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Evaluation of decarbonisation options for heritage church buildings

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ABSTRACT

Heritage church buildings are significant energy consumers and carbon emitters, but hard to decarbonise due to construction materials and designs, which presents an imperative challenge for churches that have a mission to achieve net-zero targets by 2030. The study aims to provide a clear pathway for decarbonising heritage church buildings to support net-zero planning and evidence-based decisions. The methodology involved producing a virtual replica for each building to generate valuable insight into retrofit possibilities; exploring the potential of various decarbonisation interventions using dynamic modelling simulated with site data; comparing the interventions to the baselines in terms of energy, cost, and emissions; and tailoring decarbonisation solutions according to specific conditions. The results show that for small churches, replacing the gas boiler with another technology and using existing hydronic heating could be effective for low usage, whereas replacing the current heating system with heat pumps with PV offset would be more economical for high usage; on the other hand, for large churches, heat pumps or biomass could significantly reduce emissions. It is concluded that due to the unique characteristics of heritage church buildings, there is no one-size-fits-all solution but the uniform methodology proposed in this study could be applied to support evidence-based decisions for net-zero heritage buildings. The case studies contribute towards current knowledge and understanding. The work is original as it quantifies the benefits of various decarbonisation measures in 4 case studies of different ages, sizes, and usage patterns, representing a significant portion of heritage church buildings in England.

Abbreviations

A2A	Air-to-air
A2W	Air-to-water
ACH	Air change per hour
ASHP	Air source heat pump
BES	Building energy simulation
CAD	Computer-aided design
CC	Capital costs

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CFD	Computational fluid dynamics
CI	Carbon intensity
CO_2	Carbon dioxide
EWY	Example weather year
FIT	Feed-in tariffs
GB	Gas boiler
G2A	Ground-to-air
G2W	Ground-to-water
GSHP	Ground source heat pump
HVAC	Heating, ventilation, and air conditioning
IES-VE	Integrated environmental solutions – virtual environment
LED	Light emitting diode
LZC	Low and zero carbon
NCM	National calculation methodology
OC	Operating costs
PV	Photovoltaic
RH	Relative humidity
RI	Roof insulation
SEG	Smart export programme
TH	Trench heating
U-Value	Thermal transmittance
UFH	Underfloor heating

1. Introduction

Heritage church buildings are inherently incompatible with core net zero planning strategies because they are heritage builds and cannot (should not) be rebuilt. The principal emissions from these buildings come from space heating and electricity [1]. In keeping with the net zero commitments of the Church of England by 2030, heritage church buildings are expected to reduce energy demand and replace fossil-fuel-based heating with renewable-fuel-based heating or net-zero electric-based heating. Conventional energy-saving strategies such as building insulation and cladding are neither practical nor viable [2]. However, not all historic church buildings are suitable for insulation due to the nature of the buildings, like ornate/decorated ceilings. Significant alterations to historic buildings are usually prohibited to conserve their fabric and the essence of being historical [3] because undertaking any energy-saving measures may damage the historic fabric and artefacts within the buildings [2]. Reduced temperatures in the building could reduce energy demand; however, the temperature is a prevailing concern to occupants and temperatures of 18–22 °C are expected, while relative humidity (RH) only counts when at extremes, below 30% or above 80% [3]. Nonetheless, artefacts are susceptible to changes in RH differently from humans [4]. The method with which heritage buildings manage thermal comfort could be complex, with various conflicting objectives in energy consumption, specific requirements of church furnishings, artefacts, and thermal comfort conditions [5]. Assessing the options for environmental feasibility with reduced energy and costs is challenging. The challenge goes beyond the conventional “trilemma” of meeting thermal comfort, decarbonisation, and affordability targets to become a " quadrilemma” with the addition of maintaining building fabric conservation [6,7]; the commitment to net zero emissions presents a challenge for heritage buildings for obvious reasons.

Energy consumption and evaluation of historic buildings’ heating systems have been systematically investigated in recent years. Woroniak and Piotrowska-Woroniak [8] analysed the effects of reducing energy demand and emissions of church buildings by modernising the building structure and heating system for improved energy efficiency in five church buildings in the Diocese of Drohiczyn, Poland. Significant reductions in emissions were observed across all churches, accompanied by energy demand reductions ranging from 30% to 50% and cost savings in energy expenses ranging from 20% to 87%. Qu et al. [9] evaluated the energy demand reduction using three passive methods for a 19th-century historic building in the UK. Appraisal indicators to measure the performance of retrofit combinations include energy reduction rate, thermal comfort, cost, and payback period. Optimised retrofit achieved 51.8% energy reduction and investment of £144.71/m^2 with vacuum-insulated windows, reduced gypsum air infiltration, and 2 cm Polyisocyanurate insulation. Similarly, Cho et al. [10] presented the energy demand analysis and thermal comfort of facade retrofit of a historic building for energy efficiency improvement. The combined implementation of insulation, enhancing airtightness, upgrading windows, installing blinds, and replacing traditional lighting with LED reduced heating demand by 72% and decreased total energy consumption by 60%. Aste et al. [11] presented an optimal heating system for the Basilica of St Mary of Collemaggio, Italy. The optimised system maximised energy savings and was suitable for preserving the historical elements. Galatioto et al. [12] presented an overview of the energy demand of historical buildings in Italy and assessed the efficiency improvement and demand reduction. The main barriers to feasible energy retrofit on Italian historic buildings were the significant payback times and the limitations on onsite renewable energy sources. The summaries of relevant studies on religious buildings and the software used are presented in Table 1.

Most studies presented in Table 1 used bespoke analyses and building energy simulation (BES) tools to assess the energy performance, thermal behaviour, and potential benefits of interventions in heritage buildings. Only some studies have quantified measures

Table 1
Summary of relevant studies on religious buildings.

Scope	Key findings	Limitations/gaps	Reference
Fabric and heating system refurbishment in churches (applied research). Software (not applicable).	•Energy reduction of 30-60%. •Carbon reduction of 57-100%. •Cost reduction of up to 88%.	•Focused on biomass fuel switching and fabric insulation (walls, doors, windows).	[8]
Pew heating with water based GSHP (modelling and prototype testing). Software (EnergyPlus).	•Achieved energy and carbon reduction of 70% compared to electric heating options.	•Focused on air, infrared and pew heating only. •CAPEX/OPEX not included.	[11]
Fabric and heating system retrofit of a UK Cathedral (modelling case study). Software (IES-VE).	•Energy management: Saved 6.5% of gas and 6.5% of electricity. •Underfloor heating: Saved 46% of gas and 8% of electricity. •Improved fabric: Saved 40% of gas and 19% of electricity.	•The analysis does not include low and zero-carbon technologies (e.g., PV and HP).	[15]
Electric underfloor heating system (modelling and validation). Software (IDA-ICE).	•Achieved 27% energy savings in improved windows and 2.1 to 3.7% in optimise control setpoint.	•Carbon emissions and costing not assessed, which is essential for wider adoption.	[16]
Heating strategy selection for historic church buildings using weighted matrix analysis. Software (not applicable).	•Top-ranked fuels: Gas, bio-LPG, electricity. •Top-ranked heating systems and emitter type: Air/water source HP and cushions/mats.	•The methodology was based on feature ranking for selecting potential heating strategies. •A preliminary step before performance analysis and evaluation of heating strategies using models or field trials.	[17]
Analysis of the indoor microclimate of a church using AI techniques (data-driven modelling). Software (not applicable).	•Based on the scenario analysed, the future estimates of indoor microclimate vary significantly. •Recommend further studies on heating strategies, thermal comfort, and energy for addressing climate change impacts.	•Available data restrict this methodology and is unsuitable for investigating net zero pathways where individual system parameters need to be optimised.	[18]
CFD analysis of ventilation strategies of a church building. Software (IES-VE).	•Investigated three ventilation strategies: None, natural and night purging. •These were found suitable for building conservation but not for occupant comfort.	•Bespoke analysis, suitable for detailed design stage analysis of heating strategies; once a net zero pathway is selected using simplified analysis.	[19]
Retrofit analysis of a large mosque using models and matrix analysis. Software (IES-VE).	•LED lighting and HVAC control significantly decreased energy demand. •Incorporating demand reduction, fabric efficiency and HVAC control measures achieved 50% energy reduction, emissions, and cost savings.	•The CAPEX/OPEX data for individual measures and carbon reduction were not presented, which could help the wider application of the results.	[20]
Climate change impact assessment on interiors of three church buildings. Software (Design Builder).	•Higher risk of mechanical degradation in the interiors caused by temperature and humidity fluctuations. •Implementing active mitigation systems increased energy demand by 15%. •Energy demand for artwork preservation was twice as much for thermal comfort.	•Only HVAC systems were considered for analysis of humidity, cooling, heating, and ventilation. •Emissions associated with mitigating climate effects on the church interior were not assessed.	[21]

for demand reduction and decarbonisation. These analyses need to be more detailed and adaptable as they could only be applied to exceptional cases. The Church of England building stocks are expected to achieve net zero status by 2030, and the lack of practical case studies quantifying the impact of combined decarbonisation measures could derail such an ambition. The outcomes of the few cases cannot be generalised for the entire historical building stock due to size, age, and usage variations. To achieve evidence-based decisions for net zero planning for heritage buildings, quantifying the benefits of decarbonisation measures through consistent methods is required. These knowledge gaps could be bridged if different technology configurations on heritage building stocks were analysed with uniform methodologies, considering their holistic impact on energy, cost, and emissions metrics. However, virtual assessment of typical measures becomes the only viable alternative to evaluate potential solutions and filter unfeasible combinations of measures to facilitate net-zero ambition; hence, this investigation is both timely and crucial. While the BES could reasonably represent building physics and geometry, the results depend on the quality of modelling inputs, i.e., parametric values. Therefore, validating BES models with empirical data is vital to ensure they produce realistic results [13,14].

