Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(6), 248–266
https://doi.org/10.12913/22998624/202484
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.02.25
Accepted: 2025.04.15
Published: 2025.05.01

Selected issues related to costs of thermal energy carriers and CO_2 emissions for a historic sacral building

Krzysztof Tomczuk[1*], Paweł Obstawski[1], Piotr Tomczuk[2], Marcin Chrzanowicz[3], Natalia Strzelecka[4]

[1] Department of Fundamentals of Engineering and Energy, Institute of Mechanical Engineering, Warsaw University of Life Sciences, ul. Nowoursynowska 164, 02-787 Warsaw, Poland
[2] Faculty of Transport, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland
[3] Faculty of Electrical Engineering, Warsaw University of Technology, Pl. Politechniki 1, 00-662 Warsaw, Poland
[4] Faculty of Electrical Engineering, Gdynia University of Technology, ul. Morska 83, 81-225 Gdynia, Poland
* Corresponding author's e-mail: krzysztof_tomczuk@sggw.edu.pl

ABSTRACT

The main aim of this article was estimation of the heating energy demand and annual heating costs for a classical sacral building equipped with ground source heat pump or gas boiler. For this purpose, a simulation model was developed in the Matlab Simulink 2022b. Heat losses through the building elements were analysed and elements requiring thermal insulation were indicated. According to the research, the current state of the building (without thermal insulation) requires 241.73 kW of peak thermal power and 227.03 MWh of thermal energy annually. Values were calculated for 107 days of the heating season and internal temperature of +12 °C. According to the results, it is possible to reduce peak power to 107.78 kW (44.5%), and energy consumption to 70.53 MWh (31.1%) in relation to primary values. Annual heating costs presented as a Variant 4 is 5386 EUR for ground heat pump and 7071 EUR for gas heating with CO_2 emission costs included. Variant 5 presents the possibility of additional reduction of maximum heating power, which affects the final cost of the installation.

Keywords: thermal energy losses, heat pump, gas boiler, CO_2 emission.

INTRODUCTION

Historic sacral buildings are characterized by large spaces and high ceilings; due to their other structural features, they require special approach to heating purposes. Maintaining thermal comfort during heating season requires special technological solutions and should be related to the CO_2 emission policy. This article analyses selected factors affecting thermal energy demand for different heating systems. Main issue is the verification of the results in terms of final costs.

First scientific novelty of this study is development a new simulation model in Matlab-Simulink 2022b to determine the heating costs of historic building located in the III climate zone in Poland. Heat dissipation issues regarding heat transfer coefficient of old historic building elements (envelopes), precisely set heating season, reduced ventilation losses were taken into consideration in this study. The calculations were performed based on temporary values of external temperature recorded every 1 hour throughout the year.

The error obtained during analyses was 2.58%, and determines the relationship between the value of heating costs calculated on the basis of simulation in comparison to real annual bills heating costs. Accurate results indicates the correctness of the mathematical model used in this research.

The second scientific novelty is determination of the value of the most frequently applied heating power to the building. This solution makes it possible to install a heat source with reduced peak power, adopted to the most common large spaces heating needs. Limited heating power influences indoor climate during severe frozen. According to the research, internal temperature is reduced for 10.7 days, which should not be a problem for a temple used 2–4 hours a day, especially on weekends during daytime.

The issues developed in this article can be successfully applied to all types of buildings, especially required thermal modernization. Accurate determination of the heating energy costs is crucial in terms of selecting emission-free heat sources and other aspects related to the decarbonization of buildings. Taking into account all above issues, a similar approach to the described topics or the main goals of this article, have not been found in the literature review. Below, a literature review of selected problems regarding interesting aspects focused on heating issues of historical and sacral buildings were presented.

Articles [1, 2] discuss heat generation and dissipation technologies in the context of church and building heating. Different energy carriers, including renewable energy, were analysed. This article describes ranking fuels and technologies based on selected priorities and individual preferences. It is important to consider that some technologies may have a greater impact on the historic buildings environments due to their invasive installation.

The analysis of sacral buildings in 43 parishes in the Zawiercie district of the Częstochowa Archdiocese in Poland were presented in document [3]. The internal temperature can vary from 8 °C to 16 °C. A typical service usually lasts no more than 1 h, and the visitors wear outerwear. According to current wall thermal insulation requirements U(max) ≤ 0.45, specifying a heat transfer coefficient for temperatures of 8 °C < ti ≤ 16 °C. The results calculated in this article range from 2.09 to 0.54 (W/m^{2}K). None of the church walls meet the current heat transfer requirements for public buildings.

