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Sustainable, Nearly Zero-Emission Refurbishment for Residential- Historical Buildings

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Abstract

To combat the harmful effects of climate change, many steps must be taken to reduce greenhouse gas emissions. Reducing carbon emissions in the construction sector for both new and existing buildings plays a major role in achieving a zero-emissions economy. Reaching zero emissions in existing buildings requires upgrading the building envelope, implementing efficient systems, and using renewable energy to meet the remaining energy needs. This research proposes a sustainable approach to converting an existing residential building into a nearly zero-emission house. In this study, various sustainable scenarios were considered to upgrade an existing house to a nearly zero-emission building. The case study is a house built in 1794, and to reach nearly zero emissions, the following steps were applied. First, sustainable strategies for rehabilitating the house were suggested. Secondly, Integrated Environmental Solutions and virtual environment software were used to calculate the case study energy and emissions baseline. Thirdly, sustainable materials to upgrade the envelope were considered, as well as the identification of alternatives to upgrade the house services. After this, software was used to calculate the effect of each material on energy and emissions reductions in comparison to the baseline. Fourthly, the payback period for each material was calculated by using the total construction costs divided by the revenue from energy savings. Fifthly, alternatives were selected with reasonable payback periods for the refurbishment process. Finally, renewables were added to cover some of the remaining energy needs. After applying the refurbishment steps, the house's energy consumption and emissions are reduced significantly. The total cost of the proposed renovation is £24,976.90, with a repayment period ranging from 1.1 to 11.5 years. Energy consumption and carbon emissions are significantly reduced by adding renewables when compared to improving the envelope and services. Compared to the baseline, the refurbishment achieves a considerable reduction in energy consumption and emissions by 65.3% % and 62.4%, respectively.

Keywords: sustainable refurbishment, historical buildings, residential buildings, zero-emissions buildings

1. Introduction

Many steps are needed to reduce greenhouse gases (GHG) and eliminate the harmful effects of climate change. The efforts towards a zero-emissions economy should start now, or the cost

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and time needed in future to make any development in this field will be high (Adedeji & Reuben & Olatoye, 2014). Buildings consume about 40% of the world's energy and produce more than a third of global carbon emissions (Medved, Domjan, & Arkar, 2019). Reducing carbon emissions and achieving zero emissions in the construction sector are major parts of the road towards a zero-emissions economy. To achieve this target, many new concepts in the building sector are becoming more commonplace, such as zero-emission and nearly zero-emission buildings. Zero-emissions buildings reduce their operational energy by upgrading the building envelope, using efficient systems, and using renewables to cover the remaining required energy. The target of achieving zero-emission buildings is achievable but challenging (Zabaneh, 2011). In a similar definition, Ahmed et al. (2022) state that net-zero-emissions buildings are buildings that have high operation energy efficiency, and this can be achieved by using a highly insulated envelope, highly efficient heating and/or cooling systems, and low operation energy to operate the building equipment as well as using passive techniques, then using renewables to cover the remaining energy needed.

The EU has accomplished a remarkable reduction in carbon emissions in recent decades. In 2018, the Union's carbon emissions had decreased by 23% compared to the 1990s emissions. The EU targets achieving 40% by 2030 and becoming a zero-emissions economy by 2050 (Herold et al., 2019). The EU has published numerous directives across sectors to achieve this target. In the building sector, the European Energy Performance of Buildings Directive (EPBD) was adopted in 2010. The EPBD introduces the term nearly zero-emissions buildings (NZEB), stating that all new builds should be NZEB by 2020 (Medved & Domjan, & Arkar, 2019). The UK sets an ambitious target to reach zero emissions by 2050. In the UK, buildings account for 26% of the country's total GHG emissions, and homes are the major contributor, accounting for 77% of the total buildings sector direct emissions. Only 15% of the UK residential building stock was built after 1990. Therefore, the majority of this stock was built to meet low energy-efficiency requirements. According to this, most UK homes need to be upgraded to improve their energy efficiency (The House of Commons, 2019).