This research aims to evaluate the decarbonisation potential of heritage church buildings in the UK, emphasising type and usage patterns through modelling and simulating the relevant LZC technologies compared with the baseline buildings, thus offering a path to aid net-zero planning for heritage church buildings. The research objectives are defined: (a) to develop a modelling tool that could assess the emissions and energy use in heritage buildings and their temporal evolution toward net zero resulting from alternative interventions (i.e., demand reduction, fabric efficiency, low and zero carbon (LZC) technologies and electrifying heat); (b) to create baseline models to quantify current energy use and emissions through collating and analysing granular data collected from energy audits; and (c) to assess net zero interventions and quantify the potential for decarbonisation and the economic implications compared to baseline results. By presenting a consistent approach to comparing and assessing various decarbonisation interventions, this study contributes to existing knowledge (as their impact on energy, cost, and carbon of historic buildings were quantitatively evaluated for a better understanding) and supports the decision-making process towards achieving a net-zero future. Thermal comfort analysis was out of the scope of the study, and the models simulated thermostatic dry-bulb temperature, which is consistent with the standard control strategy applied in most historic buildings using thermostats [12].

The subsequent sections of the paper are structured as follows: Chapter 2 provides an overview of the buildings, detailing the model development process and calibration methods. In Chapter 3, the paper discusses model calibration results, examining emissions reduction interventions and pathways towards decarbonisation for each building.

2. Methods

2.1. Overview of buildings

The buildings are all in Northeast England, UK, with typical churches/cathedrals design, thick stone walls, single-glazed windows, wooden doors, and gas heating. The buildings pictures, 3D models, overview and parameters used for the modelling are highlighted in 2.2.1 and detailed in Appendices.

- **Type A**—St Brandon's Church Brancepeth is a Grade I listed traditional Norman Romanesque church built in the 11th century, a rural church and infrequently used. Part of the building was restored in the 2000s. Hence, some parts of the building are of modern construction, such as the insulated roof.
- **Type B**—St Nicholas' Church Marketplace is a two-floor inner-city church and Grade II listed building built in the 1850s, frequently used with an uninsulated roof and incandescent lighting.
- **Type C**—St John's Church, suburban and frequently used, built in the 1890s and expanded in the 1990s. The building is a blend of two fabrics; the extension is of modern construction, such as insulated roofs and walls.
- **Type D**—the Cathedral Church of Christ, Blessed Mary the Virgin and St Cuthbert of Durham, commonly referred to as Durham Cathedral, is a Grade I listed Romanesque-Gothic cathedral completed in the 1130s. It is in the heart of the city and is frequently used. Only the cathedral building was considered in this analysis, and other connected buildings, were excluded.

2.2. Model development

The complexity of building technology has made building energy performance simulation an essential feature of the planning, design, and operational process. These packages are widely used in the industry during various project stages to estimate the key performance indicators. The tool IES-VE [22] used in the study enables the creation of a 3D CAD model of a building. It creates the thermodynamic model based on the geometry and the parametric values and boundary conditions such as weather and occupancy provided. Further information on the tool's physics and simulation methods is available in Refs. [23,24]. The tool has been assessed against several global and regional standards [25]. The flow chart for the study methodology is presented in Fig. 1. The data gathered (stage 1) is given in Appendix B for each building, and the other stages are given in the following sections of the paper.

2.2.1. Baseline modelling

The CAD module of the IES-VE was used to create the buildings' 3D models, as shown in Appendix A. The physical properties of each building, such as fabric materials, occupancy, air quality control, lighting, heat gains, energy usage and emissions were assigned. The overall thermal transmittance (U-value) of door, window, roof, wall, and light intensity of individual buildings are presented in Table 2. The light intensity in Table 2 was defined based on the building's occupancy profile, and it assumed that all lighting power is converted into heat.

The non-domestic heating systems model was utilised in this study based on the National Calculation Methodology (NCM) [26]. NCM is the UK government and building industry's de-facto standard for predicting energy use in buildings. The model heating was scheduled to match the buildings' thermostat timer settings. For wet central heating systems, the schedules set in the church with preheating times were adopted when investigating switching to other wet systems like heat pumps (HPs) and biomass boilers. The heating schedule was changed to occupancy times without preheating when all air-heating systems were investigated. Optimisation of heating times was not investigated due to unavailable data about real-time changes to occupancy and building activities.

The buildings were zoned and served by individual boilers through multiple circuits for wet heating, and the zones were scheduled to activate heating according to the operational profile. A building monitoring system with temperature sensors at high level controlled the triforium radiators of the Cathedral, while low-level thermostats with compensating external thermostats intended to provide constant air temperature at 18 °C controlled the convector units and underfloor systems. The models replicated all the buildings' heat networks, circuits, and controls. See Table 3 for the buildings' heating and occupancy profiles. The buildings are operated at temperature setpoints of 18 °C except for St Brandon's, with a 19 °C. For wet/all air heating systems, the simulation was set to maintain the air temperature setpoint without restricting the system's size. This approach was adopted to simulate the alternative heating options in this study. For the radiant systems, occupants were directly heated, and the air temperature was not controlled; therefore, the systems were sized based on the manufacturers' rule of thumb to restrict the sizes accordingly in the simulation for accurate energy consumption estimation. The occupancy approximated the normal usage based on the regular event calendars (see Table 3). The

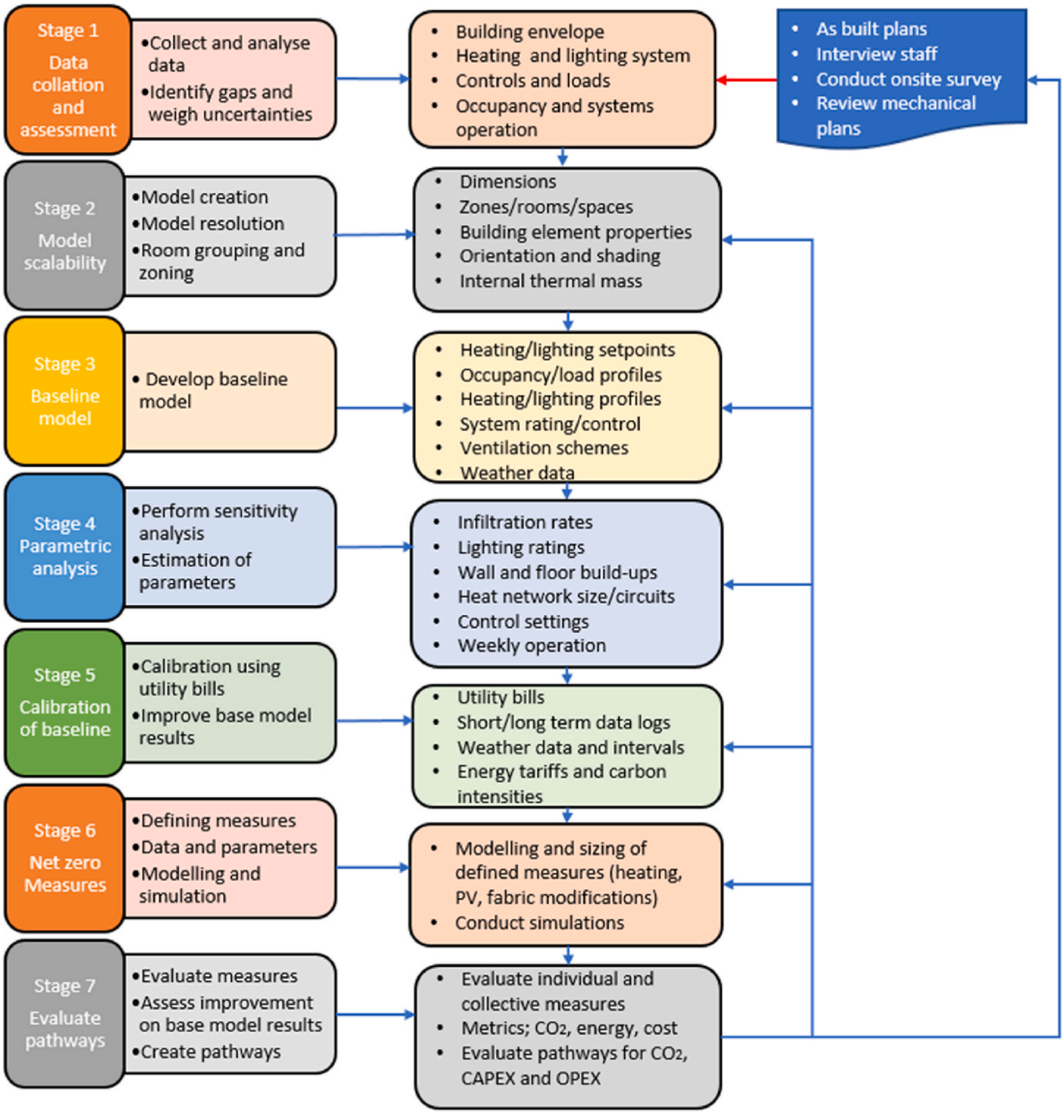

Fig. 1. Methodology applied in this study.

discrepancy in weekly compared with yearly occupancy was due to special events held at the buildings. The internal heat gains were scheduled during occupancy, and the heat released estimate was 90 W/person. Heat gains from lighting, as in Table 1, were used. The model's occupancy diversity factor was set to 1, indicating no change in the number of people during occupancy.

