Refurbishment and Retrofit of Churches – A Case Study of Ayr St Columba Church

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Abstract

In 2019, Scotland was one of the first nations to declare a climate emergency and has since set an ambitious target to become ' Net Zero ' by 2045. The Church of Scotland has set its own net zero target of 2030, identifying this as vital to delivering a core part of its mission. Addressing building-related carbon emissions in the 1000 churches they are responsible for will be one of the most important contributors to achieving the Church's net zero strategy. However, decarbonisation of the Church estate is a particularly complex problem, with heritage buildings which have been at the heart of communities for centuries presenting unique challenges.

This paper uses the case of Ayr St Columba Church in Southwest Scotland to explore potential decarbonisation strategies. The church is an example of a sandstone-built structure constructed in the early 1900s. Its substantial building proportions using sandstone as the primary construction material result in a building of significant architectural importance. A DesignBuilder model was created and calibrated with monthly utility consumption data and in-situ temperature monitoring data to investigate three aspects of building retrofit: fabric enhancements, heating system optimisation, and photovoltaic (PV) system integration. This study found that adopting ceiling insulation was a straightforward yet highly effective solution, resulting in a 16% reduction in gas consumption. Further reductions are possible through wall insulation.

In terms of heating systems, advanced control strategies show promise, potentially yielding over 7.5% in fuel savings. Replacing boilers and utilising air-to-water heat pumps prove highly effective, with heat pumps offering long-term viability and a pathway to a zero-carbon footprint.

Furthermore, incorporating PV panels on the southern roof could contribute substantially, generating 90% of electricity, albeit with seasonality considerations. By refining energy management strategies, achieving a zero-carbon operational process becomes attainable, aligning with the Church of Scotland's commitment to 'Net Zero' and broader sustainability objectives.

Keywords: Energy retrofit, Heritage churches, Net-zero emission, Sustainability

1.0 Introduction

1.1 Background

In 2019, Scotland declared a climate emergency and committed to achieving 'Net Zero' emissions by 2045 (1), urging businesses and organisations to adopt ambitious targets, with some aiming for Net Zero by 2030. This commitment extends to the General Assembly of the Church of Scotland, which aspires to meet the target by 2030 (2). Recognising the cultural and historical significance of churches, there is a growing emphasis on addressing the environmental impact of these buildings, particularly their extensive and ageing stocks.

Historic church buildings, including Ayr St Columba Church, face challenges due to rising energy costs, which are projected to remain high until at least 2030 (3). Electricity prices have significantly increased, and the escalating frequency of extreme weather events poses a risk of damage to buildings, resulting in direct costs. Addressing the environmental impact of historic churches is crucial, and this research aims to contribute insights into effective approaches for improving energy efficiency, thereby preserving cultural heritage and achieving sustainability goals.

1.2 Ayr St Columba Church - Overview

Ayr St. Columba, situated in Ayr, Scotland, faces challenges related to its sandstone structure and outdated heating systems. Constructed in the early 1900s with a focus on tuberculosis risk minimisation, the church now grapples with the consequences of its historical design choices. The floor plan shows expansions in 1902 and 1964, introducing distinctive materials. Challenges arise from the substantial energy consumption of the church, primarily driven by an outdated heating systems and rising energy costs.

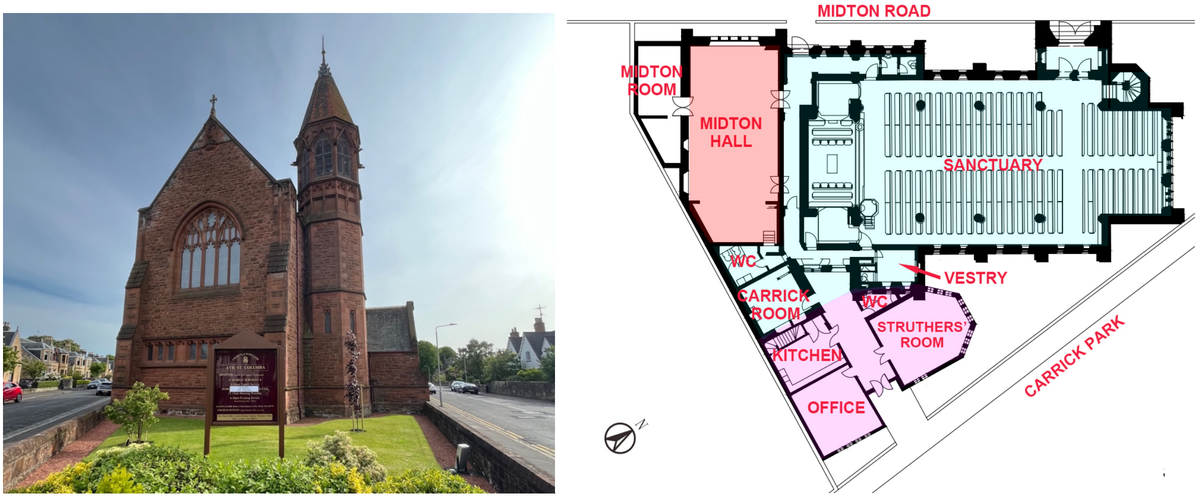

Figure 1 Ayr St Columba Church

1.3 Problem Identification

In 2022, the annual expenditure was £8,300, with electricity costs of £1,693 and gas costs of £6,607 (equivalent to the energy of about 15 homes). Projected energy charges are expected to rise significantly, when the current fixed rate tariffs expire, emphasising the need to address energy-related challenges amid diminishing church congregations and reduced income. The two major issues to be addressed are the efficient control of the heating system and the introduction of building fabric insulation.

