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Contemporary Challenges for Heating Historic Church Buildings from the Late 19th and Early 20th Centuries

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Abstract: Over the past two decades, the construction and architectural industries have increasingly recognized the need to create and maintain a sustainable built environment. This approach emphasizes reducing greenhouse gas emissions and maximizing energy efficiency to minimize environmental impact. Implementing such solutions in new constructions is relatively easy. However, these buildings represent a small fraction of the overall built environment. Most of the built environment is composed of existing facilities, many of which were constructed before the enactment of current environmental regulations or even before the establishment of any standards. Historical objects present a particularly challenging category in this context. The uniqueness of these structures lies not only in their altered or original functions, but also in their vital role as custodians of history and their contributions to the evolution of architecture and art. Consequently, aligning these buildings with sustainability requirements, or even approximating them, is an intricate task. Common approaches are exempting these buildings from adhering to any standards or applying only the most basic and limited criteria. However, this can adversely affect the usability of these structures and the conservation of historically significant construction elements and artifacts. Introducing new solutions into these existing structures presents additional conservation challenges. This article examines the energy efficiency challenges facing three churches in central Poland. The churches exemplify the predominant Christian religious denominations in Middle–Eastern Europe. This study analyzes the architectural characteristics of these churches and includes energy calculations to validate the effectiveness of proposed energy-efficiency measures.

Keywords: 20th-century churches; historical religious architecture; heating of historical churches; primary energy index; final energy index; useful energy index

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1. Introduction

Heating historic churches built in the late 19th and early 20th centuries is a complex problem that requires balancing the imperatives of historical preservation and modern energy efficiency concerns. There is widespread consensus on the need to create and maintain a sustainable built environment by reducing carbon emissions, maximizing energy efficiency, and generally minimizing the environmental impact of buildings. This approach has been adopted in the design and construction of new buildings. However, most built environments consist of existing facilities created before the currently applicable regulations were introduced, or even before any standards were established. Historical objects present a particular challenge. In addition to their current social functions, which may differ from their original intended purposes, they also serve as vital witnesses to history and as tangible evidence of the evolution of architecture and art. This dual role raises significant conservation challenges, necessitating a careful balance between preserving their historical essence and adapting to contemporary needs. Moreover, it is often important to preserve not only the general character of historical buildings, but also detailed formal solutions and original elements. For these reasons, implementing even partial modifications to improve sustainability can be difficult. The EU has introduced energy-saving directives that guide the implementation of sustainable solutions in cultural heritage sites [1].

Churches built during the turn of the 19th and 20th centuries are significant cultural monuments in European cities. However, their use has been limited or changed due to secularization, which requires adapting them to modern expectations while still maintaining their aesthetic and physical condition. This can be achieved by stabilizing the microclimate inside, preventing excessive cooling of walls and rising dampness, and ensuring thermal comfort. This article will present effective solutions that help to maintain the church's structural integrity and prevent damage to the works collected in the interiors. Selected examples of churches will be analyzed and the effectiveness of proposed energy-efficiency measures using a comparative approach to calculating energy indicators will be assessed. A novelty for this type of historic building is the assessment of energy indicators, which is not required by law. Nevertheless, it shows the effectiveness of actions aimed at reducing energy consumption in this type of large-scale building. The data obtained will contribute to developing a catalog of solutions that can be used for similar facilities and improve design work, ensuring effectiveness in solving the problems raised in this article.

Churches of various denominations hold special social and sentimental significance. They often serve as tangible reminders of a region's past and its connection to broader historical narratives. However, they also continue to play a vital role in the communal life of society. Religious heritage plays an important role in defining people's identity [2], providing not only a shared belief system, but also a common historical narrative. Churches can contribute to build social cohesion [3], as well as to culture and the emotional well-being of communities. Church buildings, with distinctive architecture and prominent locations, are also typically integral to the cityscape. For these reasons, in Europe, churches are widely perceived as having economic, historical, social, and architectural value [2]. Yet, while churches from 200–300 years ago are generally perceived as valuable regardless of their actual impact on the history of culture and architecture, buildings that are 100 years old or younger often do not receive the recognition and attention they deserve.

While many churches feature beautiful and intricate designs, they were not always built with energy efficiency in mind. As a result, heating these structures can be challenging, particularly during the winter months. This is especially important in temperate climates, where winter is associated with negative temperatures and relatively high humidity. Under such climatic conditions, the heating of historic churches becomes a significant issue [4–8]. Historical buildings must also be protected from the effects of climate change [9].

The challenge of preserving and maintaining church buildings according to sustainability principles is further amplified by the fact that churches often house valuable artifacts, including sculptures, paintings, polychromes, and musical instruments like organs, which are themselves of historical importance.

There is currently little research on protecting historical buildings against factors that, while less severe in the short term, are still harmful due to their long-term influence. One such factor is heating and its impact on the structure and interior design elements of buildings through the changes in humidity. There has also been little consideration of strategies for adjusting buildings to contemporary legal and, more importantly, social requirements, without diminishing their positive social and economic functions. Most research has concentrated either on older objects of high historical value or buildings that currently function as tourist attractions, rather than centers of worship or culture.

Much research on the heating of historic churches has focused on buildings dating back far before the 20th century [10]. The small amount of research that has concentrated on newer churches is mostly concerned with stone, brick, and wood structures. Reinforced concrete structures from the turn of the 19th and 20th centuries have received relatively little attention. Yet, these reinforced concrete structures often continue to serve their primary functions as religious buildings and play significant roles in the local community. Moreover, these churches usually feature interior elements with high aesthetic and historical value, requiring careful preservation strategies.

Churches built from reinforced concrete differ markedly in terms of their thermal characteristics from Gothic, Renaissance, Baroque, or Classical churches. Buildings from this newer era encompass a vast array of architectural styles, often drawing inspiration from past historical styles. These styles were considered aesthetically interesting and appropriate for the religious function of such buildings. Examples of this architectural diversity can be found in almost every European country, as well as in the Americas and other regions influenced by European architecture. European churches in this category include Capernaum Church (Berlin), St. Joseph's Church (Podgorze, Cracow), St. Nicholas Russian Church (Bucharest), St. John's Church (Malmö), and Gustaf Vasa Church (Stockholm). Numerous examples can also be found in the UK, including Christ Church (Brixton Road, Lambeth, London), St. Barnabas Church (Walthamstow, London), and Church of the Annunciation, (Bournemouth). Here, we examine three churches situated in the Polish city of Lodz: St. Matthew's Church (A; Figure 1), the Catholic Cathedral of St. Stanislav Kostka (B) (Figure 2), and the Orthodox Church of St. Duchess Olga Rivne to the Apostles (B; Figure 3). Both St. Matthew's (A) and St. Stanislav Kostka (B) date from the early 20th century, while St. Duchess Olga Rivne (C) dates from the end of the 19th century. Our study analyzes the architectural characteristics of these churches and includes energy calculations to validate the effectiveness of proposed energy-efficiency measures.