The papers [4, 5] describe a simulation models of the heating system of St Mary de Haura Church (Shoreham-by-Sea, Great Britain) and Honghua Temple building in Hubei Province (China) to explain the impact of different operation modes of heating systems. Heating systems based on gas boilers, radiators and underfloor heating with appropriate work schedules and ventilation strategies have a positive impact on thermal comfort. Additionally, reduction of mould growth risk using underfloor heating and energy savings can be achieved.

The paper [6] examined a Umeå (Sweden) church building with mechanical ventilation and underfloor heating. CFD simulations based on the geometry and technical data of the building were carried out. The validation based on data from ventilation and heating system. The analysis results show how the windows-to-walls ratio and the position of windows affect thermal comfort. It was found that the Heat Deficit Rate coefficient increased linearly with the windows-to–walls ratio. However, the growth rates differed for the two types of people's clothing. For heavy winter clothes, the growth rate was 14.33 W/m^2, while for light summer clothes, the growth rate was 32.70 W/m^2.

The articles [7, 8] present an innovative heating systems for a church in southern Sweden and Basilica of Collemaggio (L'Aquila, Italy) based on a combination of an air-to-air heat pump, pew heating, heating benches and ceiling radiators. The research combines the electrically heated benches with a water heating system using ground source heat pumps. This influences comfort level with significant energy savings and the low impact of temperature and humidity on the artworks and building structure. A total heat output of 30 kW was assumed for heating purposes. All analysed solutions can significantly reduce energy consumption by around 70%, in comparison to similar electric heating systems.

The article [9] describes the stages of designing and implementing a pilot system based on a ground heat pump installed in heating and cooling modes in the historic church of "Saints Marcellino and Festo" in Naples, Italy. The study demonstrates geothermal systems can be used as thermal energy sources in historical, artistic and cultural buildings. On the basis of the results, the maximum and average heating output power in winter is 4.5 kW and 2.5 kW. Heat transfer occurs in approximately 60 m of the borehole with maximum heat output at value of 61 W/m, minimum value of 32 W/m and an average value of 41 W/m. The maximum heat output in summer is 18.1 kW, and the average is 4.6 kW. Regarding the coefficient of performance (COP), the recorded data was compared with the manufacturer's certified value of 4.32. This analysis shows that the actual COP is always greater than declared by the manufacturer, with a peak value of 6.98 and an average value of around 5.65. This work has shown that the energy efficiency of a historic building can be improved by using ground source heat pumps without causing any changes in the artistic and cultural aspects of the building.

The case studies described in [10, 11] concern the medieval Church of the Holy Cross in Harju Risti in Estonia and four different sacral heritage buildings in England varying in age, size and use. The methodology involved creating a virtual replica of each building to explore different decarbonization opportunities. A dynamic simulation model was developed with real data from a every location. The results show that replacing a gas boiler with another technology and using existing hydronic heating can be effective for small churches with low energy consumption. On the other hand, replacing the current heating system with PV and heat pumps would be more economical for high energy consumption. Heat pumps or biomass could also significantly reduce the CO_2 emissions for large churches.

The case study presented in [12] concerns the 7000 m^2 historic University building "Palazzo Gallenga Stuart" in Perugia, Italy. The calculated heat transfer coefficient of walls is 2.2 W/m^{2}K and uninhabited roof is 2.8 W/m^{2}K. The energy efficiency of the entire building was determined by implementing more efficient ground source heat pump and thermal energy buffers. Total heating and cooling demand before thermal modernization was about 69 kWh/m^2 per year. Final energy consumption of 30 kWh/m^2 per year was achieved.

Large volumes of sacral buildings, high thermal inertia and periodically used spaces with a variable number of people affects the operational conditions of heating and air conditioning systems. The articles [13, 14] present a calculation method based on the internal air heat balance influencing the heating system. According to the results an measurements of the indoor climate of selected churches equipped with and without heating systems were carried out. The research was performed in selected heritage sacral buildings in Latvia. Changes in air humidity inside the building can be observed during the mass operations in winter. According to the measurements, humidity fluctuations in stone and wooden buildings decrease significantly when the temperature inside is maintained at 6–8 °C and during services at 10–14 °C.