- **Insulation**

The lack of loft insulation poses a critical challenge, and addressing this issue is essential for minimising heat loss and enhancing thermal performance. The substantial sandstone walls offer the potential for enhanced thermal performance, and the church could significantly improve energy efficiency by implementing appropriate insulation measures. It is crucial to address the breathability needs of solid stone walls, as improper insulation application may lead to damp issues.

- **Control of the Heating System**

Currently, the heating system is divided into only two zones, as Figure 2 shows: the Sanctuary and the rest of the building. Consequently, if the office requires heating, it also triggers heating of all the other rooms. Besides, it is worth noting that the rooms are not equipped with thermostats although conventional radiators are fitted with basic TRVs. The on/off of the radiators are controlled manually, which could potentially result in temperature fluctuations and energy waste.

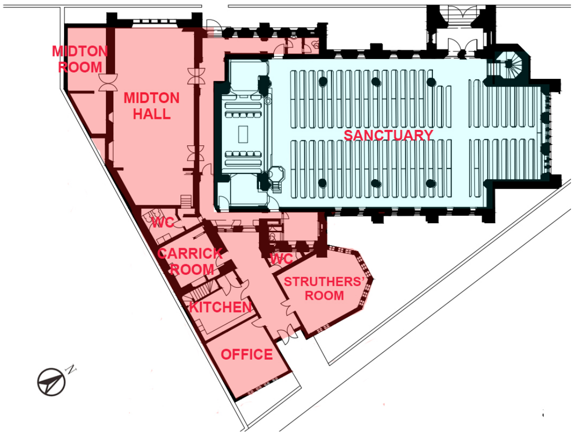

Figure 2 Two heating zones of Ayr St Columba Church

1.4 Research Aims & Significance

This research aims to utilise Ayr St Columba Church as a case study to analyse challenges and opportunities for improving energy efficiency in historic churches. The focus is on identifying and evaluating the energy performance of the church, assessing the effectiveness of retrofit measures, and proposing practical strategies for enhancing sustainability. The findings will contribute to the broader understanding of energy conservation in historic church buildings, offering valuable insights for similar projects in the future.

2.0 Literature review

2.1 Retrofit Principles

Retrofit measures, as outlined in Nick's sustainable refurbishment handbook, can be categorized into building fabric, mechanical services, and renewable energy options (4). The building fabric category addresses elements that impact a building's thermal performance. Studies using simulation tools show the positive effects of insulation and envelope upgrades on energy efficiency (5,6). The mechanical services category involves optimising heating, cooling, and ventilation systems, with studies emphasising the impact of system selection and efficiency on energy use (7,8). The renewable energy options category explores integrating sustainable sources like solar or wind energy to reduce reliance on traditional sources. Studies show the potential for achieving zero energy status and reducing CO_2 emissions through such measures (9,10). However, it's crucial to note that the effectiveness of renewable energy may be compromised in buildings heavily reliant on gas.

2.2 Guidance on Historic Building Retrofit

With a specific emphasis on historic buildings, guidance in Table 1 covers measures for improving energy efficiency, encompassing building fabric, heating systems, and renewable energy, serving as a comprehensive reference for the study.

Guidance	Year, Publication
Short Guide 1: Fabric Improvements for Energy Efficiency in Traditional Buildings	2013, Historic Scotland
Energy Efficiency and Historic Buildings: How to Improve Energy Efficiency	2018, Historic England
Guide to Building Services for Historic Buildings: Sustainable Services for Traditional Buildings	2002, CIBSE
Guideline 34-2019 - Energy Guideline for Historic Buildings	2019, ASHRAE
Commercial Renewable Energy Development and the Historic Environment	2021, Historic England

Table 1 Guidance on historical building refurbishment

2.3 Energy Retrofit of Historic Churches

When dealing with fabric measures, it's essential to consider the moisture balance remains undisturbed and offers an added safety level. Natural insulation materials such as sheep's wool and cellulose fibre allow excess moisture to be absorbed without causing condensation issues (11). Moreover, these materials release the absorbed moisture when conditions become more favourable, producing air movement (12).

For heating systems, replacing the old boiler in a heritage building with an efficient boiler can result in significant energy savings (13). Besides, adjusting the temperature setpoint and implementing appropriate time controls offer significant opportunities for energy conservation in church buildings (14). Besides upgrading current elements, researchers are continuously studying new approaches related to heat pumps. Heat pumps act as an energy-efficient solution which offers the potential in net zero path (15,16).

According to a review by Cabeza et al., integrating solar energy systems is the most popular strategy in heritage retrofit. Specifically, the focus has primarily been on incorporating photovoltaic (PV) technology into building roofs (17). This approach offers the potential to harness clean and sustainable energy sources, contributing to the environmental sustainability of heritage structures. However, the integration of solar energy faces challenges due to limited available space and the need to preserve the buildings' architectural integrity (18).

3.0 Methodology

3.1 Design Builder Model

This section establishes a Designbuiler model, whose result acts as an initial representation of the building's performance. As the model progresses through calibration, adjustments are made to improve the model's accuracy in reflecting real-world performance. The retrofit approaches were applied, and their effect on annual energy demand was analysed.

i. 3D Geometry

The DesignBuiler model (Figure 3) is constructed based on the building's dimensions, assuming the neighbouring buildings have minimal impact.