Figure 1. Location of St. Mathew's Cathedral (A) and site (background source [https://polska.geoportal2.pl/map/www/mapa.php?mapa=polska]) [accessed 15 April 2023].

Figure 2. Location of Orthodox Church of St. Duchess Olga Rivne to the Apostles (C) (background source [https://polska.geoportal2.pl/map/www/mapa.php?mapa=polska]) [accessed 15 April 2023].

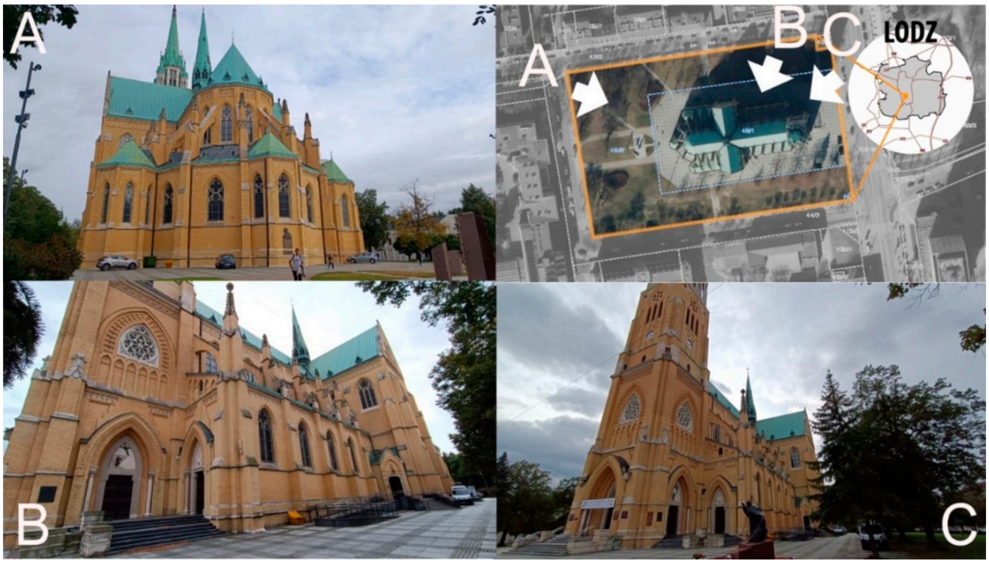


Figure 3. Location of Catholic Cathedral of St. Stanislav Kostka (B) (background source [https://polska.geoportal2.pl/map/www/mapa.php?mapa=polska]) [accessed 15 April 2023].

Used less and less or even abandoned, many religious buildings are now being converted to other functions. However, this conversion is often at the expense of their architectural integrity and neglects the need to preserve the artifacts they contain. This paper addresses this issue by outlining practical strategies to enhance the energy efficiency of church buildings, ensuring that these improvements align with the preservation of their historical and architectural significance. This approach advocates for a balanced method that respects these structures' heritage and original characteristics while adapting them to contemporary needs. The reuse potential of a church is affected by the building typology and its structural condition, the stakeholders involved, the process used, the regulatory context, and finance and site issues. The reuse of a church can also be informed by researching and documenting examples of previously successful reuse strategies.

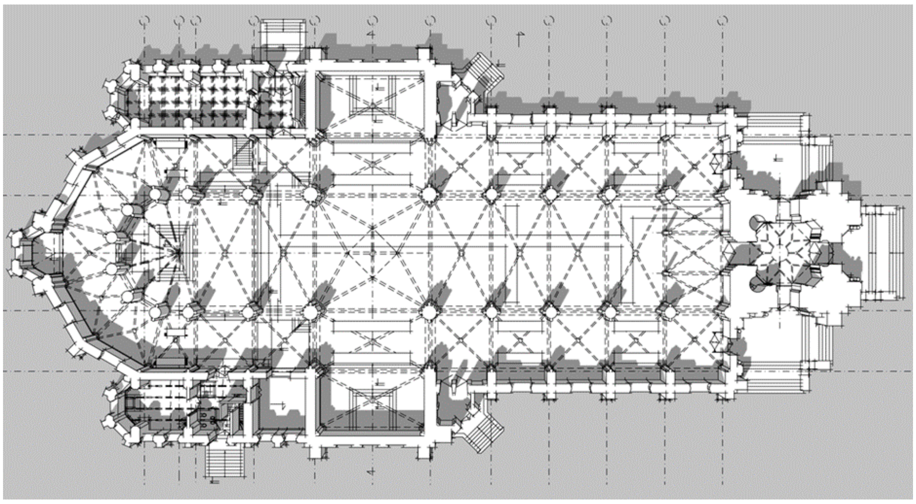
Lodz, a city in central Poland, shares a warm temperate transitional climate with many towns in Germany. This type of climate is also similar to the warm, moderate, albeit maritime, climate prevalent in the rest of Western Europe. Therefore, the results of this research can also inform strategies for heating churches dating from this historical period in Europe, especially in Germany and Poland.

2. Methodology

2.1. Analyzed Objects

The three studied buildings represent religiously diverse religious architecture from the second half of the 19th century and early 20th centuries. Buildings characterized by similar technologies and building materials can be found throughout Europe and the world. St. Matthew's Church in Lodz (A), Poland, is a notable Lutheran church and a historic landmark (Figures 1 and 4A). The Orthodox Church of St. Duchess Olga Rivne to the Apostles (C) (Figure 2) is significantly smaller than St. Matthew's Church (A). The Catholic Cathedral of St. Stanislav Kostka (B, Figure 3) is considerably larger. The construction of St. Matthew's (A) began in 1909, while St. Stanislav Koska (B) dates from 1901–1912. The construction of St. Duchess Olga Rivne (C) began in 1896. All the buildings reflect the city's cultural identity, combining various national cultures—Polish, Russian, German, and Jewish. Therefore, proper preservation of these churches, especially of the interiors and the artifacts they contain, is essential for maintaining the character of Lodz as the "city of four cultures". Unlike many churches built in the late 19th and early 20th centuries, the studied buildings are still used for their original purposes of religious devotion.