Table 2
Thermal transmittances (U-values) and light intensities of the buildings analysed in this study.

Buildings	U-value (W/m^{2}K)					Light intensity (W/m^2)
	Door	Window	Roof	Floor	Wall	
St Brandon's	1.44	5.22	0.45	0.54	1.65	1.5
St Nicholas'	1.44	5.22/1.86	2.16	0.58	1.65	18
St John's	1.44	5.22	0.64	0.71	1.65	9
St John's extension	1.75	1.5	0.45	0.2	0.33	1.5
Cathedral	1.44	5.22	3.30[a]/4.1[b]	1.2[c]/0.47[d]/1.296[e]	0.79	40

[a] slate.
[b] lead.
[c] uninsulated.
[d] insulated.
[e] suspended.

Table 3
Occupants, aggregated occupancy, and heating profile.

Buildings	Number of persons	Normal weekly occupancy (h)	Yearly occupancy (h)	Average weekly heating (h)	Yearly heating (h)
St Brandon's	30	2	184	19	1796
St Nicholas'	70	25	1375	13	666
St John's	80	24	1248	21	1092
Cathedral	600	40	2080	66.5	3458

Table 4
Utility tariffs for the buildings and green tariffs.

Energy tariff	St Brandon's	St Nicholas'	St John's	Cathedral	Green tariff [34]
Electricity (p/kWh)	16.0401	14.173	50.7	9.105	38.96
Standing charge electricity (p/day)	119	0	75	59.28	33.64
Natural gas (p/kWh)	2.7417	2.703	12.7	3.8	8.51
Standing charge gas (p/day)	175	0	203	1228.96	33.15
PV generation/export (p/kWh)	-	-	56.03/3.95	-	-

The natural air change per hour (ACH) was set at 0.25 for the Cathedral and 0.5 for all the other buildings [27]. The controlled natural ventilation was set at 0.06 through the occupancy profile for all the buildings [28]. Electricity's carbon intensity (CI) varied with the grid generation mix; for natural gas, 0.184 $kgCO_2e/kWh$ was used [29], and 0.21213 $kgCO_2e/kWh$ for electricity in the baseline and net zero models [30]. The energy tariffs for modelling were from the buildings' utility bills, excluding the climate change levy, as they do not apply to charities [31]. The energy tariffs for all buildings were fixed for the next 3–4 years and are presented in Table 4. No Photovoltaic (PV) panels were installed except for St John's, and it had a Feed-In-Tariff (FIT) of 56.03 and 3.95 p/kWh for generating and exporting electricity, respectively [32]. In line with the FIT's rules, St. John's received payment for 50% of the energy it generated. This was due to the absence of an export meter, and the associated costs were considered when calculating the baseline costing. New PV installations were enrolled on the Smart Export Guarantee (SEG) programme with 5.4 p/kWh for export [33] as the FIT was no longer available to new installations.

The roofs were slate/lead with a 25 mm air cavity, a 35 mm polystyrene insulant and a 12.5 mm gypsum plasterboard. Based on the solar shading analysis, PVs were assumed to be installed on roof parts with maximum solar irradiation. A fuel tariff of 4 p/kWh [35] and a CI of 0.01513 $kgCO_2e/kWh$ [36] were assumed for biomass.

The UK gas grid could be 100% hydrogen tolerant, with blends reaching 20% by 2035–2040 and 100% by 2050 [37]. Green hydrogen was assumed to be net zero, and the tariff was 5.5 p/kWh [38]. Regular gas boilers could cope with 20% hydrogen blended into the gas network [39], so there were no costs for switching to a 20% blend on existing boilers. Air-to-air (A2A) and air-to-water (A2W) air-source HP (ASHP) and ground-to-water (G2W) and ground-to-air (G2A) ground-source HP (GSHP) technologies were investigated. UK ASHP and GSHP A2W trials [40] and Nordic ASHP A2A trials [41] have been analysed. Evidence suggested that GSHP and ASHP have seasonal performance factors of 2.55 and 2.1, respectively, and these values were used in this study. In the A2A and G2A configurations, central heating with air distribution was assumed, and for A2W and G2W, the model central hydronic heating was assumed.

2.2.2. Calibration

As illustrated in Fig. 2, the calibration process starts with an initial CAD model of the building with IES software assigning default values to the model parameters of building fabric, systems and setpoints. The results are compared with utility data to ascertain the model performance and check for significant errors such as model holes, dimension interference, or overlapping. The second phase starts with updating the building fabric and primary heating system size, configuration, and operational parameters. The third phase

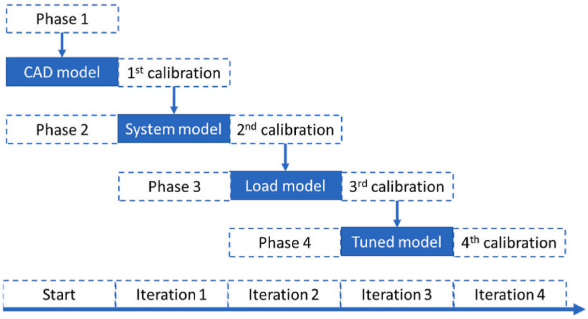

Fig. 2. The model calibration process.

involves adding load profiles and system scheduling. The fourth phase is tuning infiltration rates and scheduling parameters like door openings during occupancy. The calibration could have been done in one-step, but systematic calibration helps to identify parameters that need tuning. Concurrently calibrating all the parameters could output complicated results due to too many parameters affecting the energy balance; any error could cancel the effect of another, and comparison would become questionable.

3. Results and discussion

In order to evaluate the energy consumption and emissions of the buildings, a comparison was made between the baseline utility data acquired from energy audits and the model results in section 3.1. This comparative analysis streamlined quantifying the buildings' energy usage and emissions in the baseline. To evaluate the net zero interventions, it is necessary to comprehend the different energy flow patterns within the building; this is discussed in section 3.2. Subsequently, to quantify the potential for decarbonisation and assess the economic implications of various decarbonisation interventions compared to the baseline results, appropriate decarbonisation interventions are implemented in sections 3.3 and 3.4.

3.1. *Utility data*

Table 5 compares the actual energy consumption and the simulation results. The gas data is positioned outside the square bracket, while the electricity data is placed inside the square bracket for easy identification. The actual results post-2019 reflected the change in usage patterns of these buildings in the post-pandemic. Fig. 3 shows the correlation between the quarterly simulated result and the actual data. The discrepancies in the results were due to clashes in the buildings' operational profiles pre- and post-pandemic and other assumptions, including estimation of electrical loads, such as lighting unit ratings, that were unavailable, hidden electrical loads, such as supplementary electric heating and additional events. In addition, parameters were estimated for unavailable data like ACH, building elements (ceilings and floors), post-2019 heating and occupancy profiles. The weather profile used for the model was the Example Weather Year (EWY) of Newcastle upon Tyne because the EWY of Durham was unavailable in a required format. The EWY used contained winter data colder than the city of interest. However, a milder weather file was of concern as it could underpredict baseline emissions, and the results would be less applicable to colder parts of the UK.

With St Brandon's, the model predicted within 5% with pre-pandemic 2019 annual data. The 2020 gas consumption, as presented in Table 5, declined because of reduced activities due to the pandemic, while the electricity consumption remained unchanged because of electric heating in some of the spaces in the building, which have been running as usual during the pandemic for fabric preservation. St Nicholas' annual data calibrated within 5% with pre-pandemic 2019 data. The high gas consumption is attributed to the large number of services in this city centre church requiring significant heating. The building incorporates multiple heating circuits, and the main space is heated through carpeted underfloor heating, which takes time to warm up the spaces effectively. The activity rooms have thermostatic fan-assisted hydronic radiators and large lights, which led to higher electrical loads. St John's maintains a strict heating profile for fabric conservation and the organ irrespective of building use. As shown in Table 5, gas, and electric consumption in 2021 increased due to a surge in services returning from pre-pandemic restrictions. The quarterly data for 2020 was unavailable, so it was not used in Fig. 3. The predicted results match within 5% of the actual data for 2020. Results show that the Cathedral's gas and electricity consumption remained lower than pre-pandemic levels, and the predicted results were within 7% for gas and 5% for electricity. The difference in the results was because only the main church area was modelled, and spaces attached to the church, like the restaurant, kitchen, and shops, were not considered because their occupancy and heating data were unreliable; hence, some data were underestimated. The lighting system data was also unavailable, and the lighting loads may have been underestimated; however, these underestimations would not significantly affect the results.