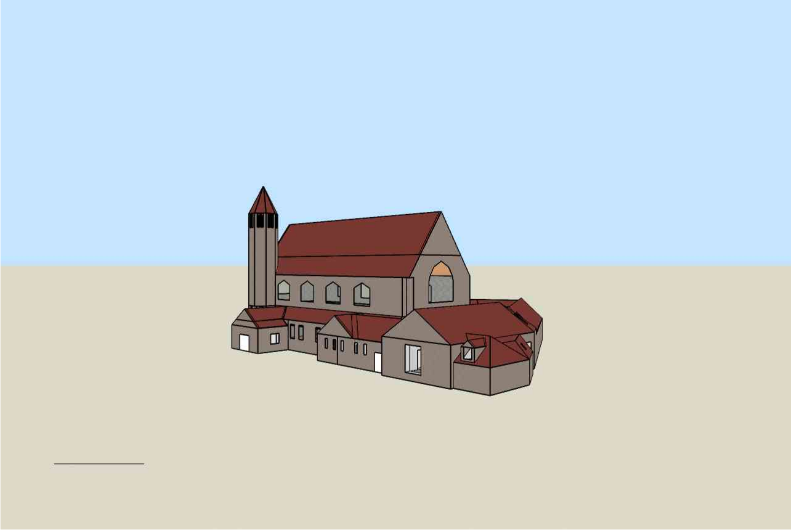

Figure 3 DesignBuiler Model

ii. Construction

The thermal properties of the material involved within the building are assumed based on Magana's study of a church resembling Ayr St Columba from the mid-19th century in Edinburgh (19). The zone capacitance multiplier is set to 1, and the infiltration rate is assumed to be 0.8; both values are then subject to further calibration. Construction build-up and properties of materials are summarised in Appendix. A.

iii. Openings

All windows, including skylights, are single-glazed with a thickness of 12mm and are non-openable. A U-value of 5.5 W/(m^2·K) is assumed for the windows, which is suggested by Historic Scotland (20). Due to the unavailability of the Solar Heat Gain Coefficient (SHGC), a value of 0.5 is assumed, and this value is further investigated. All doors in the building are wooden and the properties are summarised in Appendix. A (19).

iv. Occupancy, schedule

The occupancy data were obtained from the church's engineer, shown in Table 2. The activities conducted in the building were assumed to be light office work and no holidays were considered.

Room	Day	Time	occupancy
Sanctuary	Sunday	9:30 – 12:30	100
Midton Hall	Monday	14:00 – 17:00	20
	Wednesday	14:00 – 16:00	15
	Thursday	09:00 – 12:00 17:00 – 20:00	25
	Friday	17:00 – 20:00	25
	Sunday	10:00 – 12:30	25
Office	Sunday, Monday, Tuesday, Thursday	08:30 – 13:00	6
Struthers' room	Sunday	10:30 – 13:00	25
	Thursday	18:30 – 21:00	25
Vestry	Monday to Friday and Sunday	09:00 – 13:00	1

Table 2 Occupancy schedule of rooms

v. Equipment

The equipment was assumed to exist in the office and the kitchen. Following the CIBSE Guide A, the power densities for the office and kitchen areas are assumed to be 12 W/m^2 and 34 W/m^2, respectively (21). The operation of the equipment follows the occupancy schedule of offices.

vi. Lighting

A survey was performed, and the results were inputted as absolute zone power. The schedule of lighting follows the occupancy schedule summarised in Table 2.

vii. Ventilation

In the absence of a mechanical ventilation system and with non-openable windows, the assumption is that natural ventilation meets the minimum requirements for occupied rooms (12 L/s/person) (21).

viii. Heating system

The building utilises a central heating system comprising two boilers and radiators setup. The main entrance and tower areas are not heated. Additionally, a separate space within the Sanctuary relies on electric radiators, functioning independently from the central system. The remaining rooms are heated using hot water radiators, which are interconnected and supplied by the two boilers.

- ***Operating schedule***

The heating system typically operates from mid-September to mid-May, and the heating schedule is summarised in Table 3. There are three heating hot water loops for the building, namely: the Sanctuary, the Midton hall and the other rooms. The hot water loop for other rooms has no motorised valve to isolate it from either the sanctuary hot water loop or the Midton hall loop, which means the heat is supplied to the other rooms whenever the boilers operate. Thus, whenever the Sanctuary or the Midton Hall is heated, other rooms are also heated.

Zone	Day	Time
Sanctuary	Monday to Thursday	5:30 – 9:30
	Sunday	5.30 – 12.30
Midton Hall Other Rooms	Monday, Wednesday, Thursday, Friday	5:30 – 19:00
	Tuesday	5:30 – 14:00
	Sunday	5:30 – 12.30

Table 3 Heating system operation schedule

- ***Heating setpoint***

The heating system cannot be controlled automatically by a setpoint in the absence of thermostats. Instead, the valves of the radiators are manually switched on and off. However, the temperature loggers were installed to collect room air temperature data from the end of February 2023, which enabled the heating setpoints for the Sanctuary and Midton Hall to be assumed. For the other rooms where temperature sensor data is unavailable, the heating setpoint is assumed based on CIBSE Guide A regarding different room types (21), and the assumed heating setpoints are shown in Table 4. It is assumed that manual control aligns with the operation schedule. Consequently, DesignBuilder employs setpoint controls based on the corresponding schedule to simulate manual adjustments, ensuring that heating behaviour and temperature regulation mimic manual control.