The article [15] presents a case study of the Church of San Francisco in San Giovanni in Persiceto near Bologna (Italy). This is one of the most representative examples of architectural structures of the Bolognese Baroque, built by Alfonso Torreggiani. The work analyses the possibilities of achieving indoor comfort using HVAC devices to reduce energy consumption without affecting the historical values and artistic perception of the building. The dynamic thermal behaviour of the building has been analysed, and an air conditioning system coupled with a heating system was proposed. This solution This ensures a climate with the proper humidity level and optimal temperature for the comfort of visitors and artworks. In winter conditions, the air treatment system and the heating system work together to improve indoor climatic conditions in accordance with requirements.

The articles [16, 17] presents a preliminary energy audit of the historic building of the Faculty of Engineering and Architecture in Bologna (Italy) and Tegs Kyrka sacral building in northern Sweden. Particular attention was paid to the energy consumption for heating in the winter season. The energy analysis results show savings around 15% during thermal energy control in the building and more than 30% when improving windows thermal loses. The obtained results are presented below:

- Energy savings up to 27% can be achieved after windows replacement with energy-efficient ones. In the case of historical buildings, providing additional internal glazing can also reduce energy consumption,
- Changing the operating modes of the heating system can reduce energy consumption in the range of 2.1–3.5%,
- The highest changes in the temperature value occurred during periodically switching the heating system on and off,
- Time-activated heating may not be suitable for buildings with large volumes, especially in cold climates, due to the risk of condensation on the windows.

In the Basilica di Collemaggio (L'Aquila, Italy), an innovative solution of a hydronic, high-efficiency bench heating system combined with a ground source heat pump and electric heating surfaces has been developed. This system is presented ithe n article [18], were a three-dimensional analysis of the computational fluid dynamics (CFD) heating solution was carried out. The simulation presents heat exchange between the human body, the environment and heated benches. The results indicate that the internal air temperature is not significantly dependent on the heating system, and the heat emitted by people provides comfortable conditions and does not degrade works of art.

The papers [19, 20] present the design of a PV and two-stage subcritical compressor heat pump operating in an air-to-water system and using environmentally friendly refrigerants for heating historic buildings in a cascade system. The heat pump is dedicated to buildings with a high-temperature central heating system with wall radiators. The first stage of the heat pump was filled by R290 refrigerant, and the second stage was filled by R1234 ze(E) refrigerant. Both refrigerants are climate-neutral (low GWP – Global Warming Potential). The temperature of the lower source of heat in the range of -20–10 °C. The operating temperature range is unique for a heat pump, and the presented solution can be used to heat the churches equipped with wall radiators supplied with temperatures up to 60 °C.

Additionally cooperation of the heat pump with a PV installation were estimated for three different climate zones in Poland. The achieved consumption of PV energy to supply electric power to the heat pump compressors was determined at 16.9–19.0%. The seasonal coefficient of performance (SCOP) of the heat pump is 1.825–2.038 without PV and 2.515–2.970 with PV. This is one of the possible methods of heating costs reduction.

The study [21] assessed the possibility of using a new approach, called "Building Information Modeling", to accurately determine the energy demand for proper selection a heating system based on renewable energy sources for a historic building. The analysis includes different scenarios for the modernization of a more than 300-year-old building with the use of heat pumps. The building is currently powered by a 550 kW coal boiler with an open combustion chamber. It was proven that the proposed modernization scenario reduces the final energy demand by 72.9%, while improving thermal comfort and reducing annual emissions by 121.1 Mg CO_2 and 1.0 Mg PM10.

