the carbon payback period. The carbon payback time for the three scenarios (high, moderate and Net-Zero) is 6.5, 6.8 and 7 years respectively.

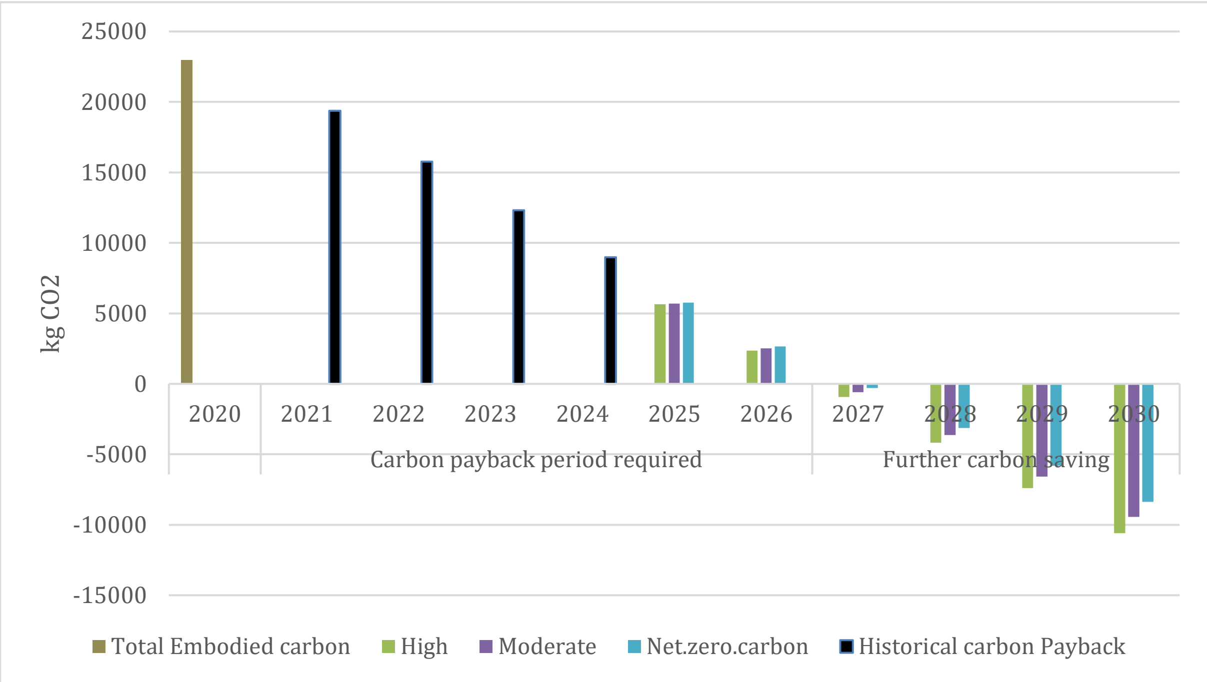

Figure 11 Cumulative carbon saving and carbon payback period per retrofit.

When compared to the standard energy cost prediction, carbon payback takes place between 5.9 to 6.4 times faster than cost payback whereas for the decreasing energy cost scenario, carbon payback is between 7.4 to 7.9 times quicker than cost payback.

When compared to other case studies (6), the carbon payback is within the range calculated in the Bienert et al. report; however, the report analysed multi residential and commercial buildings where embodied carbon could be lower due to scale. Bienert et al. calculated the average embodied carbon of the retrofits at 80 $KgCO_2e/m^2$ whereas this case study solutions accumulated to 359 $KgCO_2e/m^2$ +/−20%. This can be explained due to the retrofit depth of this case study but also due to the solar panel embodied carbon variability. In this case study, PV panels were manufactured in 2019 and imported from overseas with a calculated embodied carbon at 533 $KgCO_2e/m^2$ of solar panel accumulating for 64% of the total carbon emissions of the retrofit, whereas in Bienert et al. case studies PVs contributed from 104 to 297 $KgCO_2e/m^2$. The use of local and low-carbon PVs could reduce the carbon payback for this study to 4 years. Another significant difference is that in this study the average annual carbon savings are 51 $KgCO_2e/m^2$ whereas in Bienert et al. deep retrofit case studies achieved annual savings at 25 $KgCO_2e/m^2$. This indicates the benefit of a whole-house energy system retrofit approach where demand reduction, renewable energy generation and electric storage maximises carbon savings.

6.0 Conclusions

This paper introduces a method for calculating cost and carbon payback of deep housing retrofits by using energy cost and carbon intensity projections scenarios. It considers the initial capital cost, embodied carbon of the retrofit solutions and the annual energy savings from retrofits. The energy savings are converted into carbon and cost savings using historic and predicted conversion factors. The study calculates three carbon intensity scenarios based on the UK's 2030 clean power target and two energy cost projections using UK and international trends. The methodology has been applied to six social homes that underwent a deep low-carbon retrofit, using pre- and post-retrofit data.

Future trends in energy costs indicate price stability whereas the grid carbon intensity will improve based on existing targets and projections. Electricity grid carbon intensity is projected to reduce significantly whereas carbon intensity of gas and other fossil fuels cannot be reduced, and alternative carbon capture techniques should be considered.

The carbon and cost payback calculations can be applied by using cumulative equations for linear cost and carbon emissions projections. When applying the methodology to the deep retrofit case study, avoiding the use of fossil fuels such as gas is the most significant saving for both cost and carbon. Electricity import reduction is significant even with the addition of a GSHP when on-site renewable generation and storage are implemented. Energy export contributes to both cost savings and carbon reduction.