Room		Setpoint (°C)
Sanctuary		18
Midton Hall		21
Other rooms	Office	21
	Struthers' room	20
	Vestry	21
	Corridor	19
	Toilet	17

Table 4 Heating setpoint temperature

- ***Temperature distribution***

Given the considerable sanctuary space, the warm air tends to move upwards. Therefore, the temperature distribution within the sanctuary space cannot be ignored and is typically analysed by Computational Fluid Dynamics (CFD). Țurcanu et al. investigated the microclimate in a 14 m high church heated by radiators (22). The results suggest that the radiator system generated convection currents with air velocity exceeding 1 m/s, whereas the internal temperature remained homogeneous when the system ran continuously. Similarly, another study on a church with a height of 9.8 m confirmed this finding (23). Therefore, the air temperature is assumed to be homogeneous in the Sanctuary.

System configuration

Figure 4 illustrates the system configuration, consisting of two connected boilers of the same size (102 kW each) to supply hot water in the three heating loops. The efficiency of the boilers was approximately 80% when new but deteriorated over time. Therefore, the estimated efficiency of 60% is suggested (24). In the Designbuilder model, a detailed radiator heating system including additional sanctuary space electrical radiators is unheated as Figure 5 shows. The inlet air temperature is 55 °C and the radiators are auto-sized to meet the heating demand of the zone with a sizing factor of 1.2.

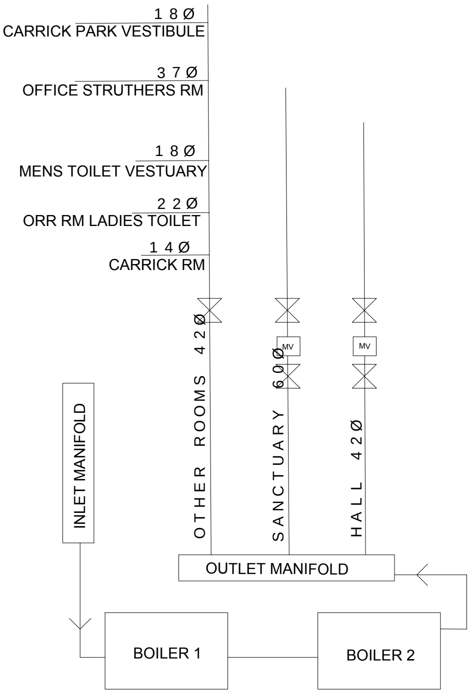

Figure 4 Heating hot water loop configuration

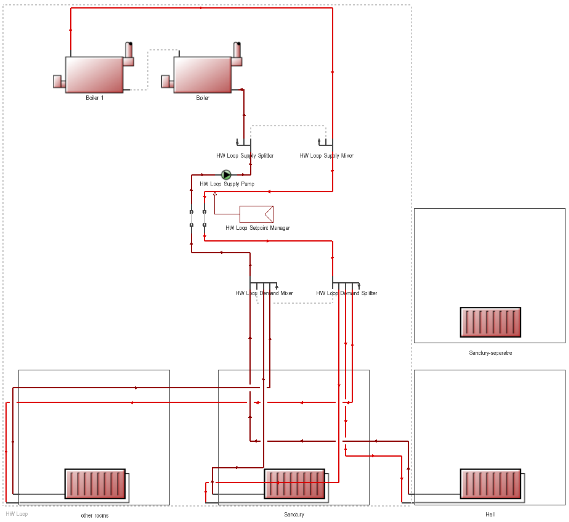

Figure 5 Heating system configuration in DesignBuiler

- ***Existing Heating Controls***

The control of the temperatures in the church buildings is by three thermostatic controllers which are connected to the main boiler control panel. These controllers are preset on a weekly basis based on the following week's scheduled activities. The emitters in the main sanctuary consist of 89 mm OD cast iron pipes located at floor level and conventional radiators which are currently fitted with basic on-off valves. The Midton Hall and the 'other rooms' heating circuits contain conventional radiators which are fitted with basic TRVs.

3.2 Model calibration

In this section, the model calibration process and acceptance criteria are presented. This process establishes an operational baseline for the church building, which serves as the initial reference point for subsequent dynamic model comparison.

i. Metered data

The daily gas meter readings (in m^3) recorded from September 2022 to January 2023 are available. While having a complete year of data would have been preferable, it was not available during the study, and the provided readings adequately cover the heating period.

ii. Parametric analysis

The parametric analysis is performed based on the assumed infiltration rate, SHGC, and thermal capacitance multiplier. An assessment of the impact of uncertain parameters such as annual gas consumption is conducted through a parametric study using the following inputs:

Infiltration rate (ach)	0.8-8
SHGC	0.25-0.65
Thermal capacitance multiplier	1-20

Table 5 Parameters range

Initially, each parameter is adjusted independently to assess its impact on gas consumption. These adjustments are plotted collectively, illustrating the percentage change in output relative to the corresponding percentage change in input.

iii. Calibration

The model uses the incorporated weather file for simulations during the data recording period (25). Gas consumption is then calculated from the model inputs and compared to actual metered gas consumption data, indicating any disparities between real data and the simulations.

The calibrated results of the model should meet monthly criteria specified in ASHRAE Guideline 14 (26), which means the coefficient of variation of root mean squared error (CVRMSE) should be below 15% and the normalised mean bias error (NMBE) should be within ±5%.