(A) St. Mathew arc cathedral ground floor plan



(B) Orthodox Church of St. Duchess Olga Rivne to the Apostles ground floor plan

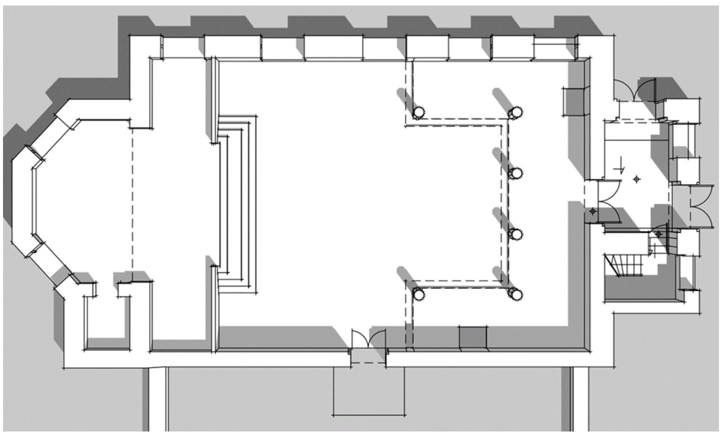


Figure 4. *Cont.*

(C) St. Mathew's ground floor plan

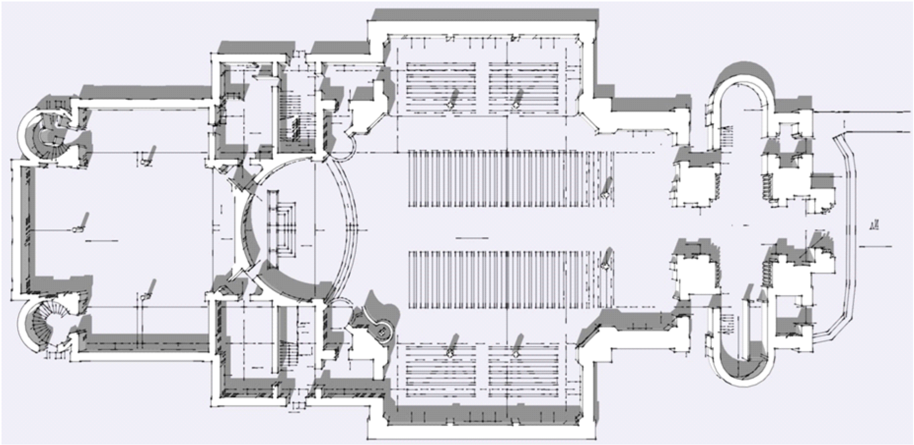


Figure 4. Ground floor plans. T. Grzelakowski.

Church of St. Stanisław Kostka (B)—In the 19th century, the rapidly developing city of Lodz had two parishes, one with already over 58,000 believers. It was therefore decided to create a third parish. On 23 May 1895, a competition for the design of a new church was announced. The project presented by the German architect Zellman from Berlin won the competition. In 1900, the foundations of the Church of St. Stanisław Kostka (B) were laid. Construction began on 20 May 1901, and on June 16th, the cornerstone was consecrated. In the years 1902–1909, the walls of the current cathedral were built, and on 22 December 1912, the unfinished church was consecrated, despite still missing the tower. Work on the tower began in 1912, but was interrupted by the outbreak of World War I. In 1927, construction of the tower was completed, and the cathedral roof was covered with copper sheet. With the tower, the church is 104 m high, making it one of the tallest buildings in Lodz. Both the exterior and interior of the church were built in neo-gothic style. The outer part was faced with light clinker brick and sandstone elements. The top of the soaring tower and the vaults have a reinforced concrete structure, which is uncommon for the period. Inside, there are richly decorated altars, a pulpit, stained glass windows, benches for the congregation, and numerous commemorative plaques designed by famous sculptors. On 11 May 1971, the cathedral caught fire. After renovation, the temple reopened on 16 December 1972. In 1977, damaged structural elements and equipment were repaired [11].

The church walls are made of ceramic bricks on lime-cement mortar, plastered inside, and faced with yellow clinker bricks on the outside. Reinforced concrete vaults form the naves and the tower's crowning—a unique solution for the time of its construction. Part of the vaults are made of bricks (annexes), the ceiling above the bishop's crypt is reinforced concrete, and the remaining part is segmental (arched—made of brick). The roof truss is a steel structure. The roofs are covered with copper sheet. The floors are granite and balconies wooden. The base and wall decoration elements are made of sandstone. The church of St. Stanisław Kostka (B) (B) is modeled on the German Ulmer Münster cathedral and built on a Latin cross plan, with the presbytery located on the west. The two-bay transept crosses the five-bay nave. The interior layout is reflected in the body of the church. Narrow, ogival windows and buttresses between them emphasize the rhythm of the bays outside. Above the buttresses, there are retaining arches that give the structure lightness and clearly define its style. The articulations of the facade are enriched by stone elements in the form of the plinth, cornices, and buttresses, as well as pinnacles above the buttresses and window tracery. During renovation in 1980–1990, parts of window frames were replaced with reinforced concrete (central post and frame) to transfer the loads, which destroyed the original stone frames. The tower, built on a square plan, is located on the axis of the facade and slightly protrudes from the face of the wall underlining the main entrance to the cathedral. The light openwork construction, housing the church bells, together with the slender dome and triangular roofs constitute a clear dominant and is complemented by small towers placed in the corners of the central octagon. Inside, stone pillars divide the space into three naves. The walls of the main nave above the side aisles are divided by a strip of blind triforia and above them, there are high pointed windows. The interior is enriched with altars placed in the presbytery and on the side walls of the transept. The neo-Gothic style of richly carved, colorful, and gilded religious representations perfectly complements and determines the uniformity of the stylish whole. Above the main entrance is a choir balcony with an organ, supported by two delicate columns. Due to its stylistic features, artistic expression, and composition, it is widely considered one of the outstanding works of architecture representing the French Gothic style in Poland [11].