3.2. *Energy flow*

The baseline heat losses from the buildings are presented in Fig. 4. Heat loss from external walls, windows, and natural ventilation was dominant in St Brandon's. Draughts and heat loss through the door were very few. St Nicholas' heat loss from the roof dominated as its roof is uninsulated, and there was less heat loss through the windows than in St Brandon's because smaller spaces, such as the shop and activity areas, sheltered the main heated spaces. Carpeted floor and underfloor heating reduced heat loss to the ground. The cathedral had an even distribution of heat loss through windows, walls, ground, roof, and natural ventilation. Most of the ground floor had no underfloor heating, and thus significant heat loss through the ground floor.

Table 5
Modelled and actual annual gas and electricity consumptions.

Building	Modelled gas [electricity] consumption (MWh)	Gas [electricity] consumption in 2018 (MWh)	Gas [electricity] consumption in 2019 (MWh)	Gas [electricity] consumption in 2020 (MWh)	Gas [electricity] consumption in 2021 (MWh)
St Brandon's	86.8 [4.2]	-	91.4 [4.4]	51.7 [4.0]	-
St Nicholas'	166.8 [13.5]	[15.1]	167.1 [13.6]	128.1	-
St John's	34.2 [1.0]	-	-	35.1 [0.9]	40.1 [1.4]
Cathedral	1196.6 [403.4]	-	1948.4 [575.8]	1228.8 [536.2]	1275.1 [420.7]

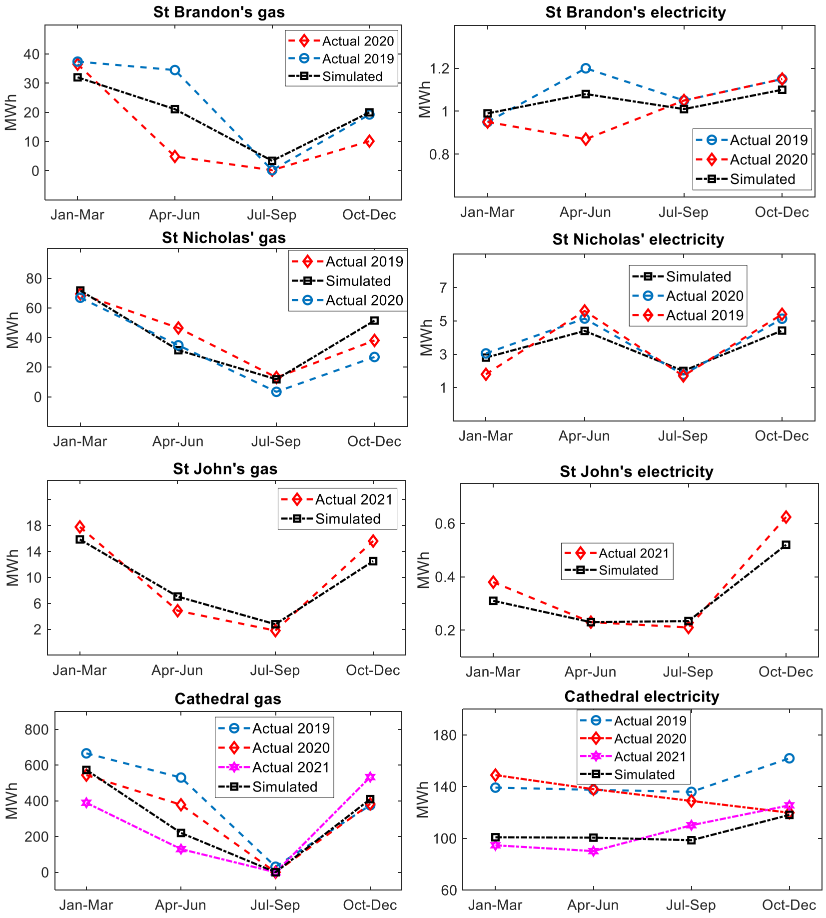

Fig. 3. Utility data calibration.

3.3. *Emissions reduction interventions*

In this study, identifying the path to net zero interventions suitable for each building was based on the practicality of the technology to the available resources, maintenance and building integrity. The interventions were selected for enhanced fabric efficiency, introducing LZC technologies and electrification of heat. The impact of each intervention on the running costs and emissions savings with corresponding investment/capital costs were the focus. In subsequent tables, figures with a negative sign (-) and no sign indicate a decrease and an increase, respectively, compared to the baseline figures presented in Table 6.

3.3.1. *Demand reduction*

Setting the thermostat at the most comfortable temperature is more valuable to some people than others, and understandably, there is a cost to every degree of space heating. Table 7 shows the change in operating cost and emissions when the setpoint was reduced by 1 °C from the initial building setpoints. St Brandon's and St Nicholas' had about 10% emissions reduction, while the Cathedral had about 1%. St Brandon's, St Nicholas', St John's, and Cathedral had operation cost savings of 5.6%, 8.3%, 14.6% and 0.7%, respectively. Compared to the other buildings, the 1% emissions reduction and cost savings associated with the Cathedral resulted from the type of heating installed, the heating time, and the large volume of the Cathedral. It implied that it would take very long before the Cathedral could attain its current setpoint temperature and might not be able to achieve it during the allocated heating period in most cases. This could result from undersized or inefficient heating systems or underdesigned system instrumentation. Replacing incandescent lights with LEDs would reduce electricity demand but would also reduce heat gains and might increase costs (Table 7). As observed in St John's, the cost change in switching to LED was higher than the cost of gas for the increased heat load; this happened because the saved electrical load from switching to LED was PV generated, and the cost of PV export FIT was less than the cost of natural gas to complement the added heat load. While in the other buildings, where there was no PV installation, the cost of buying electricity was always more than natural gas. It implied that it would be more economical to size and optimise electricity demand during occupancy to fully utilise available renewable generation even to electrify heat rather than sending it to the grid. This is because the cost of grid gas that would provide equivalent heating would be more expensive than the export FIT. Entirely replacing incandescent lamps with LED in the Cathedral could yield the most savings, with a reduction in emissions at 13.5% and operational costs at 27.7%, compared to St Nicholas, which yielded a 1% emission and 15.6% operating cost savings. This was attributed to the high

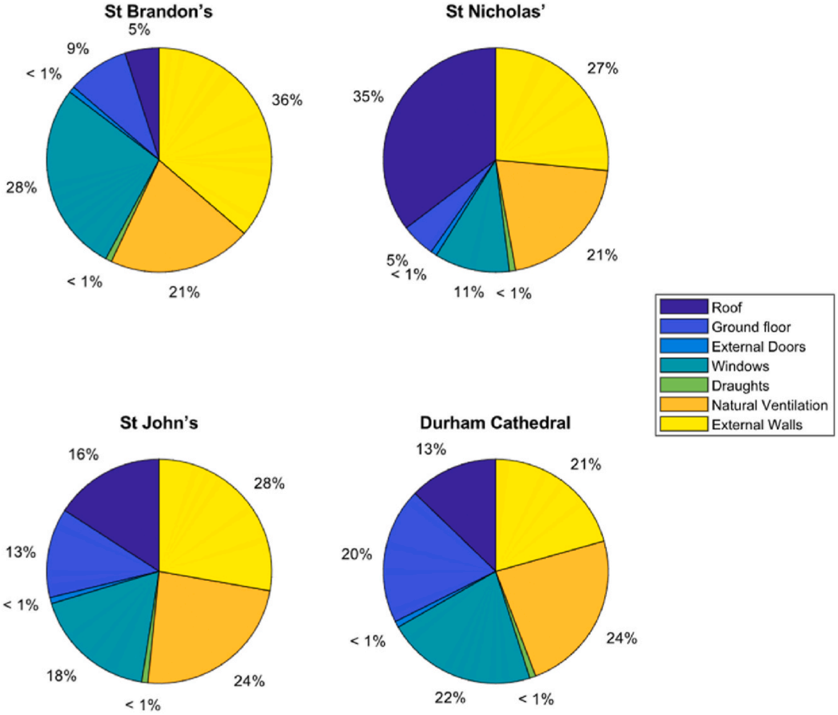

Fig. 4. Heat losses in the buildings.

Table 6
Building features, energy, emissions, and cost in the baseline model.