Specific steps are required to achieve NZEB in existing buildings: upgrade the building envelope, install highly efficient equipment, and add renewable energy. Reaching NZEB in a new building is a complicated process, but it is more complex in existing buildings (Torgal, 2013). Many of the aspects applied in the new build to achieve NZEB could not be applied to existing buildings because of their existing features, such as site, orientation, and building massing. All these challenges complicate and problematize the target of achieving NZEB in existing buildings (Menassa & Ortiz-Vega, 2013). One of the main challenges in refurbishing existing buildings to achieve NZEB status is the high initial cost and long payback periods (Asadi et al., 2013). The only way to justify the high cost of the energy-efficiency refurbishment is a reasonable payback period (Menassa & Ortiz-Vega, 2013).

To reduce the overall environmental impact of the refurbishment, the three sustainability pillars (environmental, social, and economic) should be considered. Sustainable refurbishment can generate many benefits, such as reducing energy consumption/emissions, waste, and water consumption, as well as improving the indoor environment. Moreover, using sustainable materials during refurbishment is important for reducing the embodied energy of the process (Chan, 2014). Construction materials should have a low environmental impact to improve the environmental performance of the construction process. One of the tools used to measure the product's environmental performance is the Life Cycle Assessment (LCA), which measures the product's environmental impacts throughout the whole life of the product, starting from the extraction of the raw materials to the production process, and then the use of the product and ending with the product's end of life (Passer et al., 2015). The Environmental Product Declaration (EPD) system provides LCA data for different products, prepared by manufacturers and verified by a third party (BRE Global, 2020).

This research suggests a process for refurbishing an existing house. It proposes different sustainable alternatives and scenarios that will achieve nearly zero-emission criteria. These scenarios will be evaluated by calculating the best payback periods.

2. Methodology

This study proposes various sustainable scenarios for upgrading an existing house to achieve NZEB status. A single house built in 1794 was selected as a case study, and then the following steps were applied. Firstly, a sustainable approach to refurbishing the house was suggested by reducing energy consumption and emissions, using sustainable materials, and limiting the required work to reduce costs and waste while preserving the main building's architectural features. Secondly, Integrated Environmental Solutions-Virtual Environment (IESVE) software was used to calculate the energy and emissions baseline. Thirdly, sustainable materials with an EPD certificate were suggested to upgrade the envelope and provide alternatives for upgrading the house services, where the software was also used to calculate each material's effect on energy and emissions. Fourthly, the payback period for each material was calculated by dividing the total construction costs by the energy-saving costs. Fifthly, the materials that have the lowest payback period were selected. Finally, renewables were added to cover some of the remaining required energy and to measure their effectiveness in reducing emissions.

3. The Case Study

This study proposes a sustainable refurbishment method to reduce energy demand in existing domestic buildings. As part of this study, an existing house is used to evaluate the different suggested refurbishment scenarios. The case study is a single house built in 1794, sited on the Peffermill Playing Fields in Edinburgh, Scotland.

Figure 1. The case study

Table 1. Case study construction elements

House element	Materials	U value
External walls	mass masonry construction	0.94 W/m²K
Roof	timber frame	1.6 W/m²K
Floor	exposed timber floorboards	1.04 W/m²K
Windows	timber casement windows	2.5 W/m²K
Doors	timber panelled	2.6 W/m²K
Ceiling	lath and plaster	0.980 W/m²K
Space heating	gas combined boiler	-

4. Refurbishment Steps

The suggested approach to refurbishing the house is a sustainable one by considering the following:

- Reducing the house energy consumption and emissions.
- Using sustainable materials that have low environmental impacts according to their EPD certificate.
- Reducing the amount of required work to reduce the cost and waste.

- Save the main building architecture features by adding the materials to the inner side of the walls and roof.

The two main steps for the refurbishment are improving the building envelope and services and then integrating renewables.