3.3 Refurbishment measures

This section outlines approaches for applying the retrofit measures. The calibrated model is set as an operational baseline, and the results after applying these measures are compared to the baseline result.

i. Fabric

The fabric upgrades focus on the ceiling, windows and external walls as Table 6 indicates.

	Baseline: W/(m²·K)	Retrofit: W/(m²·K)	Strategy
Ceiling	4.8	0.14	Cellulose fibre 270mm
Window	5.5	1.7	Secondary glazing
Wall (1964)	0.8	0.45	Aerogel blanket
Wall (1902)	1.3	0.26	Cellulose blown into gaps

Table 6 Summary of fabric upgrades

Cellulose fibre is chosen as the loft insulation material because it can be easily cut and adjusted without compromising its thermal efficiency (27). Additionally, it substantially improves airtightness compared to mineral fibres (28).

Installing secondary glazing panels is a moderate-cost and moderate-risk measure, which achieves a U-value of 1.7 W/(m²·K). It is implemented on all windows except stained glass in the Sanctuary.

For the wall constructed in 1902, blown cellulose insulation (60 mm thick) fills the empty spaces behind the wall linings. This material is selected for its breathability, which aligns with the characteristics of the original 600 mm sandstone walls. For the later construction, no gaps are available for blown insulation. The implementation of aerogel blankets in Historic Scotland trials has yielded a spectrum of thermal enhancements (20). A high-performing aerogel blanket of 10 mm thickness is applied to the interior surface of the walls without compromising the indoor space.

ii. Heating System

For the heating system upgrade, the following two retrofit scenarios are developed.

	Scenario 1	Scenario 2
Control	Operation schedule control	Operation schedule control
Heat source	Condensing boiler	Air to water heat pump

Table 7 Heating system retrofit options

- **Operation schedule control**

The absence of control valves for certain rooms in the current heating system leads to potential significant energy wastage as they are heated when there is no heating demand. To address this issue and improve energy efficiency, the schedule is set based on the usage of these rooms.

- **Boiler replacement**

Since the current boilers are old and likely to exhibit low efficiency, replacing them with modern, high-efficiency ones is a straightforward approach. Condensing boilers are assumed due to their superior efficiency at 94% as a replacement for both boilers in the heating system (29). As the fabric measures discussed above would reduce the heating load of the building, the capacity of the boiler is determined based on the results from the heating design calculation after applying fabric upgrade measures. It is worth noting that replacing boilers is a cheaper approach but will not achieve the net zero ambition.

- **Heat pump**

Considering the impending ban on installing new gas boilers in Scotland (30), the possibility of replacing the existing boiler with modern efficient boilers is reduced. One viable option is to employ heat pumps to supply heat to radiators. Figure 6 shows an air-to-water heat pump with an integrated water tank. The heating coil capacity is based on the results from the heating design calculation after applying fabric upgrades. An average Coefficient of Performance (COP) of 3.2 is assumed for the heat pump (31), and ASHP LowT COPFT is used for heating COP.

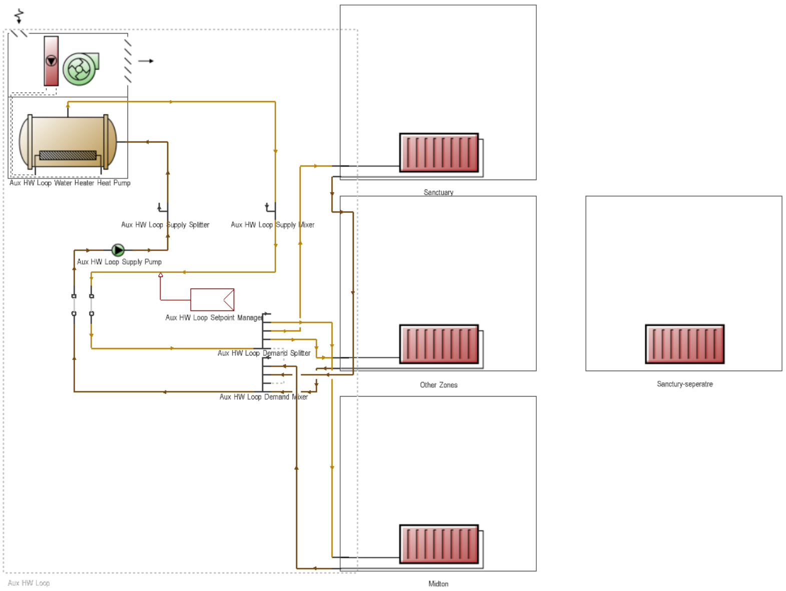

Figure 6 Heat pump system configuration

iii. PV system

Abundant space on the south-facing roof of Midton Hall presents opportunities for integrating solar solutions, offering a potential option to diminish carbon emissions without compromising the aesthetics. A PV system (Figure 7), which covers a combined surface area of 150 m^2 is assumed to be implemented, employing bitumen felt as the primary material. The proposed position of the PV panels is not on the roof of the main church building, but one of the smaller contiguous church buildings and hence the visual impact of the PV panels is not considered to be significant. The panels follow the simple performance type with an efficiency rating of 0.15. This on-site electricity generation setup operates on direct current, with an inverter facilitating the conversion with an efficiency of 0.95. The simulation is conducted based on the scenario after integrating a heat pump.