The Church of St. Duchess Olga Rivne to the Apostles (C) is located at 12 Piramowicza Street, a few hundred meters from the Cathedral Church of St. Aleksander Nevski, which is the most important Orthodox temple in Lodz. It was consecrated on 16 October 1898. The Church of St. Duchess Olga Rivne to the Apostles (C) was built as a reaction to both this increase in the number of believers in the city and (primarily) in connection with the creation of an orphanage for Orthodox children, the construction of which began in 1896. Although the orphanage is no longer in use, the passage from the nursery to the church and the doors connecting both buildings have been preserved to this day. The church and the orphanage building are on a rectangular plot at the corner of Piramowicza and Narutowicza streets. On the same plot, there are two other buildings: on the south side, a single-story building, and on the north part of the plot, a two-story building [12].

The church is built of brick on lime mortar, plastered on both sides. There is a wooden ceiling with a half-ceiling of plastered reed, brick above the presbytery, and wooden rafter-collar truss with iron beams. There is also a wooden dome structure. The roofs are covered with galvanized sheet metal [12].

The church is oriented with the main entrance from the west side (Piramowicza Street) and the entrance for clergy from the east. The church was built on a rectangular plan, on a high basement. The interior was planned as a single nave. Instead of typical Orthodox domes, the church features a flat ceiling covered with carpet paintings. Adjacent to the chancel from the north is a small rectangular sacristy. On the west side, wide stairs lead on both sides to the terrace in front of the main entrance. Above is a two-story tower, square at the bottom and octagonal at the top, with a characteristic dome covered with rhombus-shaped pieces of sheet metal. The remaining gable roofs over the church nave, the single-pitch roof over the sacristy, and the multi-pitched roof over the presbytery are covered with sheet metal. The external decoration of the facade is limited to accentuated horizontal divisions in the form of stepped cornices running under and above the windows. Similar cornices separate the individual levels of the tower. The body of the church is topped with a characteristic arcade frieze. This separates the tower's upper floor, which is topped with a cubic frieze running just below the spire. The interior is decorated with floral and geometric polychromes on the flat ceiling and side walls. It is the only Orthodox church in Poland without paintings of saints on the walls [12].

The Evangelical Augsburg Church of St. Matthew in Lodz (A) (Figures 3 and 4C) is one of the most precious monuments in Lodz. Its location on the city's main street, Piotrkowska, near the archcathedral, further increases its importance in its space and history. Its origins date back to the beginning of the 20th century, when the Evangelical-Augsburg community of Lodz numbered about 80,000 people. The existing parishes could not accommodate such numbers, especially in the southern part of the city. Therefore, around 1900, it was proposed that a third Evangelical-Augsburg church be built [13]. On 1 November 1901, a meeting was held at St. John's Church, where a church building committee was established [14].

The future parish of St. Matthew's (A) was initially located between Piotrkowska Street and Rzgowska Street (today's Niepodleglosci Square). However, thanks to the allocation of additional funds by the Scheibler family, plots were purchased at 279 and 281 Piotrkowska Street. In the spring of 1906, out of three proposals (by Robert Nestler, Johannes Wende, and Pavel Rübensahm), Johannes Wende's design was selected for construction. The project was put on hold in 1905–1906, and the final version was developed by the architectural and construction firm Wende and Klause. Approval for the church's construction was given in January 1909, and construction work began in the summer of that year. The cornerstone was consecrated on October 8th. First, a confirmation chapel was erected, ready in mid-1910, the idea being that it could be used by the faithful while the church was being erected. At the same time, the decision was made to enlarge the church, and the existing design was revised accordingly. By 1913 the reinforced concrete dome over the central space was completed. With the shell of the temple almost ready, further work was interrupted by World War I. The church was finally completed in 1928 [15].

The church is built of brick on cement mortar, plastered on both sides. The ceilings are reinforced concrete, except for those in the auxiliary rooms (flat brick ceilings—Kleina). The roof truss is wooden, and the roof is covered with tiles and galvanized sheet metal. The floors are terrazzo and ceramic, or wooden on galleries. The doors are wooden, and there are single windows with steel frames [15].

The church is built on a plan of a Greek cross. Its main space is preceded by a tripartite porch with a high tower, forming a monumental façade like those in Rhine Romanesque churches and Berlin's Kaiser-Wilhelm–Gedächtnis-Kirche. A monumental reinforced concrete dome with decorative ribs and a magnificent chandelier covers the central nave. It ends with a chancel with a semicircular apse, where the main altar is placed. The altar is made of white marble and decorated with a bas-relief depicting Christ at prayer in the Garden of Gethsemane. The walls of the apse are filled with frescoes depicting the Stations of the Cross, the Crucifixion of Christ, and the deposition to the tomb. Lodz-based artist Robert Laub executed the entire work in 1926–1928 [16]. He used the famous al fresco method of painting with paints on wet plaster, which gave the work distinctive colors. The paintings combine the influences of realist and Byzantine painting, with a golden abstract background given to most of the compositions. The painted realist figures in the scenes represent biblical heroes, historical figures (William Tell with his family, Dante) and ordinary people, indicating that everyone comes to the cross: king and beggar, young and old, healthy, and sick, peasant and bourgeois, worker, and poet.

The nave is intersected by a transept equal in height to the central nave. The arms of the transept, ending in a rectangle, have giant rosettes filled with stained-glass windows. The stained-glass windows are a highly characteristic element of the church's interior. In addition to the rosettes, they decorate all the window openings. The windows were created in 1926–1927 by the Wroclaw company owned by Adolf Seiler and were designed by Berlin artist Prof. Herman Hofmann [17]. Among the church's greatest treasures is the organ. It is the largest organ in Lodz and one of the largest in Poland, made by the Rieger Brothers Orggelbau company of Jägerndorf. Similar organs made by the same company are found in concert halls in Vienna and at the Mozarteum in Salzburg. They are housed on a vast balcony with room for a 200-seat choir and an orchestra. The church has thus become one of the important concert halls in Lodz. The many valuable and diverse artifacts in the church increase the challenge of heating the building in the autumn and winter seasons. This is especially true in the case of the organ, which has both wooden parts and pipes, which are exposed to external factors [18–20].

2.2. Methodology of Analysis

The time frame for this study was narrowed to objects built in the last two decades of the 19th century and the first two decades of the 20th century. This time frame allows for the selection of objects with similar aesthetic assumptions, responding to similar needs of society, and functioning within relatively uniform cultural and civilizational conditions, which would only be changed by the First World War. This means that there is a certain uniformity within the structures, in terms of functional and ideological assumptions, which are reflected in their construction.