4.1. Calculations of the Case Study Baseline

The first step is modelling the case study using IESVE to find a baseline, similar to the house performance, by entering the data of the case study, such as the construction elements' U values, lighting (fluorescent lamps used at 0.8 W), internal gain (in this case, four people), the refrigerator (150W), and the cooker (1500W). The calculated baseline for the case study is a total yearly energy consumption of 62 MWh and total carbon dioxide emissions of 25,094 kgCO2.

4.2. Upgrading the House Envelope

EPD certifications require production-stage emissions as a mandatory requirement, which consist of emissions from raw material extraction, transport to the manufacturer, and the manufacturing process. These stages are known as A1-A3. Therefore, in this study, the suggested EPD-certified materials are those with lower environmental impacts across the mandatory criteria A1-A3. The methodology here is to search the EPD website for certified products and then exclude those produced within the EU to avoid long-distance transport. Then, the findings are compared according to the environmental impacts listed in the certificate, as measured by Global Warming Potential (GWP) in kg CO2 eq.

When applying the search methodology to suggest products to upgrade the house envelope with products that have an EPD certificate and have originated within the EU, the findings are:

- 25 window types match the searching criteria, and 9 are suitable to be used for the case study. When comparing the GWP, the lowest environmental impact is Elitfönster AB - IKI-AL windows, EPD number S-P-03418, with GWP 15.8 $kgCo_2eq$.
- 18 door types match the searching criteria, and 4 are suitable to be used for the case study. When comparing the GWP, the lowest environmental impact is the wooden door from Daloc, EPD number S-P-01392, with GWP 49 $kgCo_2eq$.
- 110 insulation materials for walls and roofs match the search criteria, and 50 are suitable to be used for the case study. When comparing the GWP, the lowest environmental impact is Glass Mineral Wool Rolls from Knauf Insulation, EPD number S-P-04975, with GWP 0.722 $kgCo_2eq$.
- The suggested flooring insulation is carpet to avoid extra construction work for removing and replacing, which can add more cost and waste. Two carpet types match the search criteria, and both are suitable to be used for the case study. When comparing the GWP, the lowest environmental impact is carpet flooring Desso Ecobase from Tarkett, France, with EPD number S-P-01356 and GWP 5.03 kgCo2eq.

After this, a simulation using the IESVE program was run to measure each material's effect on the house's energy consumption and carbon emissions. Then, this impact on the baseline was compared to determine the material effect on energy consumption and emissions.

The next step is to calculate the payback period using the following steps. First, the energy revenue per year is calculated by multiplying the yearly energy saving by the natural gas UK grid cost (which is 4.25p - Department for Business, Energy & Industrial Strategy, 2022) - improving the envelope thermal performance will mainly result in reducing the energy used for space heating, and the heating system in this house uses a traditional boiler with gas as fuel. Secondly, the cost is calculated by adding these materials, including the material and construction costs. Spon's Architects' and Builders' Price Book 2022 prices are used for this. Thirdly, the total cost is calculated by multiplying the total area of each material by the element cost. Finally, the payback period is calculated by dividing the total cost by the revenue from the energy saving.

Table 2. The suggested material to upgrade the house envelope.

Product name	GWP A1-A3 $KgCo_2eq$	U value W/m2K	Energy saving – carbon emissions reduction	Energy revenue yearly	Total cost	Payback period per year
Window Elit-fönster AB IKI-AL	15.8	1.12	62.3-61.6=0.7 MWh 25093.9– 24931.5= 162.4 $kgCO_2$	700 x 4.25 =£29.75	The number of windows is 13 the window cost is 466.51 13x466.5=£6064.6	6064.6/29.75= 203.8 years
Door: Wooden door from Daloc	49	1.2	62.3-62.2=0.1 MWh 25093.9–25065.8= 28.1 kgCO2	100 x 4.25 =£4.25	The number of doors is 2 the door cost is 485.03 2x285.03=£970.06	970.06/4.25= 228.3 years
Wall insulation	0,722	0.037	62.3-57.9=4.4 MWh 25093.9 –24147.4= 946.5 $kgCO_2$	4400 x 4.25 =£187	The total external wall area is 303.9m2 303.9x7.06=£2145.5	2145.5/187= 11.5 years
Roof insulation	0,722	0.037	62.3-57.7=4.6 MWh 25093.9 –24105.3=988.6 kgCO2	4600 x 4.25 =£195.5	The total roof area is 126.3m2 126.3x6.06=£765.4	765.4/195.5= 3.9 years
Floor insulation	5.03	0.084	62.3-61.9=0.4MWh 25093.9 – 25017.6= 76.3 $kgCO_2$	400 x 4.25 =£17	The total floor area is 98.9m2 98.9x20.5=£2027.45	2027.45/17= 119.3 year