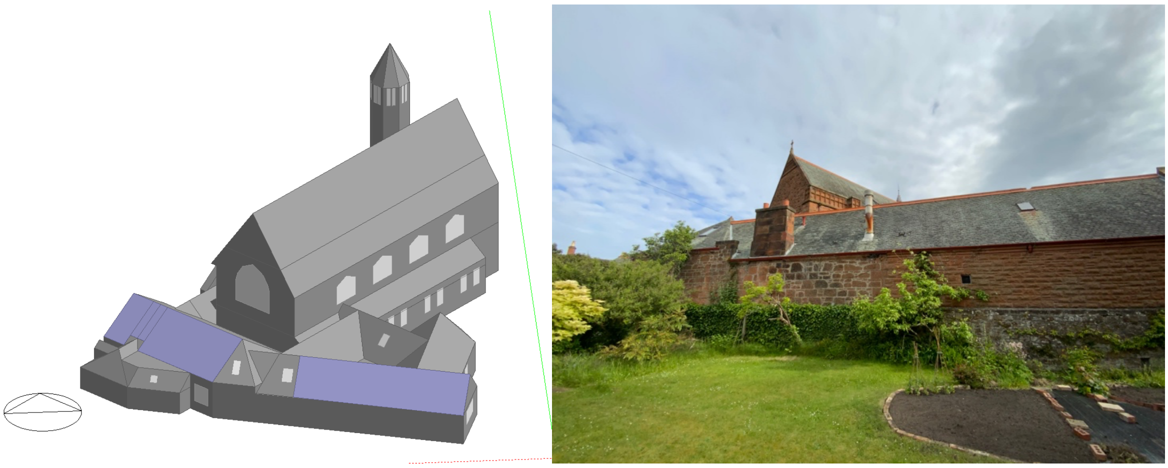

Figure 7 PV system

iv. Evaluation method

A thorough assessment is employed to evaluate the retrofit measures' effectiveness, focusing on energy savings, cost reductions, and GHG emissions. This entails comparing post-retrofit energy consumption data against the initial baseline (pre-retrofit) results, including fabric and heating strategies. The financial implications of the heating system retrofit interventions are assessed by computing the monetary advantages of reduced energy usage using the unit energy cost. The overall cost is determined using energy prices from July to September 2023, with electricity priced at £0.3 per kWh plus an additional £0.53 daily standing charge (32) and gas at £0.08 per kWh with a daily standing charge of £0.29. Finally, a comparative analysis of CO_2 emissions is conducted based on the DesignBuilder results.

4.0 Results and Discussion

4.1 Initial representation

Figure 8 illustrates a comparison between the metered gas consumption data and simulation results. The gas consumption patterns for September and December show similar values in the metered data and simulations. For October, November, and January, the simulation results indicate lower gas consumption compared to the metered data. January shows a particularly significant difference with much lower gas consumption in the simulation results.

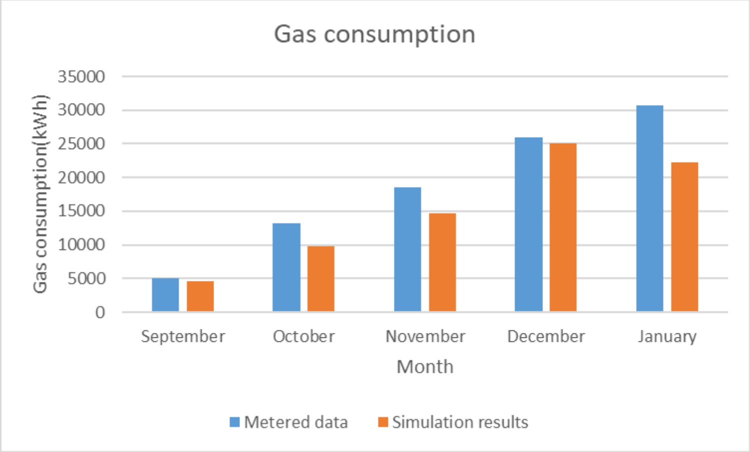

Figure 8 Metered data vs Simulation results

For the initial representation, the calculated NMBE is -17.3%, and the CV-RMSE is 24% which does not meet the established criteria for accuracy. To understand the factors causing these discrepancies, the following aspects are considered:

- Actual operation

When the heating is switched off, the boilers still consume a small amount of gas (Pilot light: 15-30 kWh), enabling the boilers to reach full capacity quickly. Besides, there is a noticeable amount of gas consumption on Saturdays due to random activities such as weddings and festivals. Since these activities happen occasionally, the higher values on Saturdays are replaced with 20 kWh, which assumes no special activities happen on Saturdays. In addition, two missing values at the end of September are identified, and therefore the simulation on those days is not considered for the monthly value.

- Input data

Parametric analyses are carried out regarding the input parameters. It is found that both the infiltration rate and the zone capacitance multiplier have a significant influence on gas consumption, while the influence caused by SHGC is less pronounced when compared to the impact of these two other variables. As a result, the infiltration rate and zone capacitance multiplier are adjusted.

4.2 Operational baseline

By setting the infiltration rate to 1.2 ach and the zone capacitance multiplier to 4, the calculated NMBE is -1.6%, and the CV-RMSE is 7.3%. These values satisfy the ASHRAE criteria for calibration (26).

The heating design results from the DesignBuilder model show that the church buildings have a total design capacity of 130 kW, which indicates that the current system could be oversized (the total capacity of the two boilers is 204 kW). The results indicate that annual gas consumption is 157638 kWh and total gas usage is 6627 kWh, which serves as the operational baseline against which the outcomes after implementing measures are compared.