The selection of buildings from Central and Eastern Europe for analysis ensured that the studied objects were not only products of shared cultural values and experiences, but also built under similar environmental conditions. This geographical focus provided a coherent yet diverse range of examples, making them ideal for large-scale analyses.

Finally, the selected facilities are located very close to each other to emphasize the importance of local issues (i.e., heating methods from available sources) and to minimize the impact of environmental and cultural factors resulting from differences in geographical location (including specific climate). This research was based on available sources interviews with users, available data and technical inventories, and in situ analyses of facilities.

Searching for the phrases “churches”, “heating” and “early 20th century” produces two results in Science Direct, with the first article not actually about heating and the second about a church from the seventeenth century. Both articles come from 2015/2016—practically a decade ago. The search for the phrases “Churches” and “heating” gives an average result of over three hundred articles each year from 2019–2023 and over two hundred for 2024. A large number of topics are not related to the problems addressed in this article. The articles also include descriptions of specific cases (e.g., Sustainable church heating: The Basilica di Collemaggio case-study Energy and Buildings 15 March 2016 Niccolò Aste Stefano Della Torre Massimiliano Manfren [21]) as well as of general issues (e.g., Field measurements and numerical analysis on operating modes of a radiant floor heating aided by a warm air system in a large single-zone church Energy and Buildings 15 January 2022 Ying Zhang Chenbo, Zhao Angui Li [22]).But they mainly concern medieval objects and those located in other climatic zones. A search for “churches heating” yields 34 articles between 1942 and 2024, with the vast majority of one article per year, mostly focusing on the impact of heating on historic furnishings. These are articles that have some connections with the topics presented below. Most often, however, they concern either general issues, older churches, churches made of different materials, or those located in other zones/climatic conditions (e.g., wooden churches in mountainous regions).

When analyzing the heating of buildings, including religious buildings, it is important to determine basic energy indicators like the primary, final, and utility energy indices. These indices are crucial in assessing a building’s energy efficiency. Although they typically do not require energy certificates, the analysis of religious structures should be conducted in accordance with the methodology outlined in Polish regulations, employing the calculation method [23–26]:

$$PE = \frac{Q_P}{A_f} \ [\mathrm{kWh/m^2 year}] \quad (1)$$

$$FE = \frac{Q_K}{A_f} \ [\mathrm{kWh/m^2 year}] \quad (2)$$

$$UE = \frac{Q_U}{A_f} \ [\mathrm{kWh/m^2 year}] \quad (3)$$

where:

Q_P—annual demand for non-renewable primary energy for technical systems (kWh/year);

Q_K—annual demand for final energy supplied to the building for technical systems (kWh/year);

Q_U—annual demand for usable energy (kWh/year);

A_f—area of rooms with regulated air temperature (heated area) (m^2).

The calculations considered heat transfer coefficients for partitions and stained-glass windows in existing buildings. All buildings originated from a similar period and had a similar structure. The value of the heat transfer coefficient for walls was approx. 0.82–0.90 W/m^2K, and for stained glass windows, it was approx. 3.0–3.5 W/m^2K.

Due to the fact that the buildings are powered by the municipal heating network, the calculations assumed a primary non-renewable energy input coefficient of 0.57, in accordance with the heat supplier's data.

3. Heating of Churches

Heating is a crucial element in maintaining a suitable microclimate within historic churches, serving two primary purposes: ensuring thermal comfort for users and providing a dry environment to protect materials from damage. However, the increasing demands for thermal comfort intensify the use of heating systems in these churches, posing significant challenges in preserving both the historic structure and the artworks within (Figure 5) [27]. When implementing heating systems in historic churches, a key consideration is maintaining the building's structural integrity. This requires heating systems to be meticulously designed and installed to prevent any interference with the building's original architecture, such as thoughtfully integrating ductwork and other components.

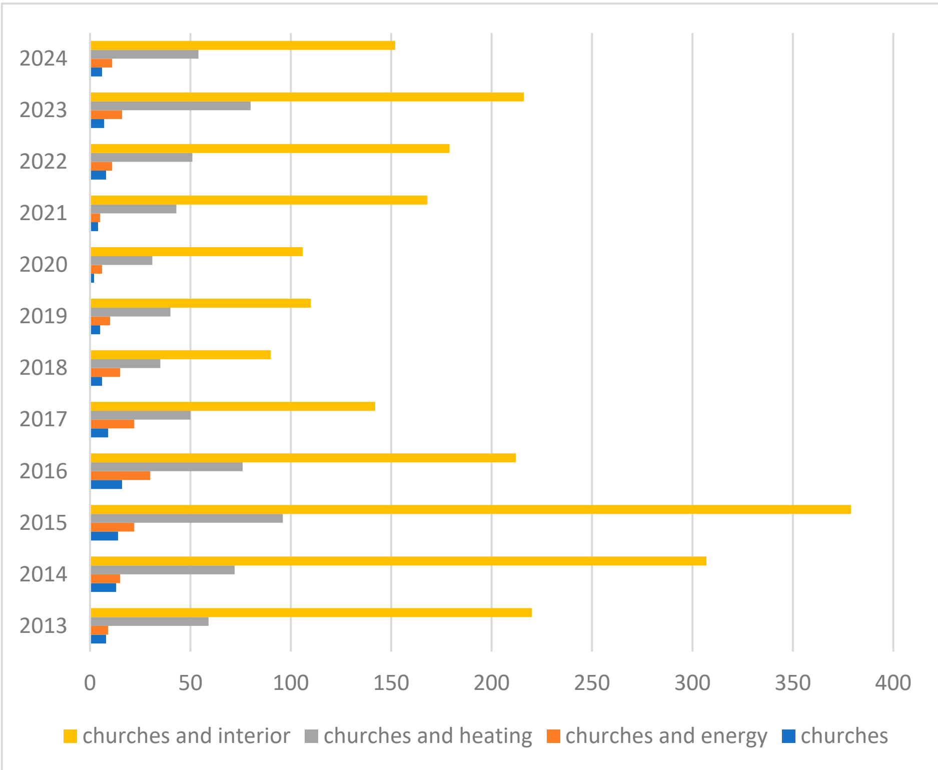


Figure 5. Number of records in SCPOPUS base for searched words.