	Floor area (m^2), [volume] (m^3)	Heating system	LED light	Pews/Roof insulation	Gas [electricity] consumption (MWh)	CO_2 (t/yr)	OC (£10^3)
St Brandon's	540 [3048]	GB + UFH + TH	Yes	No/Yes	86.8 [4.2]	16.9	4.1
St Nicholas'	730 [4923]	GB + UFH	No	No/No	166.8 [13.5]	33.6	6.4
St John's	467 [2166]	GB + radiator	50/50	Yes/Yes	34.2 [0.95]	5.7	3.1
Cathedral	6024 [96225]	GB + UFH + radiator	No	50/50/No	1196.6 [403.4]	305.8	86.9

GB=Gas boiler, UFH=Underfloor heating, TH = Trench heating, OC=Operating cost.

Table 7
Roof insulation, secondary glazing, setpoint and LED.

Buildings	Roof insulation (RI)			Secondary glazing (SG)			Setpoint		Replacing with LED		
	CO_2 (t/yr)	OC (£10^3)	CC[a] (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC[a] (£10^3)	CO_2 (t/yr)	OC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC[a] (£10^3)
St Brandon's	-	-	-	-1.03	-0.15	130	-1.54	-0.23	-	-	-
St Nicholas'	-5.31	-0.80	36.2	-0.5	-0.073	77	-3.62	-0.53	-0.33	-1.0	18.7
St John's	-	-	-	-0.06	-0.038	41	-0.66	-0.46	-0.01	0.026	6.2
Cathedral	-11.9	-2.5	202.5	-13.05	-2.7	1003	-2.99	-0.62	-41.3	-24.1	133.5

CC = capital cost.
[a] Cost of scaffolding was omitted.

occupancy and larger floor area of the Cathedral.

Improving the fabric efficiency of a building through roof insulation could save energy and reduce heat loss but required feasibility assessment as each building is different. The baseline roof insulation and secondary glazing features are presented in Table 7 and Appendix B. While roof insulation could save 16% emissions and 12% running cost on St Nicholas', it was 3.8% and 2.8% for the Cathedral. This wide variation in result was due to the average roof height in the Cathedral, which was 16 m and 6.7 m for St Nicholas'; therefore, more heat loss occurred through the walls in the Cathedral than the roof and vice versa for St Nicholas'. The baseline buildings' windows were mainly single-glazed, accounting for 10–28% of the total heat loss. Replacing these windows with double-glazed could be the most practical approach. However, replacing the original windows was not permitted for most historic churches. An alternative approach was to add an internal secondary glazing element to reduce the overall U-value for the window element. Heat loss through the window was the highest in St Brandon's, 28% and in Cathedral, 22% of the total loss (see Fig. 4); however, just about 6% and 4.2% of emissions and 3.6% and 3.1% in cost, respectively, could be saved with secondary glazing and with substantial capital costs. Secondary glazing was the least economically attractive demand reduction method due to custom design and non-unplasticised polyvinyl chloride cabinetry requirements, making it much more expensive. Some quotations indicated that the cost could be twice that of domestic windows.

3.3.2. *Low and zero carbon technologies*

Analysis of implementing relevant LZC technologies, including PV, biomass, hydrogen, and green tariffs, focused on emissions and costs compared with the baseline and are in Table 8. Additional maximum PV added to St John's baseline and new installations on the other buildings were calculated with SEG tariff because FIT was no longer available to new installations. All the buildings could achieve net zero with green tariffs, but there could be cost implications. 100% hydrogen nearly achieved net zero in the buildings and integrating PV with biomass or hydrogen achieved net-zero in the buildings except for the Cathedral. However, given the timeline of the Church of England's net zero targets of 2030, it seemed doubtful that a 100% green hydrogen supply would be available, and that safety and risk policies be developed for such buildings. There are no cost savings on all the LZC interventions except for PVs, and operating costs were high in green tariffs and 100% hydrogen, while there was a huge capital cost on biomass. However, there was an exception in operation costs for St John's, as the cost decreased from baseline with every intervention. The reasons were that St John's had PVs installed and received generation and export FIT and again had a high electricity and gas tariff more expensive than biomass, 100% hydrogen and green tariffs (see Table 4). St John's would offset more emissions than the baseline emissions with biomass and 100% hydrogen because the installed PV emissions offset, and the electrical demand in the building is 2.7% of the total energy demand, which the installed PV could provide. Therefore, decarbonising only heat in St John was enough to achieve net zero. There could be practical operation and storage issues with biomass intervention in some of the church settings, as discussed in 3.4.

3.3.3. *Electrifying heat*

Because the electricity grid is rapidly decarbonising and will continue, various technologies are becoming popular to electrify heat, even though electricity costs are currently higher than gas. Therefore, electrifying heat is a potential means of achieving carbon neutrality in heritage buildings. Pew and radiant heaters, direct electric boilers, electric radiators and HPs were investigated in this study. Emissions and costs associated with pew heaters, radiant heaters, electric boilers, and electric radiators are presented in Table 9. Pew, radiant and electric radiator heating were all scheduled with occupancy, while the electric boiler was scheduled with the baseline heating profile. Results in Table 9 suggested that electrifying through Joule heating favoured buildings with a high ratio of baseline gas demand (97.3%, 95.4%, 92.5%, and 75%, for St John's, St Brandon's, St Nicholas', and Cathedral, respectively) from the total building energy demand. At the same time, pew and radiant heaters would benefit buildings with small volumes and high heating demand, like St John's and St Brandon's, with 2166 m^3 and 3048 m^3 volume and 97.3% and 95.4% of energy demand used for heating, respectively. Electric boilers and pew heaters seemed the least and most attractive electrifying through Joule heating interventions, respectively, based on operation costs and emissions offset.

In heat electrification through HPs, central heating with air distribution was assumed in the A2A and G2A HPs, and the baseline central hydronic heating was assumed for the A2W and G2W HPs systems. The hydronic HPs operate at lower temperatures and thus would require modification to existing systems, like replacing the existing radiators with larger radiators to deliver equivalent heat transfer by boilers. These modification costs were excluded from the capital cost presented in Table 10. There could be challenges deploying HPs to the various buildings ranging from unavailability of lands for the GSHP to installing air ducting for A2A and G2A systems; these are discussed case-by-case in 3.4. The GSHP offset more emissions and showed economic benefits in operating costs compared to the ASHP; however, it had higher capital costs. The non-hydronic (G2A and A2A) systems could offset more emissions and be more economical than the hydronic (G2W and A2W) systems, especially in systems with shorter heating times like St Nicholas', St Brandon's, St John's, with 13, 19 and 21 h per week, respectively. In contrast, the hydronic system favoured buildings with higher heating times, like the Cathedral, with 66.5 h of weekly heating because it took more time to warm the water in the heating circuit.

3.4. *Paths to net zero*

The pathway to decarbonising historical church buildings can be challenging because of heritage preservation. While every building needs to identify its interventions depending on the users, building feasibility/viability, planning requirements, and financial affordability, a structured approach (see Fig. 5) is essential for selecting appropriate interventions. Demand reduction is the most basic,

Table 8
Emissions and costs of PV and biomass boiler, 20% and 100% hydrogen, and green tariff.

Buildings	PV			Biomass			20% hydrogen		100% Hydrogen			Green tariffs	
	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)
St Brandon's	-3.04	-1.2	18.0	-14.61	0.55	51.0	-3.19	0.48	-15.96	1.75	23.4	-16.9	9.26
St Nicholas'	-2.25	-1.5	13.5	-28.44	1.5	67.0	-6.14	0.93	-30.69	4.67	15.6	-33.6	19.70
St John's	-1.71	-0.21	13.3	-5.79	-3.8	43.0	-1.26	-0.49	-6.29	-3.20	9.1	-5.7	-0.92
Cathedral	-8.56	-4.3	66.6	-195.6	3.6	833.0	-44.04	4.01	-220.2	15.86	182.0	-305.8	25.92

Table 9
Emissions and costs for pew heaters, radiant heaters, electric boilers, and electric radiators.

Buildings [Tariff] (p/kWh)	Pew heaters			Radiant heaters			Electric boilers			Electric radiators		
	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)
St Brandon's [16.04]	-8.56	-0.47	7.4	-7.47	0.40	13.2	2.23	10.73	5.3	-13.63	-0.62	10.0
St Nicholas' [14.17]	-8.48	2.85	11.2	-7.91	6.01	12.8	-0.31	15.77	6.0	-14.64	6.21	15.3
St John's [50.7]	-2.13	-1.70	3.7	-2.62	-0.81	8.8	0.43	9.64	5.1	-2.65	3.03	9.8
Cathedral [9.11]	-69.47	7.97	30.9	42.34	58.30	178.4	46.74	64.50	21.7	43.03	67.40	14.7

Table 10
Emissions and costs for various HPs technology.