4.2 Building fabric

In the context of the examined fabric measures in the case study, enhancement approaches primarily focus on the ceiling, walls, and windows. Notably, the influence of these measures on electricity consumption remains, as their impact is predominantly concentrated within the separate space of the Sanctuary, which exclusively employs electricity for heating. Figure 9 shows the gas consumption after applying each fabric enhancement measure. Among the array of measures, ceiling insulation emerges as the most viable and least intrusive option, posing minimal risk while substantiating a significant reduction in gas consumption by approximately 16%.

Conversely, the treatment of walls, contributing to a reduction of around 10%, demands careful consideration due to the considerable surface area involved, accompanied by installation complexity and associated material expenses. As for the windows, specifically the application of shutters followed by secondary glazing, their collective effect on gas usage reduction amounts to approximately 5%. Given the visual implications and low effectiveness, a careful assessment of their effectiveness is required.

In summary, the priority of fabric measures should lie in implementing ceiling insulation, which stands out as the most cost-effective measure. In achieving a zero-carbon objective, wall insulation should be considered. Simultaneously, a thorough evaluation of measures related to glazing is warranted, given the significant visual effects that would arise from the glazing measures.

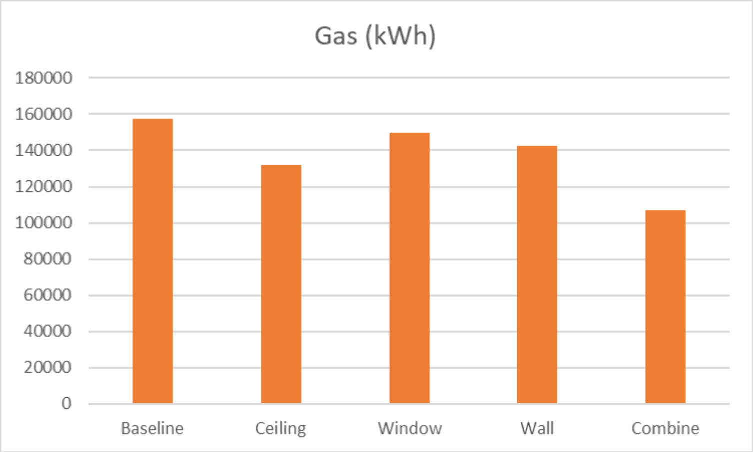

Figure 9 Annual predicted gas consumption with fabric measures applied

4.3 Heating system

Table 8 summarises the energy usage of two retrofit options. It is found that both measures result in a reduction in energy usage, and the option involving a heat pump is more effective in reducing energy usage. To better evaluate these, the cost and carbon emission are presented.

	Electricity (kWh)	Gas (kWh)	Total energy	Reduction
Current system	6021	106996	113017	-
New schedule + boiler replacement	6019	60289	66407	41%
New schedule + Heat pump	25980	0	25980	77%

Table 8 Energy usage under two options

Figure 10 plots the annual CO_2 emissions and running costs associated with both options alongside the present situation. The plots indicate that replacing the boiler yields the least operational costs while heat pump alternatives result in a higher reduction in CO_2 emissions.

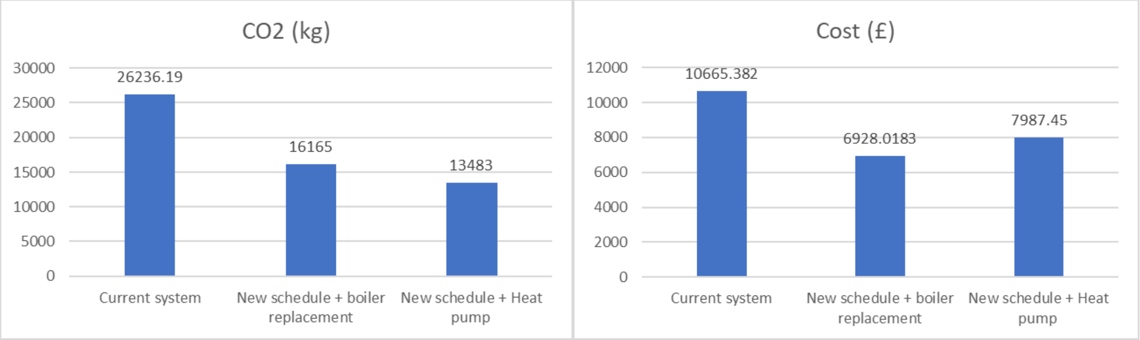

Figure 10 Evaluation of carbon emission and running cost of two options

Above all, both options effectively reduce energy usage, where using new boilers leads to a 40% energy usage reduction, and heat pump leads to a 77% reduction. In the context of condensing boilers, it is important to acknowledge the additional expenditure associated with providing suitable flues for modern condensing units would lead to rigorous design and financial appraisals.
Replacing the boilers with condensing boilers is likely to be significantly cheaper. However, it is essential to acknowledge the possibility of impending boiler bans, underscoring the importance of future-proof decision-making. From a long-term perspective and environmental consideration, a heat pump solution is better aligned with sustainability goals.In summary, the optimal solution for heating systems necessitates multifaceted control methods, solving component efficiency and alternative technologies. As the transition toward more environmentally effective energy systems advances, using heat pumps emerges as a better choice since generating electricity from renewable energy sources is possible.