4.3. Upgrading the House Services

The suggested upgrade for the house services is to change the boiler and lights. Replace the gas boiler with a combined heat and power (CHP) boiler and replace the fluorescent lights with LED ones.

The boiler currently in use is 70% efficient, and the suggested CHP unit is 95% efficient. The IESVE software was used to calculate energy savings and carbon emissions reductions for the proposed boiler compared with the baseline. The average cost of replacing the boiler is £5000. CHP boilers produce both heat and electricity; therefore, to calculate the energy revenue per year, one can use a 1:1.6 ratio for heat and electricity produced by the CHP (Heat Network Partnership for Scotland, 2017), then multiply it by the yearly energy cost, which is 4.25p for natural gas and 20.84p for electricity (Department for Business, Energy & Industrial Strategy, 2022). Then, calculate the payback period by dividing the total cost by the revenue.

Changing the fluorescent lights to highly efficient LED lights will reduce energy consumption as the current lights consume 80W, while the LED ones use 10W. The simulation was used to calculate energy savings and carbon dioxide emissions reductions for the LED lights compared with the baseline. The energy revenue was calculated by multiplying the energy saved by the grid electricity costs (20.84p). Then, the payback period was calculated by dividing the total cost by the revenue.

Table 3. The suggested services

The services	Energy saving – carbon emissions reduction	Energy-saving yearly	Energy revenue yearly	Boiler cost	Payback period
CHP	62.3-59.6 =2.7MWh 25093.9–23939.3= 1154.6 KgCO2	2.7MWh 2700 KWh	1038.5x4.25=£44.1 1661.5x20.84=£346.3 Total £390.4	£5000	5000/390.4= 12.8 Years
LED lights	62.3-62 =0.3MWh 25093.9–24821= 272.9 KgCO2	0.3 MWh 300 kWh	300 x 20.84=£62.5	3 x 22=£66	66/62.5= 1.1 years

4.4. Integrating Renewables

The suggested renewables for the case study are solar PV and Air Source Heat Pumps (ASHP). By adding 20 solar panels to the property's roof (south-facing), the simulation shows the panels will produce 13.5 MWh and reduce emissions by 7026.6 kgCO2 each year. Solar panels produce both heating and electricity; therefore, to calculate the energy revenue per year, one can use the 1:2 ratio for the heat and electricity produced by the panels, then multiply the yearly energy reduction by the natural gas UK grid cost (4.25p) and the electricity UK grid costs (20.84p) (Department for Business, Energy & Industrial Strategy, 2022). The solar panels are eligible for the Renewable Heat Incentive (RHI) for the energy used for hot water, which pays 21.36p per kWh produced by the panels (Home heating guide, 2019). After that, calculate the payback period by dividing the total cost by the energy revenue.

The second choice for renewables is using an ASHP. The heat pumps are eligible for the RHI, which accounts for 10.71p for any kWh produced by the ASHP (Home heating guide, 2019). The software was used to calculate the ASHP's energy savings and their effects on energy consumption and carbon emissions. Then, the energy revenue was calculated by multiplying the energy saved by the gas cost (4.25p). After that, the payback period was calculated by dividing the ASHP's total cost by its energy revenue.