The usage of renewable energy systems during the renovation of a building is a challenge that has been addressed in articles [22, 23]. The document outlines different approaches and highlights their role in best practices for energy efficiency, good air quality and environmental sustainability. The first approach to consider is improving the energy efficiency related to implementing external building insulation and window modernization. Similar examples can be found in Palazzo Ex-INPS (Benevento, Italy), Albergo dei Poveri in the Cargonara Valley (Genoa, Italy), Ca'S. Orsola (Treviso, Italy), Palace of the Hungarian Academy of Sciences (Magyar Tu- dományos Akadémica, Budapest, Hungary). The integration of solar energy in historical buildings is usually difficult due to a lack of space or the need to preserve the exterior architecture. Solar lighting has been carefully studied for places such as the Monastery of Santa Maria El Paular, Rascafría (Madrid, Spain) or solar-powered lighting developed for traditional Turkish baths in North Africa. Heat pumps and other HVAC systems are the most popular for improving energy efficiency in historic buildings without compromising their architecture. Examples can be found in: Zena Castle (Italy), The cloister of the ancient Baroque monastery connected to the church of Michele e Gaetano in Florence (Italy), The Church of St. Francis in San Giovanni in Persiceto (Italy) and the Crucifiers complex in Venice (Italy).

Another aspect of this subject is the possibility of determining the thermal properties of a historic stone building, where the structure and materials of masonry walls are unknown. The articles [24, 25] presents relatively simple method of step response test, were the thermal properties of the building can be determined. Achieved results can be used to calculate the heating time. This enables to control the heating system, where the heating time is determined with the model. That solution minimizes energy consumption and negative impact on sensitive building equipment. The combination of low-temperature heat source with radiant systems can achieve acceptable thermal comfort with energy reduction by about 12%.

The articles [26, 27] clearly illustrate the significant impact of passive strategies on the historic building. A dynamic simulation model was created using TRNSYS software and validated through wall with monitoring of experimental data. Implementing changes such as: replacing windows with double glazing providing superior thermal insulation and adding internal shading reached satisfactory results. These actions have led to a reduction of up to 30% in annual energy demand.

The articles [28, 29] discuss the criteria, methods of analysis and decision-making processes to evaluate energy modernization in historic and traditional buildings. The issues related to energy consumption and the impact of climate change were discussed. Methods for measuring retrofit performance were presented. Guidelines and decision-making processes for retrofit selection were developed. Possibility of using an innovative material based on silica aerogel as a thermal insulation of historic buildings was shown. Using this innovative insulation material, it is possible to reduce the heating requirements by 40 % using aerogel or 25% using a traditional type of insulation. Using aerogel only in shaded areas reduces heat loss by about 25% in summer and 20% in winter in comparison to no insulation.

The articles [30, 31] are case studies of the historic buildings "Albergo dei Poveri" in Genoa (Italy) and the "Palazzo Bosco Lucarelli" in Benevento (Italy). The study considered the possibility of increasing the energy efficiency of buildings in accordance with the requirements of the Conservator's Office. According to the research, the following heat transfer coefficients of the building elements were estimated:

- vertical wall: analytical calculations of U-value is about 0.87 W/(m^2K), while field analysis with a heat flow meter showed a U-value of 0.80 W/(m^2K),
- floor: the calculated U-value is 1.83 W/(m^2K), while the field analysis with a heat flow meter showed a heat transfer coefficient of about 1.80 W/(m^2K),
- window frames do not provide tightness. The heat transfer coefficient of the entire window is about 3.1 W/(m^2K).

The results of the analysis show that if the assessment in terms of energy reduction does not reach a satisfactory value, it can be maximized by focusing on other elements of the building, such as historical value and the presence of works of art. Not always energy savings are possible to achieve.

The aim of the research presented in the paper [21, 32] was to develop a method linking historic buildings indoor climate parameters with wooden elements cracks. Analysis of indoor climate parameters showed that damage in the form of cracks is more common in buildings with higher energy consumption and buildings with heating. The overall results indicate that decreasing the temperature saves energy and has a positive effect on the wooden elements.

The research [33, 34] presents an energy audit of public music school historic building, next is "Ca' Lupelli Wolf Ferrari" (Venice, Italy), built between 1649 and 1756 and "Opera Santa Croce" (Florence, Italy), built between 1294 and 1385. Gas and electric energy bills were analysed and indoor temperatures were recorded for over a year. A simulation model was developed on the basis of specialized TRNSYS18 software, using weather data from 2021. Tests of the model enabled to meet the requirements. Additionally, ground and air source heat pumps and a condensing gas boiler with an air-to-water air conditioner were analysed. According to the control strategy the achieved results indicates differences in energy demand and peak loads. Finally, the results present ground source heat pump system as the best solution in the all analysed cases. New heating and cooling schedules and settings were defined, resulting in a 55.2% reduction in energy demand.