Buildings	ASHP					GSHP				
	CC (£10^3)	A2W		A2A		CC (£10^3)	G2W		G2A	
		CO_2 (t/yr)	OC (£10^3)	CO_2 (t/yr)	OC (£10^3)		CO_2 (t/yr)	OC (£10^3)	CO_2 (t/yr)	OC (£10^3)
St Brandon's	49	-6.95	3.79	-14.39	-1.83	70	-8.91	2.31	-14.67	-2.04
St Nicholas'	66	-16.36	5.06	-21.37	1.71	95	-18.89	3.37	-22.37	1.05
St John's	42	-3.12	1.17	-3.82	-0.50	61	-3.69	-0.20	-4.01	-0.96
Cathedral	542	-91.63	5.17	-80.63	9.88	783	-113.42	-4.17	-94.83	3.80

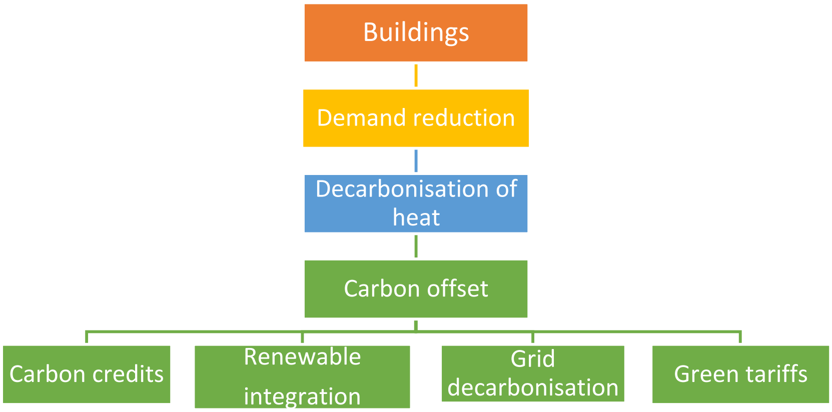

Fig. 5. Stages of building decarbonisation.

followed by the decarbonisation of heat and options for carbon offset from the integration of renewables, carbon credits, green tariffs, and decarbonisation of the power grid. The assessment for various heating technologies was categorised into two configurations: Configuration 1; replacing the gas boiler with another technology and continuing to use the existing hydronic heating, and Configuration 2; replacing the current heating system with warm air or radiant heating systems.

3.4.1. Case study 1—St Brandon's

Table 11 summarises the outcomes of the assessment. For configuration 1, emissions could be reduced by 95% with 100% green hydrogen and 85% with biomass. However, biomass would need high capital costs, and concerns over operation and storage require careful planning. A G2W HP could reduce emissions by 50%. However, it would require agreements with adjacent landowners because St Brandon is an ancient church with burials and an archaeologically sensitive site, which would further increase the cost of HP technology. Similarly, an A2W HP would reduce emissions by 41%; therefore, different carbon-offset strategies would be required to achieve net zero with HPs. There was no payback for any technology in Configuration 1, as operating costs were above the baseline. With Configuration 2, HP technologies reduced emissions and operating costs by at least 85% and 44%, respectively. This was feasible if the trench vents in the church were utilised for warm air distribution; if new ducting was needed, it could make HP technology unattractive.

The UK electricity grid comprises 34% renewable [42], low-carbon electricity is projected at 83% by 2040 [43], and electric grid CI was estimated at 76 g CO_2e/kWh by 2035 [44]. That implied that for the same PV generation in 2022, the grid displaced emissions in

Table 11
Summary of various heating technologies with St Brandon's baseline.

Configuration 1				Configuration 2			
Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)
Electric boiler	2.23	10.7	5.3	Radiant heater	-7.47	0.40	13.2
20% hydrogen	-3.19	0.48	0	Electric radiator	-13.63	-0.62	10.0
A2W	-6.95	3.8	48.5	A2A	-14.39	-1.8	48.5
G2W	-8.91	2.3	70.1	G2A	-14.67	-2.0	70.1
Biomass	-14.61	0.60	51.0	Pew heating	-8.56	-0.54	18.0
100% hydrogen	-15.96	1.8	23.4				

2022 would be higher than what they would be in 2035 when the power grid CI would be low. Investigating whether investing in PV for emission offset would be economical in achieving net zero or better to let the grid decarbonise, leading to decarbonised electric heating over time, was essential. Results indicated (see Table 12) that long-term PV investment was suitable because local renewable generation would continue to be profitable even if it would offset fewer emissions in the future as the grid decarbonised. Heating emissions would reduce by 2035 and approach net zero through electric radiators as the power grid decarbonised over time. Integrating with PV could achieve the net zero goal quicker than waiting to decarbonise the grid in 2035. PV at a maximum capacity would offset 3 tonnes of emissions annually and reduce the operating cost through export tariffs. Integrating PV with other technologies, such as electric radiators, biomass, and non-hydronic HPs, would achieve net zero, as indicated in Table 12. Carbon credits could accomplish a similar emission offset if PV were not affordable. Green tariffs were not an economical solution for emission offset, as their unit rate was more than double the current building tariff. The investment decision would depend on the technology's acceptability and cost.

3.4.2. Case study 2—St Nicholas'

St Nicholas' is in the City Centre with higher intermediate usage. With the Configuration 1 scheme, as shown in Table 13, 100% hydrogen and biomass could reduce emissions by 91% and 85%, respectively. The G2W HP would require agreements with adjacent landowners because of its location, and there seemed no potential adjacent land for this technology to be feasible, while the A2W HP costs were high and could only reduce emissions by 49%. Configuration 1 offered no payback, and operating costs were above the baseline. The configuration 2 systems showed that electric radiators could reduce emissions by 45%, with similar operational costs to radiant heaters. The A2A HP performed better than A2W HP, as it could reduce emissions by 65% and cost thrice less on annual operating costs than A2W HP. An air distribution system would be required for the A2A HPs, which might be challenging as overhead ducting is not preferred in such buildings. However, smaller ducts could be placed underfloor to supply heating. As the power grid was decarbonised (Table 14), emissions would approach net zero through HPs in 2035. PV would offset 2.25 tonnes of emissions annually and reduce operating costs through FIT with a payback of 9 years. PV integrated with demand reduction and HPs or biomass/100% hydrogen would achieve 75% emissions reduction and net zero, respectively. Like St Brandon's, green tariffs were more than double the current building tariff and might not be considered economical.

Table 12
Emissions offset through power grid decarbonisation and with PV.

Offset through grid decarbonisation			Offsetting with PV			
Technology	2022 CO_2 (t)	2035 CO_2 (t)	Configurations	CO_2 (t)	OC (£10^3)	CC (£10^3)
Baseline	16.9	16.3	Baseline	16.9	4.1	-
Radiant heaters	9.43	7.2	PV + Electric radiator	-16.7	1.2	28.0
Electric radiators	3.27	1.2	PV + Biomass	-17.6	-0.66	69.0
Biomass	2.29	0.85	PV + G2A	-17.7	-3.9	88.1

Table 13
Summary of various heating technologies with St Nicholas' baseline.

Configuration 1				Configuration 2			
Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)
Electric boiler	-0.31	15.8	5.3	Radiant heater	-7.91	6.0	12.2
20% hydrogen	-6.14	0.93	0	Electric radiator	-14.64	6.2	15.3
A2W	-16.36	5.1	65.7	A2A	-21.37	1.7	65.7[f]
G2W	-18.89	3.4	94.9	G2A	-22.37	1.1	94.9[f]
Biomass boiler	-28.44	1.5	67.0	Pew heating	-8.48	2.9	11.2
100% hydrogen	-30.69	4.7	15.6				

[f] cost of ducting not included.

Table 14
St Nicholas' emissions offset through power grid decarbonisation and with PV.

Offset through grid decarbonisation			Offsetting with PV and demand reduction			
Technology	2022 CO_2 (t)	2035 CO_2 (t)	Configuration	CO_2 (t)	OC (£10^3)	CC (£10^3)
Baseline	33.6	31.7	Baseline	33.6	6.4	-
Radiant heaters	25.69	15.0	PV + LED + RI + A2W + SG	-24.7	-0.53	211.1
Electric radiators	18.96	6.8	PV + LED + RI + G2A	-26.6	-1.8	163.3
A2W	17.24	6.2	PV + LED + RI + biomass	-32.7	-1.3	135.4
A2A	12.23	4.4	PV + LED + RI + 100% Hydrogen	-32.9	3.2	84

3.4.3. Case study 3—St John's

St John's could achieve negative emissions with 100% hydrogen or biomass, with over 100% operating cost savings and 3 and 11 years of payback, respectively, though because of the building's high energy tariff and with contribution from PV FIT, as explained in 2.2.1. A GSHP was feasible, as shown in Table 15, because there is a lawn with the potential for such an installation, and it could reduce 65% of emissions. The ASHP could reduce emissions by 55% with increased operating costs. Further emissions offset strategy was required to achieve net zero with HPs. The electric boilers increased emissions and operating costs by 7.5% and 300%, respectively. Assessment of Configuration 2 solutions showed that pew heating had a payback of two years and would save 37% of emissions and 54% of operating expenses. Radiant heaters could achieve 46% and 26% savings in emissions and operating expenses, respectively, with a payback of 11 years. ASHP and GSHP would reduce emissions by 65% and 70% and operating costs by 16% and 30%, respectively. Emissions offset with the biomass and 100% hydrogen were more than the baseline because of additional offset by the building's installed PV (Table 15). Further integration with maximum PV capacity on the church roof would offset 1.71 tonnes of emission annually and save 6.7% of operating costs. Table 16 indicates that St John's baseline emissions would increase to 6.1 tonnes by 2035 despite grid decarbonisation. This was because the installed PV would offset fewer emissions as the grid was decarbonised than it could offset presently. However, emissions would reach net zero through radiant heaters and electric radiators by 2035 through grid decarbonisation. Another means to achieve net zero would be PV integrated with ASHP and green tariffs, as shown in Table 16. The energy tariffs for St John's were more expensive than the green tariffs and switching to green energy would achieve net zero with annual operating costs savings of 29%.