Table 4. Suggests renewables

The services	**Energy saving – carbon emissions reduction**	**Energy-saving yearly**	**Energy revenue yearly**	**Total cost**	**Payback period**
Solar panels	62.3-46.8 =13.5MWh 25093.9– 18067.3=7026.6 $KgCO_2$	13.5MWh 13500 KWh	9000 x 20.84=£1875.6 4500 x 4.25=£191.3 RHI4500x21.36=£961.2 Total £3028.1	£7000	7000/3028.1= 2.3 Years
ASHP	36.4- 21=15.4MWh 16191.4-10910= 5280.9 $KgCO_2$	15.4MWh 15400 KWH	15400 x 4.25=£654.5 RHI yearly 15400 x 10.71 =£1649.3 Total 2303.84	£10000	10000/2303.8 =4.3 years

Table 2 shows the payback periods for upgrading the house windows, doors, and floor are 203.8 years, 228.3 years and 119.3 years, respectively. These periods are longer than the house's expected life, which is usually 60 years; therefore, upgrading the house windows, doors and floor is excluded from the suggested refurbishment due to the long payback period. The payback periods for adding walls and roof insulation are 6.6 years and 2.6 years, respectively. These payback periods are reasonable; therefore, adding insulation to the roof and walls should be considered for the house refurbishment.

Table 3 shows the payback periods for upgrading the house boiler and lights: 12.8 years and 1.1 years, respectively. These payback periods are reasonable; therefore, upgrading the house's boiler and lights should be considered as part of the refurbishment.

Table 5. The selected materials for the house refurbishment

Selected materials	**Total cost**	**Payback period per year**	**Energy-saving per KW/h**	**Emissions saving per $KgCO_2$**
Wall insulation	2145.5	11.5	4400	946.5
Roof insulation	765.4	3.9	4600	988.6
Boiler	5000	12.8	2700	1154.6
LED lighting	66	1.1	300	272.9
Solar panels	7000	2.3	13500	7026.6
ASHP	10000	4.3	15400	5280.9
Total	24976.9		40900	15670.1

Table 4 shows the payback periods for adding solar panels and ASHP, which are 2.3 and 4.3 years, respectively. These payback periods are reasonable; therefore, adding solar panels and ASHP should be considered for the house refurbishment.