This paper demonstrates that cost payback ranges from 41.5 to 51.5 years depending on the fuel energy price scenario whereas carbon payback varies from 6.5 to 7 years depending on the carbon emission scenario. Carbon payback is highly dependent on the embodied carbon of photovoltaic (PV) panels. Implementing less carbon-intensive manufacturing processes and sourcing PV panels locally could significantly reduce the carbon payback period.

When the payback period exceeds the warranty duration of low-carbon solutions, the capital costs associated with the embodied carbon of replacements should be taken into account. Additionally, the increase in property value should be factored into cost payback calculations to provide a more comprehensive assessment of financial feasibility.

Given the UK carbon emissions targets, retrofit stakeholders should include carbon payback in the decision-making process. The findings of this analysis suggest that carbon payback periods align with the Net-Zero targets set for 2030 and 2050. This alignment has the potential to encourage the adoption of low-carbon solutions, particularly those that combine low embodied carbon with significant operational carbon savings. However, it is essential to ensure that other co-benefits, such as improvements in health, wellbeing, and the alleviation of fuel poverty, are not compromised. A holistic approach is necessary to guarantee that only interventions suitable for the specific housing type and condition are implemented in practice.

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Appendix

Formula derivation of Carbon payback time

If the annual carbon saving decreased year by years in a certain percentage, the carbon saving in 't' year could be calculated by Equation 11.

$$1 - \alpha$$

Equation 11

Where α is the ratio of annual reduction of carbon saving within the choose timeframe.

Assuming carbon saving of starting year is $C_{saving,0}$, the carbon saving in the 't' year could be calculated by Equation 12 and the formula derivation processes are from Equation 13 to Equation 16

$$C_{saving,t} = C_{saving,0} * (1 - \alpha)^t$$

Equation 12

If, the '0' year carbon saving is:

$$C_{saving}(0) = C_{saving,0}$$

Equation 13

The '1' year carbon saving is the '0' year carbon saving multiplied the decrease ratio, which is:

$$C_{saving}(1) = C_{saving,0} * (1 - \alpha)$$

Equation 14

The '2' year carbon saving is the '1' year carbon saving multiplied the decrease ratio, i.e.

$$C_{saving}(2) = C_{saving,0} * (1 - \alpha) * (1 - \alpha) = C_{saving,0} * (1 - \alpha)^2$$

Equation 15

The 't' year carbon saving is the 't-1' year carbon saving multiplied the decrease ratio, which can be presented by Equation 16.

$$C_{saving}(T) = C_{saving,0} * (1 - \alpha)^t$$

Equation 16

Then, the cumulative carbon savings ($C_{saving}\ (T)$) can be calculated by Equation 17, Equation 18, or Equation 19.

$$C_{saving}\ (T) = C_{saving,0} + C_{saving,1} + C_{saving,2} + \cdots C_{saving\ ,t}$$

Equation 17

Which equals to

$$C_{saving}\ (T) = C_{saving\ ,0} * 1 + C_{saving\ ,0} * (1 - \alpha) + C_{saving,0} * (1 - \alpha)^2 + \cdots C_{saving,0} * (1 - \alpha)^t$$

Equation 18

And,

$$C_{saving}(T) = \sum_{k=1}^{t} C_{saving,0} * (1-\alpha)^k$$

Equation 19

Where: $C_{saving}(T)$ refers to the amount of carbon savings in t years ($kg\ CO_2$), $C_{saving,0}$ is the amount of carbon savings in starting years ($kg\ CO_2$), α stands for the ratio of annual reduction in carbon savings.

The equations (Equation 17, Equation 18, or Equation 19) for calculating cumulative carbon savings can be solved by Geometric sequence sum formula (Equation 20).

$$S_n = \frac{a_1 * (1-q^n)}{1-q}$$

Equation 20

Where: S_n is the sum of the first n terms of a geometric sequence, a_1 is the first term of a geometric sequence, q is the common ratio of geometric sequence, n is the number of terms.

The Equation 19 can be refromed as Equation 21.

$$C_{saving}(T) = C_{saving,0} * \sum_{k=1}^{t} (1-\alpha)^k$$

Equation 21

Hence,we know when 'k=0', the $(1-\alpha)^0$ is 1, then we have Equation 22 based on Equation 20.

$$\sum_{k=0}^{t} (1-\alpha)^k = \frac{1 * (1-(1-\alpha)^{t+1})}{1-(1-\alpha)}$$

Equation 22

Therefore, we combined Equation 21 and Equation 22 to have Equation 23 to calculate cumulative carbon savings in (T) years

$$C_{saving}(T) = C_{saving,0} * \frac{1-(1-\alpha)^{t+1}}{\alpha}$$

Equation 23

The next step is to solve the 't'. From Equation 23, we can have Equation 24, then we can get 't' by Equation 25.

$$(1-\alpha)^{t+1} = 1 - \frac{C_{saving}(T) * \alpha}{C_{saving,0}}$$

Equation 24

$$t+1 = \frac{\ln(1 - \frac{C_{saving}(T) * \alpha}{C_{saving,0}})}{\ln(1-\alpha)}$$

Equation 25

For the α in Equation 12, we can reform it
From Equation 26

$$C_{saving,t} = C_{saving,0} * (1-\alpha)^t$$

Equation 26

To Equation 27

$$\frac{C_{saving,t}}{C_{saving,0}} =* (1-\alpha)^t$$

Equation 27

To Equation 28 by taking the logarithm of both sides

$$\ln(\frac{C_{saving,t}}{C_{saving,0}}) = t * \ln(1-\alpha)$$

Equation 28

To Equation 29 by taking the antilog

$$e^{\frac{\ln(\frac{C_{saving,t}}{C_{saving,0}})}{t}} = \ 1-\alpha$$

Equation 29

$$e^{\frac{\ln(\frac{C_{saving,t}}{C_{saving,0}})}{t}} = \ 1-\alpha$$

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