3.4.4. Case study 4—Cathedral

The results for the Cathedral are presented in Table 17. With 100% green hydrogen, emissions could reduce by 72%. This points to the high electricity demand in the Cathedral, which meant a 100% decarbonisation of heat was not enough, and the Cathedral's electricity must decarbonise to achieve net zero. Biomass could reduce emissions by 64%; however, they would require high capital costs, and operation and storage requirements would need careful planning. The G2W GSHP could reduce emissions by 37% and was the only option in Configuration 1 that offered operational cost savings. The Cathedral is an archaeologically sensitive site; therefore, it would likely be unsuitable for GSHP. A ventilation system exists in the Cathedral. Configuration 2 solutions could save 30% and 26% of emissions, with 4.4% and 11% increased operating costs for A2A and G2A, respectively. Generally, Configuration 2 technology would save fewer emissions and have higher costs per emissions savings than Configuration 1 for the Cathedral and the opposite effect with St Brandon's.

Because of the Cathedral's high-energy demand resulting from high usage, multiple sections, and large air mass, different offset strategies would be required to achieve net zero. Analysis of the effect of grid decarbonisation by 2035 showed that HPs and biomass would reduce emissions by 75% and 83%, respectively, as shown in Table 18. The maximum PV installation on the Cathedral roofs

Table 15
Summary of various heating technologies with St John's baseline.

Configuration 1				Configuration 2			
Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)
Electric boiler	0.43	9.6	5.1	Pew heating	-2.13	-1.7	3.7
20% hydrogen	-1.26	-0.5	0	Electric radiator	-2.65	3.0	9.8
A2W	-3.12	1.2	42.0	A2A	-3.82	-0.5	42.0
G2W	-3.69	-0.12	60.7	G2A	-4.01	-0.96	60.7
Biomass	-5.79	-3.8	43.0	Radiant heater	-2.62	-0.8	8.8
100% hydrogen	-6.29	-3.2	9.1				

Table 16
St John's emissions offset through power grid decarbonisation and with PV.

Offset through grid decarbonisation			Offsetting with PV and green tariff			
Technology	2022 CO_2 (t)	2035 CO_2 (t)	Configurations	CO_2 (t)	OC (£10^3)	CC (£10^3)
Baseline	5.7	6.1	Baseline	5.70	3.2	-
Pew	3.57	3.5	PV + A2A	-5.53	-4.6	55.3
Radiant heaters	3.08	2.6	PV + G2A	-5.72	-5.0	74.3
Electric radiator	3.05	1.1	Green tariff	-5.70	-2.2	-

Table 17
Summary of various heating technologies with the Cathedral baseline.

Configuration 1				Configuration 2			
Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)	Technology	CO_2 (t/yr)	OC (£10^3)	CC (£10^3)
Electric boiler	46.7	64.5	21.7	Radiant heaters	42.3	58.3	169.5
20% hydrogen	-44.0	4.1	-	Electric radiators	43.0	67.4	146.8
A2W	-91.6	5.2	541.8	Pew heaters	-69.5	78.0	27.6
G2W	-113.4	-4.2	782.6	A2A	-80.6	9.9	301.0
Biomass	-195.6	3.6	833.0	G2A	-94.8	3.8	481.6
100% hydrogen	-220.2	15.9	182.0				

Table 18
Emissions offset through PV and power grid decarbonisation.

Offset through grid decarbonisation			Offsetting with PV			
Technology	2022 CO_2 (t)	2025 CO_2 (t)	Configurations	CO_2 (t)	OC (£10^3)	CC (£10^3)
Baseline	305.8	250.8	PV + LED + RI + A2W + SG	-171	-28.9	1947.4
Pew heaters	235	117	PV + LED + RI + Pew heaters	-137.8	-22.0	430.2
A2W	214	77	PV + LED + RI + A2A	-150.5	-20.0	703.6
G2W	192	69	PV + LED + RI + A2W	-159.4	-23.9	944.4
A2A	225	80	PV + LED + RI + G2A	-166.8	-27.1	884.2
G2A	211	76	PV + LED + RI + G2W	-183.6	-34.3	1185.2
Biomass	110	52	PV + LED + RI + Biomass	-274.8	-25.6	1235.6

could reduce emissions by 8.56 tonnes. Demand reduction integrated with PV and biomass could reduce emissions by 90% (Table 18). However, there has yet to be a confirmation that much roof area would be allowed for PV installation. If PV installation would be allowed, PV integrated with biomass, LED and RI could achieve net zero by 2035 with grid decarbonisation. The green tariff rates were four times more expensive than the Cathedral tariffs.

3.5. Summary and insights

Demand reduction and decarbonising heat are essential in achieving net zero heritage church buildings, especially in this part of the world where heating is of primary energy demand. Renewable integration or electric grid decarbonisation would be required in cases where electric demand was high to achieve net zero. An appropriate heating system for net zero would depend on the building type and its operation pattern, and no single solution can suit all heritage church buildings. A reduction in setpoint temperature would reduce demand with no costs; however, it affected occupants' comfort. Secondary glazing would save fewer emissions than the setpoint reduction and cost more; thus, it might not be considered adequate in some cases as lots of heat loss occurred through the walls, which cannot be insulated. Switching to LED would have the most negligible capital costs of the demand reduction interventions, except for setpoint reduction. In small and low-use churches like St Brandon's, the Configuration 2 scheme was a more economical and practical route to decarbonisation, especially the HPs technology with PV offset. In small and high-usage churches like St John's, Configurations 1 and 2 were effective; however, Configuration 2 would require further offset with PV. In large and high-usage churches, like the Cathedral, HPs or biomass could significantly reduce emissions. A 100% hydrogen achieved 72% decarbonisation, which suggested that a 100% decarbonisation of heat was not enough in cases with high electricity demand, and the electricity must decarbonise to achieve net zero. GSHP would be inappropriate for some heritage buildings because of the sensitive nature of the land around them, and non-hydronic HPs would require air distribution ducting systems, which might affect the church's interior. Demand reduction through setpoints and LED would need to consider occupants' thermal comfort and the effect of local PV generation, respectively. As observed in St John's, with local PV generation, a reduction in electricity demand through LED intervention led to increased operating costs.

Further analysis shows that for buildings with high electricity demand, more than decarbonising heat would be needed to achieve net zero; this indicates the necessity of decarbonising the electricity grid, particularly when there is limited potential for generating sufficient internal renewable energy. In cases where a building's electrical demand is low and can be met by internal renewable generation, decarbonising heat alone would be adequate to achieve net-zero emissions. Joule heating technology was most beneficial for buildings relying significantly on natural gas as energy demand. Pew and radiant heaters were particularly beneficial for smaller buildings with a high ratio of gas demand compared to total energy demand. Electric boilers were considered the least attractive option, while pew heaters were the most appealing regarding cost-effectiveness and emissions reduction. With heat pump technologies, ground-source heat pumps demonstrated greater emission reduction and lower operating costs than air-source heat pumps, albeit with higher initial capital costs. Non-hydronic heat pump systems were more efficient and cost-effective than hydronic systems, especially in buildings with shorter heating periods. Contrarily, hydronic systems were more suitable for buildings with longer heating durations due to the additional time required to warm the water in the heating circuit.

Energy retrofits in heritage buildings are seldom deployed due to planning restrictions and finance and, in most cases, reluctantly due to a lack of tools and case study data to assess the impact and feasibility assessment criteria, such as emission reduction effectiveness and return on investment. Secondly, quantifying the benefits of decarbonisation measures through consistent methodology is essential for achieving evidence-based net zero planning for heritage buildings. This study addressed these gaps by analysing various technology configurations on heritage building stocks to assess the holistic impact on energy, cost, and emissions metrics. The results have demonstrated the prospects and challenges of reducing emissions and highlighted the importance of tailoring heating systems to specific building types, operational patterns, and the availability of low-carbon grid electricity or on-site renewable power.

3.6. Conclusions

Knowledge in decarbonising heritage church buildings is hindered by a lack of case studies using site data to assess possible interventions, impact, and feasibility. Heritage church buildings remain significant energy consumers and carbon emitters; it is imperatively challenging for heritage church buildings to achieve net-zero targets by 2030 due to their construction materials, building designs, planning restrictions, and finance. Aiming to provide heritage church buildings a clear decarbonisation pathway, this study explores decarbonisation interventions (through demand reduction, low-carbon technologies, and electrifying heat) for four distinct heritage church buildings. The results show that:

- For small church buildings with light usage, heat pump-based systems and biomass boilers would be the most economical, with fewer emissions.
- Heat pump-based systems would demonstrate strong performance for small church buildings with intermediate usage; however, biomass and hydrogen would deliver the greatest cost and emissions savings.
- For large church buildings with high usage, biomass and hydrogen would offer significant emissions savings and be competitive in running costs with heat pumps.