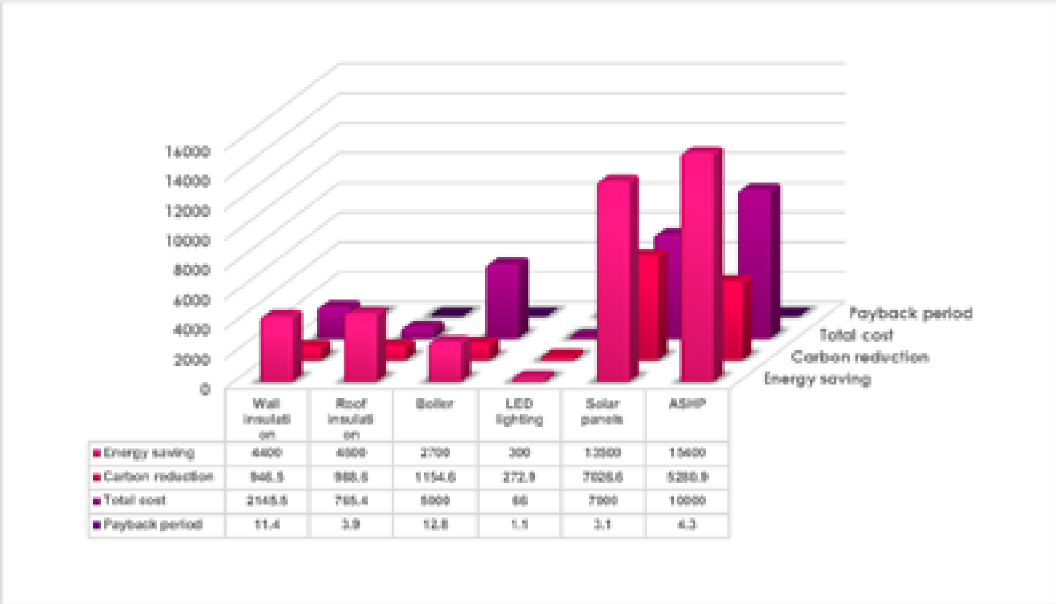

Figure 2. Comparison of refurbishment of selected materials and renewables

5. Discussion

For the suggested house envelope upgrades, the lowest payback period is for roof insulation, at 3.9 years, because most of the building's heat escapes through the roof, and the cost of roof insulation is reasonable. All these make adding roof insulation the best investment for the existing house's refurbishment. The lowest-cost investment is replacing the lights with highly efficient ones, which costs £66 in the case study. The advantage of this upgrade is that it requires no construction work or additional labour costs. Adding external wall insulation and replacing the boiler with a highly efficient one have reasonable payback periods and could be suitable investments for the house's owners.

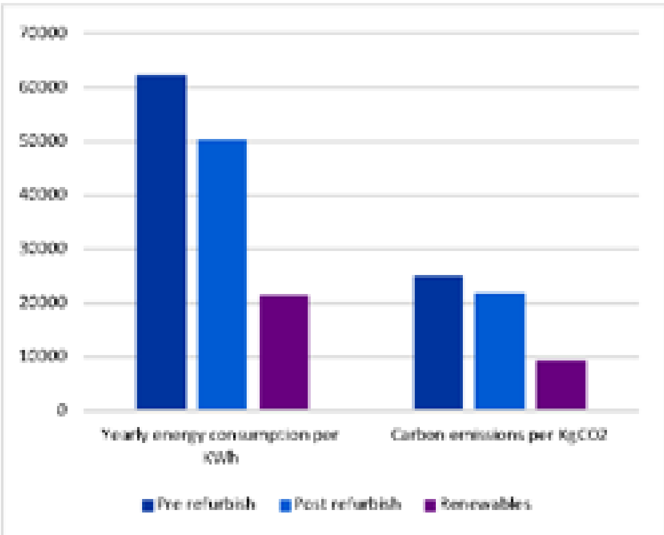

Figure 3. Comparison of energy consumption and carbon emissions pre- and post-refurbishment

When comparing the energy consumption and carbon emissions reduction of the refurbishment with the baseline, which totals a yearly energy consumption of 62.3 MWh and total carbon dioxide emissions of 25,093.9 kgCO2, the envelope and services upgrades reduce energy consumption to 50.3 MWh yearly, and emissions to 21,731.3 kgCO2. Therefore, upgrading the house envelope and services reduces energy consumption by 19.3% and carbon emissions by 13.4%. After adding renewables, the total yearly energy consumption increased to 21.4 MWh, and total carbon dioxide emissions increased to 9,423.8 kgCO2. Renewables reduce energy consumption by 46% and carbon emissions by 49% compared with the baseline. Therefore, adding renewables has a greater impact on energy consumption and carbon emissions than upgrading the envelope and services does.

6. Conclusions

This study suggests a sustainable approach to refurbishing an existing house to achieve near-zero emissions. The approach consists of suggesting EPD-certified materials to upgrade the house envelope, services and then integrating renewables.

The total cost of the case study refurbishment is £24,976.9, resulting in a reduction in energy consumption and the carbon emissions post-refurbishment to 21.4 MWh and 9423.8 kgCO2 annually, respectively. Therefore, the total saving from the refurbishment is 40.9 MWh annually in energy consumption and 15670.1 kg CO2 in carbon emissions.

In conclusion, the refurbishment achieved a 65.3% reduction in energy consumption and a 62.4% reduction in carbon emissions. This makes the house nearly zero-emission.

Conflict of Interests

No potential conflict of interest was reported by the author.

Endnotes

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