Properly adjusting the heating method and amount to the specific conditions of historic churches is also crucial. Research indicates that extreme conditions, such as a lack of intermittent heating or overheating, can be detrimental. The absence of heating raises the risk of mold growth, affecting both the structure and aesthetics, including artworks. Conversely, overheating can reduce the relative humidity (RH) below 50% during cold periods, posing risks to wooden structures and leading to potential damage, like cracks or delamination of gesso [28]. Changes in humidity resulting from changes in the heating method compared with the original conditions may cause wooden elements to dry out. Therefore, they require the development of systems that control this aspect of the environment. They are also confirmed by observations in the examples described—where heating modernization led to problems, e.g., with elements of the organ in the church of St. Matthew (A).

Additionally, changes in temperature distribution (differences in the time and temperature of heating rooms at different heights or in different locations) may lead to stresses in the material and, consequently, to damage to the facility's historic equipment. Thus, microclimate management is essential for preserving both the artworks and the structure. Ensuring a comfortable temperature for visitors and worshippers is vital, requiring the installation of efficient and compatible heating equipment in buildings originally not designed with such systems in mind (Figure 6). Care must be taken to ensure that any new equipment is compatible with the building's infrastructure.

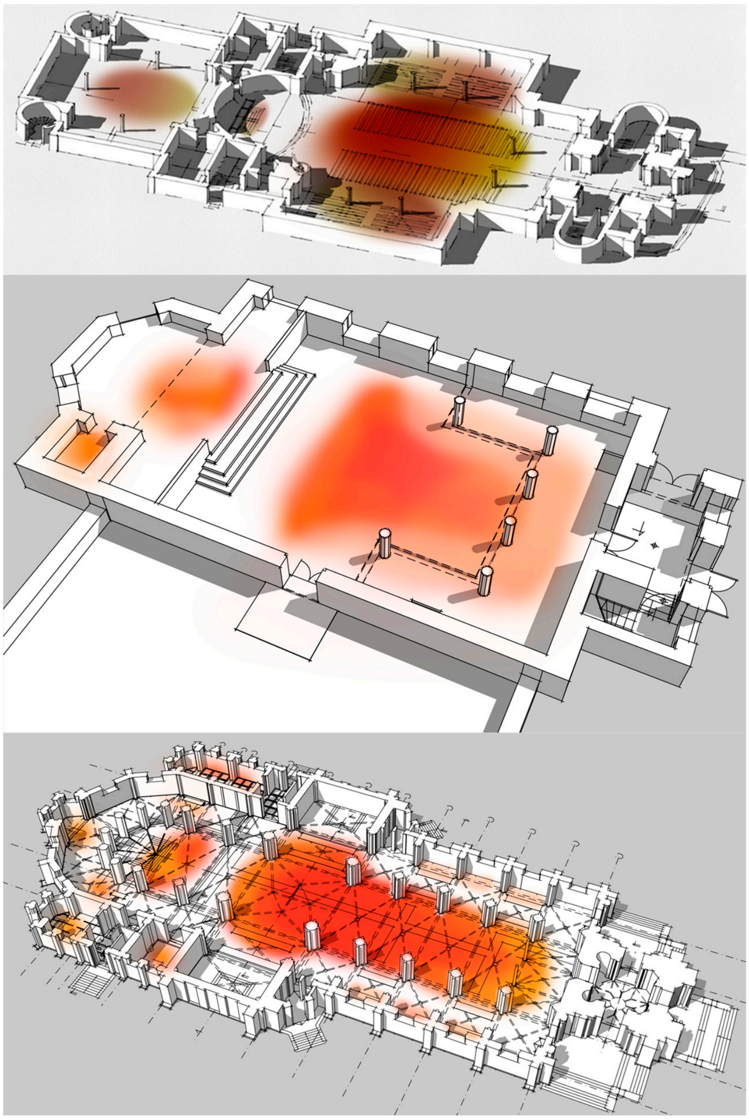


Figure 6. Places where people gather while using the facility.

The usage patterns of churches pose a significant challenge in selecting an appropriate heating system (Figure 7). These buildings often experience long periods of vacancy interspersed with short periods of high occupancy during services, such as the one to two-hour services on Sundays at St. Mathew Church. This irregular schedule demands a heating system capable of quickly adjusting to significant temperature requirements within short timeframes [29]. Additionally, the financial aspect is critical, encompassing both the costs of renovation and ongoing operation. The challenge is compounded by the large space and inefficient thermal envelope of heritage buildings, necessitating insulation solutions that are not only effective but also economically viable [30].

(A) Areas of higher heat demand. Auth. T. Grzelakowski

(B) St Kostka Heating. Auth. A. Zagula

(C) St Olga, Heating Auth. A. Zagula

Figure 7. Areas of higher heat demand and heating.

One option for heating historic churches is to use radiant heating systems (Figure 8). Radiant heating works by directly heating objects in a room, rather than heating the air. This can be particularly effective in large, open spaces like churches, where heating the air can be complicated and inefficient. Radiant heating systems can also be installed in a way that minimizes visual impact, preserving the historic character of the building. Another option for heating historic churches is to use a geothermal system. Geothermal heating uses the Earth's natural heat to warm the building. This is achieved by circulating water through a series of pipes buried deep in the ground. While geothermal systems can be expensive to install, they are highly efficient and significantly reduce heating costs over time.