4.4 PV system

According to Table 9, it is seen that integrating a PV system on the south-facing roofs presents a significant opportunity to harness renewable energy. Ayr St Columba church is a grade B listed building and hence any alterations to the external building fabric would require detailed local authority planning approval. The proposed position of the PV panels is not on the roof of the main church building, but one of the smaller contiguous church buildings and hence the visual impact of the PV panels is not considered to be significant. This system holds the potential to generate a substantial (90%) of the electricity demand. However, the intermittent nature of solar power generation results in periods when the generated electricity exceeds the immediate need, which in turn would result in only a 15% contribution to overall usage.

Effective energy management strategies are crucial in achieving a zero-carbon position for the building. Energy storage systems can play a pivotal role by storing excess energy during high-generation periods and distributing it during low-generation or high-demand phases (33). Hence, surplus PV energy generation could increase the contribution.

In addition, grid interaction and net metering mechanisms offer additional avenues for enhancing PV system benefits. Excess electricity can be fed back into the grid, yielding credits. This encourages solar system owners to support grid stability and renewable energy integration.

In conclusion, the initial PV system holds great potential for achieving net zero, coupled with suitable management.

	Electricity (kWh)	Percentage of total usage
On-Site Electricity Source	23441	90%
Electricity from Utility	22265	85%
Surplus Electricity going to the Utility	18570	71%

Table 9 Electricity data with PV generation

4.0 Conclusion

4.1 Conclusion

In conclusion, the absence of loft insulation prompted the adoption of ceiling insulation for rooms other than Sanctuary as a direct and highly effective measure to minimise heat losses, resulting in a noteworthy 16% decrease in gas consumption. Regarding heating systems, implementing control strategies holds promise, and enhancing the efficiency of the heat source can contribute to reduced energy demand. While both boilers and heat pumps exhibit favourable cost considerations, the long-term benefits of heat pump options stand out.
Furthermore, the significant contribution of photovoltaic (PV) panels on the southern roof, generating up to 90% of electricity, is noteworthy, albeit with seasonal variations.

4.2 Limitation

- While the present study offers valuable insights into air distribution dynamics within the Sanctuary, the heating pipes under the pews introduces a variable. A survey of the heating system layout has been conducted (Figure 11), and further Computational Fluid Dynamics (CFD) analysis will be carried out to examine temperature distribution within the Sanctuary.

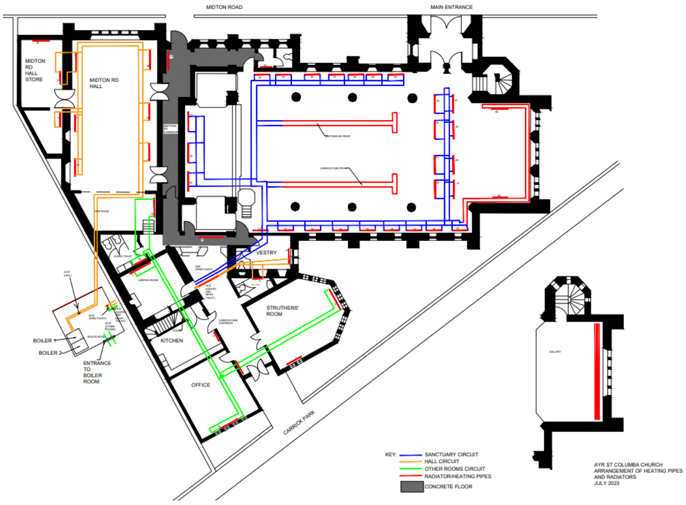

Figure 11 Heating system layout

- Owing to the constraint imposed by data availability, the calibration procedure has been carried out exclusively using gas consumption data within specific periods. Although the current calibration methodology successfully meets the criteria at a monthly level, its effectiveness diminishes when attempting to achieve precision on a daily scale. To address this constraint, ongoing collection of meter data is necessary, and additional research should be conducted to enhance precision.
- Although the PV system shows great potential towards net zero, Ayr St Columba church is a grade B listed building and hence any alterations to the external building fabric would require detailed local authority planning approval. The suitability of the current roof condition should be evaluated and the actual amount of PV to be installed will be assessed in the next stage of the project.
- Generally, this study focuses on the effectiveness of retrofit measures, the financial aspect related to the measures is not evaluated, as pricing typically relies on the quotations provided by manufacturers. The cost-effectiveness is an important aspect to consider and will be evaluated at a later stage.

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Appendix. A: Building Construction

Material	Thickness(mm)	Conductivity(W/m·K)	Density(kg/m³)	Specific heat(J/kg·K)
External wall – 1964, U = 0.8 W/(m²·K)				
Sandstone	100	1.83	2200	920
Cavity	75	-	-	-
Common brick	100	0.6	1700	800
External wall - 1902/1898, U = 1.3 W/(m²·K)				
Sandstone	600	1.83	2200	920
Air gap	50	-	-	-
Lath and plaster	10	0.16	950	830
Internal partition, U = 0.4 W/(m²·K)				
Plaster	10	0.25	2800	896
Common brick	100	0.6	1700	800
Plaster	10	0.25	2800	896
Celling, U = 4.8 W/(m²·K)				
Timber	12	0.14	1602	1760
Roof, U = 4.7 W/(m²·K)				
Timber	12	0.14	1602	1760
Slates	5	0.84	1900	800
Floor, U = 3.6 W/(m²·K)				
Timber	12	0.14	650	1760
Door, U = 3.6 W/(m²·K)				
Wood	40	0.14	650	1760