Due to the unique characteristics of individual heritage church buildings, there is no one-size-fits-all solution. This study would help heritage building management define a plan of action for decarbonisation by estimating emissions and costs. The study also reports that decarbonising heat alone would be adequate to achieve net-zero emissions if a building's electrical demand is low and can be met by internal renewable generation; however, decarbonising the electricity grid is necessary to achieve net zero for buildings with high electricity demand, particularly when there is limited potential for generating sufficient internal renewable energy. Future studies shall investigate setback heating and fabric conservation, which are not covered in this study but could be an essential factor in determining net zero alternatives, particularly in cases that require strict control of temperature and humidity.

Authors' statement

Yousaf Khalid: Methodology; Software; Data Curation; Formal analysis; Validation; Project administration; Writing-original draft.

Ugochukwu Ngwaka: Data curation; Investigation; Formal analysis; Validation; Writing-original draft; Writing-review and editing.

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Andrew Smallbone: Conceptualisation, funding acquisition, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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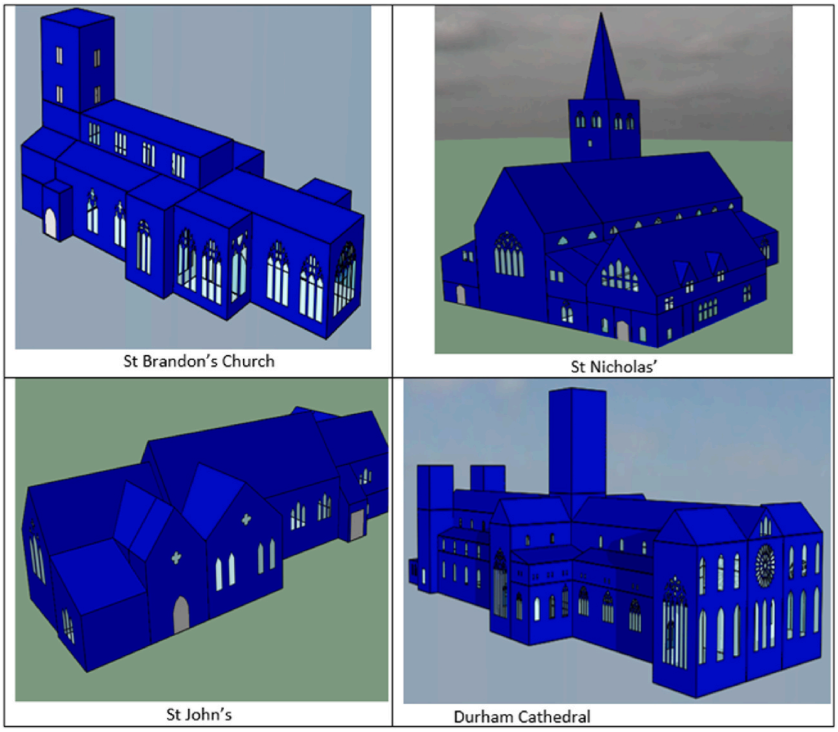
Appendices.

Appendix A

Source: The Church of England (www.achurchnearyou.com)

Fig. A.1. Pictures of the church buildings used in the case study, type A, St Brandon's Church, type B, St Nicholas', type C, St John's and type D, Durham Cathedral.



St Brandon's Church

St Nicholas'

St John's

Durham Cathedral

Fig. A.2. 3D models of the buildings.

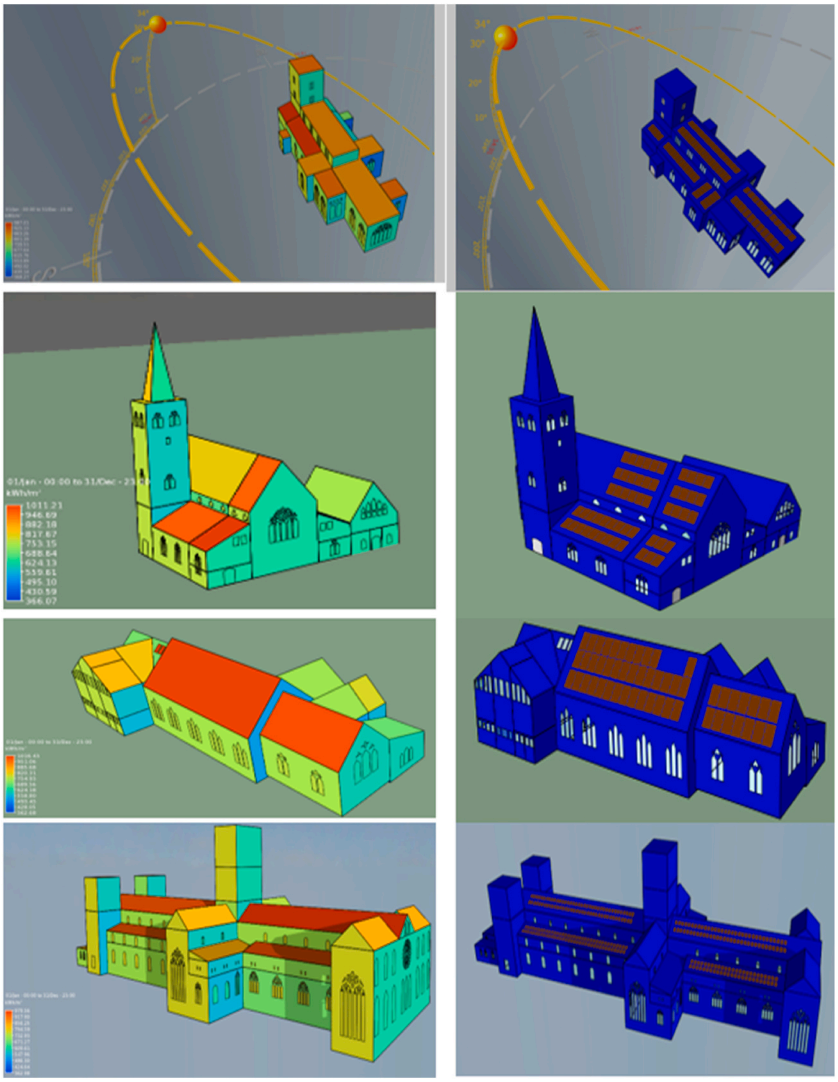


Fig. A.3. Solar shading analysis and PV installation.

Appendix B

Table B.1
Heat loss from building under old and new roof installations.

	Insulated roof	Heat loss (%)	Baseline roof U-value (W/m^{2}K)	Roof area (m^2)	New roof U-value (W/m^{2}K)	New heat loss (%)	CO$_2$ (t/yr)	OC (£/yr)
St Brandon's	Yes	5	0.45	469	-	-	-	-
St Nicholas'	No	36	2.16	882	0.64	15	-5.31	-779
St John's	Yes	16	0.64/0.45	398/140	-	-	-	-
Cathedral	No	13	3.30/4.1	4938	0.58/0.65	6	-11.9	-2463

Table B.2
Cost of various insulations [45].

Rendered insulation	£21.94/m^2
Fibreglass insulation	£20/m^2 (including installation)
Insulation boards/insulation panels	£20–25/m^2 (including installation)
Rock wool	£30/m^2 (including installation)
Spray foam insulation (PUR)	£30/m^2

Table B.3
Cost of roof insulation installation.

	Roof area (m^2)	Cost (£/m^2)	Capital and installation + scaffolding cost (£)	Comments
St Brandon's	469	25 + 16	11,725 + 7504 = 19229	Installed already
St Nicholas'	882	25 + 16	22,050 + 14112 = 36,162	
St John's	538	25 + 16	13,450 + 8608 = 22,058	Installed already
Cathedral	4938	25 + 16	123,450 + 79008 = 202,458	

Table B.4
Heat loss from windows.

	Secondary glazing (Yes/No)	Heat loss (%)	Baseline window U-value (W/m^2K)	Window area (m^2)
St Brandon's	No	28	5.22	130
St Nicholas'	No (church), yes (extension)	11	5.22/1.86	77/20
St John's	No (church), yes (extension)	18	5.22/1.5	41/24
Cathedral	No	22	5.22	1003

Table B.5
Reduction in U value, heat loss, CO_2, and cost savings.

	New window U-value (W/m^2K)	New heat loss (%)	CO_2 (t/yr)	OC (£/yr)
St Brandon's	2.9	17	-1.03	-154.08
St Nicholas'	2.9/1.86	6	-0.5	-72.98
St John's	2.9/1.5	12	-0.06	-38.1
Cathedral	3.04	12	-13.05	-2694

Table B.6
Secondary glazing capital costs.

	Window area (m^2)	Cost (£/m^2)	CC (£)
St Brandon's	130	1000	130,000
St Nicholas'	77/20	1000	77,000
St John's	41/24	1000	41,000
Cathedral	1003	1000	1003,000

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