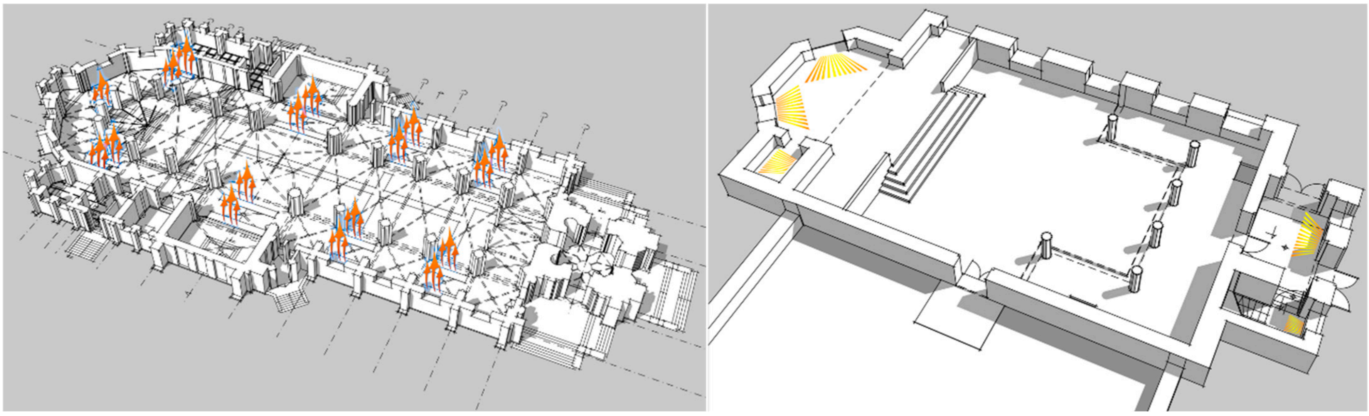
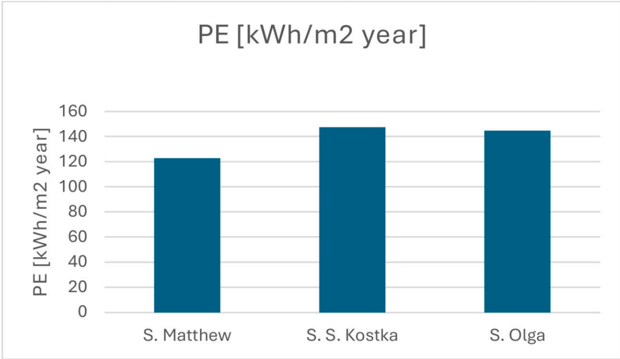


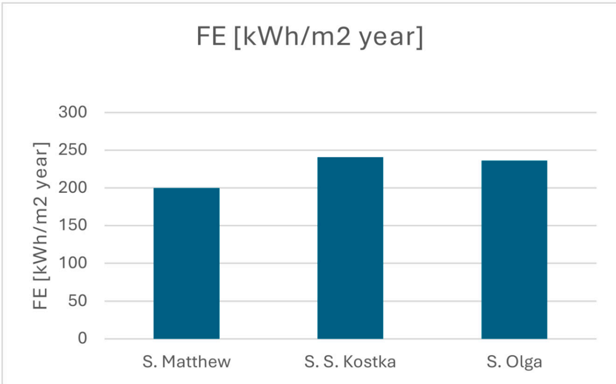
Figure 8. Examples of heating of historic churches.

In addition to heating systems, other steps can be taken to improve the energy efficiency of historic churches. For example, insulation can be added to walls and ceilings to reduce heat loss. Windows can also be replaced with more energy-efficient models, although care must be taken to ensure that new windows match the building's original design (Figure 9). This, however, should always be combined with a careful analysis of results from the conservation of heritage point of view. The methods should be limited by their invasiveness. Churches with plaster-finished facades may, in theory, be insulated. Still, the thickness of the insulating material will influence the proportion of elements on the façade (i.e., columns, windows etc.) and, to some extent, the ratio of the church itself [31]. Given that the most common materials used for churches from the mid-19th century and beginning of the 20th century in Europe are stone and bricks, this method may also alter the visual aspect and overall perception of the building. An example can be seen in the monumental stone church in Choholow, a small village in southern Poland. The building was designed by a skilled and well-known architect from Krakau, Feliks Ksiezarski, in 1853 and erected in 1872. In 1998, in a renovation effort, it was partially covered with Styrofoam and plaster. This changed the original design and devastated its aesthetic integrity. In 2018, after extensive conservation work, the building was returned to its original form [32]. This example shows the problems with external thermos-insulation of historical buildings. On the other hand, due to their rich inertial decorations, it is also often impossible to introduce inner-insulation layers in churches. Since this solution is also less effective, it may lead to damp condensation in the partition.

(A) Comparison of the primary energy index for the analyzed church buildings



(B) Comparison of the final energy index for the analyzed church buildings



(C) Comparison of the useful energy index for the analyzed church buildings

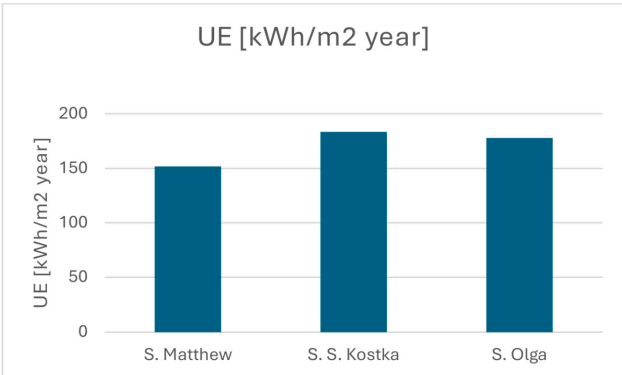


Figure 9. Comparison of energy indicators.

4. Results and Discussion

Heating historic churches involves balancing the demands of heritage conservation with the practical needs for thermal comfort. This challenge is compounded by factors like the building's height and the heating system's interaction with ventilation. Compromises often need to be made between user requirements (primarily thermal comfort during services) and the guidelines of preservationists aimed at protecting interior design elements, paintings, and organs [33]. Facility owners must also consider operational costs, leading to strategies like lowering temperatures or intermittently shutting off the heating system. Designing an effective heating system therefore requires considering the time needed to heat the church's volume [34], while maintaining a stable microclimate crucial for preserving key elements like woodwork and paintings over the years [35,36].

In Europe/Poland, it is generally assumed that the temperature in a church when not in use should be approximately 8 °C. During services, the temperature should be between

12 and 15 °C. The heating and cooling time should not exceed 1.5 K/h. When heating with warm air, the temperature measured at the outlet from the supply element should not exceed 45 °C. However, the air velocity during floor supply should not exceed 1.5 m/s. Relative humidity should be in the range of 45–75% [37–40].

Each of the churches in this study has a heat source in the form of a heating node powered by the municipal heating network from the heat supplier (Veolia) [23]. The churches are heated by a heating and ventilation system. In the case of the church of St. Matthew's (A), an air handling unit with heat recovery is used to supply fresh air to the facility while maintaining the temperature requirements for thermal comfort. Similarly, the church of St. S. Kostka (B) is heated by preheated air. The church of St. Olga's (C) is equipped with heating and ventilation units. Auxiliary rooms in the churches are heated using a traditional central heating radiator system. The use of such air heating systems allows for rapid achievement of the desired thermal comfort parameters (in around less than an hour) with reasonable heating costs. The parameters of the central heating system and heat supply to the heaters are 80/60 C, and the heating medium is water. The facilities have the ability to regulate heating depending on the outside temperature and on the period and duration of their use.

In church buildings not subject to strict preservationist guidelines, where thermal modernization is feasible and new floors can be laid, underfloor heating systems are increasingly being installed. An example is the church in Rzerzeczyce, located in the Czestochowa diocese and sharing the same climatic zone. These systems often integrate with renewable energy sources like heat pumps [24]. This approach is particularly effective for smaller church buildings and aligns with the trend toward decarbonizing historic buildings, which traditionally consume significant energy for heating [25].

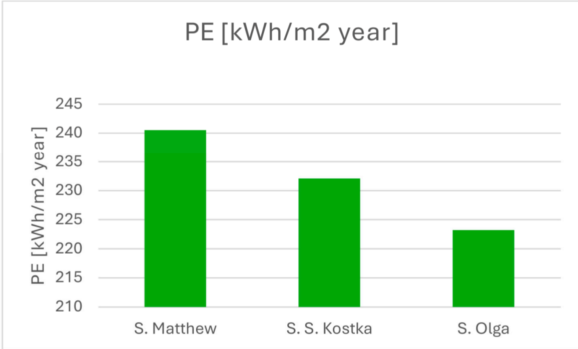
The results of these indicators for the analyzed buildings are detailed in Figure 9.

For comparison, the same energy indicators were calculated assuming that the heat source in the analyzed buildings would be air–water compressor heat pumps. The result is presented in Figure 10.

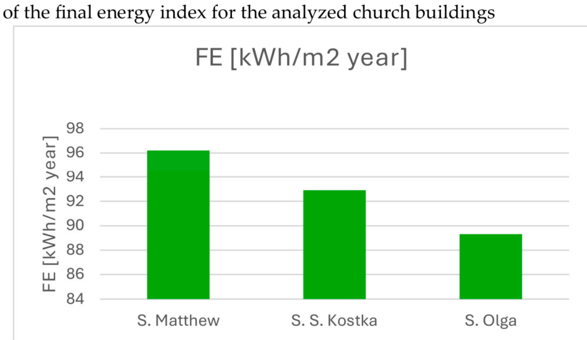
The calculated indicators for each of the studied buildings showed similar values. The PE index was between 122.6 kWh/m^2/year for the church of St. Matthew (A) and 147.3 for the Archcathedral Basilica of St. S. Kostka (B). However, the FE index was in the range of 199.6–2 40.8 kWh/m^2/year, and the EU index was 151.6–183.2 kWh/m^2/year. The similar values for the designated indicators may be explained by the fact that the analyzed religious buildings are in the same climatic zone, were built during the same period, use similar building materials, and employ very similar heating methods. Approximately 15–20% of their energy consumption is used for lighting. The rest is used for heating and ventilation. Similar energy consumption values have been reported for other religious buildings located in other regions and climatic zones (e.g., in Indonesia or the USA), although in those cases, lighting accounted for the highest energy use [41,42]. The calculated energy consumption in the buildings is consistent with data from the literature [37], assuming that the energy needs for church exploitation are approximately 900 h/a under full strain with a base temperature of 8 °C.

Comparative calculations of energy indicators using heat sources in the form of air—water compressor heat pumps showed that the PE indicator increased and amounted to 223 kWh/m^2/year to 240.5 kWh/m^2/year. The increase in this indicator is due to the fact that heat pumps need electricity to drive them, which in Poland is produced mainly from fossil fuels (coal); hence, the value of the non-renewable primary energy input coefficient for generating and supplying energy to the building was assumed to be 2.5. For comparison, the value of this coefficient was assumed to be 0.57 for the heating system powered by Veolia. The FE index for heat sources in the form of a heat pump for each building was lower than that for the system powered by the heating network and ranged from 89.3 kWh/m^2/year to 96.2 kWh/m^2/year.

(A) Comparison of the primary energy index for the analyzed church buildings



(B) Comparison of the final energy index for the analyzed church buildings



(C) Comparison of the useful energy index for the analyzed church buildings

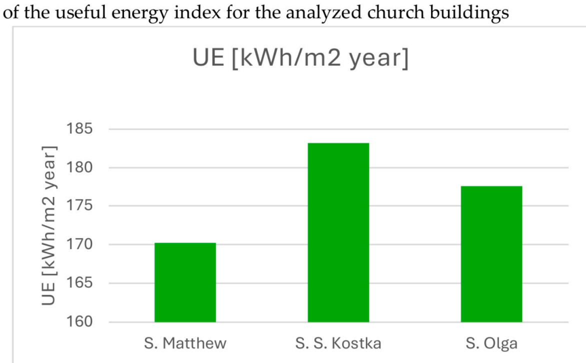


Figure 10. Comparison of energy indicators—air–water compressor heat pumps.

5. Conclusions

There are about 600,000 churches in Europe and 37 million worldwide, which vary considerably in terms of their architecture and usage. The challenges of modifying and maintaining historical church structures are considerable, especially considering that they often house valuable artifacts like sculptures, paintings, polychromes, and musical instruments, including organs, which are in themselves important cultural monuments. Churches often hold significant emotional and historical importance for communities. Often integral to community life, both religious and secular, they are also key elements in city landscapes, marked by their prominent locations and architectural value. Over time, due to socio-political changes, the demand for the functions performed by these buildings has evolved. Across Europe, these shifts have impacted how these structures are used. Churches from the late 19th and early 20th centuries are increasingly recognized as part of cultural heritage, often of significant aesthetic value, as evidenced by their inclusion in monument registers.

However, they have not yet reached the same level of public recognition or tourist attraction as medieval or Renaissance buildings.

The examples given in this article highlight the complexity of developing sustainable heating strategies for historical church buildings from the late 19th century and early 20th century. This article has also introduced a comparative approach of calculating energy indicators for these buildings, a practice not usually performed for this type of historic structures. The studied objects are key landmarks, both spatially and symbolically. While maintaining the structural integrity of these buildings is crucial, providing a comfortable temperature for visitors and worshippers is also essential. The microclimate of an unheated church is often erratic and inadequate. To address this, radiant heating and geothermal systems can effectively heat these structures. Insulation and window replacements can also help to improve energy efficiency. Controlled, periodic heat introduction helps to stabilize the interior microclimate, preventing excessive wall cooling in winter, high humidity conducive to mold growth, and condensation on artwork surfaces. These measures are crucial for preserving historic churches for future generations while minimizing their environmental footprint.

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