The study [35, 36] investigated the daily thermal profiles and thermal comfort in 16 apartments of historic houses before and after thermo-modernization. The research included multi-parameter measurements and continuous monitoring of the thermal environment. The differences detected in the mean temperature value (12.6 °C) of daily temperatures did not explain the results of the thermal comfort research concerning individual thermal feelings and preferences. The research showed that the time of day when the maximum or minimum temperatures occurred and the ability to control in comparison to costs are more important for residents. Detailed consumption models were developed for each building, comparing actual data with simulation model. In 33% of the buildings energy savings were obtained in

21%. In 17% of the buildings, energy consumption increased by 20%. In the remaining 50% buildings, no significant change in consumption were indicated.

The studies described in [34, 37] present a historic building in the Otto Wagner area in Vienna, which has undergone a deep modernization. The process involves improving the energy efficiency and PV energy production potential of the building. Finally, the building was redesigned to a plus energetic building. The article includes individual values of the heat transfer coefficient for the roof, walls, floor and underground wall. Various insulation materials to reduce overall energy demand were presented as well. The energy consumption for heating, cooling, and lighting purposes was decreased annually from 248.9 kWh/m² to 54.3 kWh/m², achieving a 78.2% of energy reduction. The annual amount of renewable energy generated in the local PV system was 22.5%. Finally, building met the standards of a passive house in Austria.

Modelling the temporal and spatial effects of weather on energy demand in buildings are crucial for the decarbonization of energy systems. The article [38] presents a model of hourly demand for heating and cooling for about 5000 buildings located in 43 regions of the world on four continents. As a result of the tests of the model, the following conclusions were obtained:

- A reduction of 1 °C in thermostat settings in all buildings in Europe could reduce annual gas consumption by 240 TWh,
- In some regions of the world, there has been a steady 5% increase in demand for cooling energy for many years,
- 5 billion people have more than 100 additional cooling days per year compared to the previous generation.

The main aim of the article [39, 40] was optimization of building envelope and technical equipment. Multi-criteria analyses assuming global cost, investment prices, primary energy index, carbon dioxide emissions were taken into account during simulations. The presented method can be applied to new designed and thermally modernized buildings. Analyses results indicate the economic possibility of achieving the low-energy building standard and indicate the requirement to concentrate activities on installation technology and the energy source.

The study [41] presents detailed a situation analysis of the 15 premises in buildings build before World War II. A multi-criteria assessment method was proposed, taking into account emissions, energy consumption for heating purposes, energy costs, and usage comfort. It was found that in 9 of the examined premises, energy costs and the impact to the environment were reduced, while the usage comfort was drastically reduced. The average reduction in energy costs after modernization is 41%. It was found that even after modernization, there is a risk of improper use in 5 premises (underheating of the rooms due to high energy costs). Taking into account all assessment criteria, overall situation of the examined premises after modernization improves by an average of 60% [46, 47].

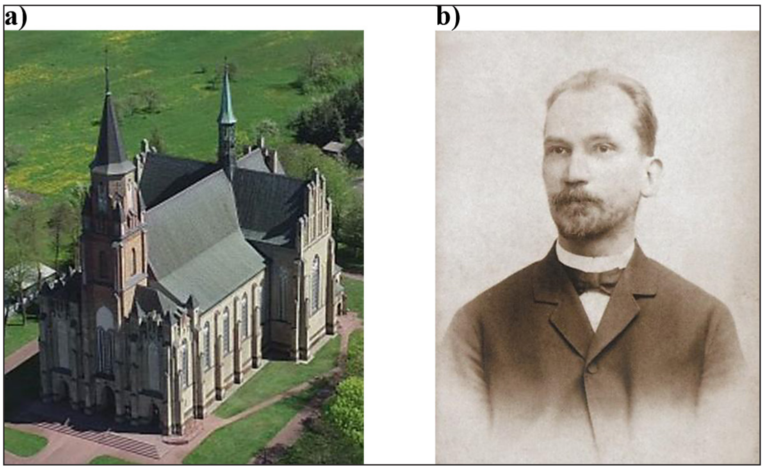

Figure 1. (a) View of the church [42], (b) Photo of the architect Józef Pius Dziekoński (1844–1927) [43]

MATERIALS AND METHODS

Description of the building and architect

The research subject is a neo-Gothic church in Kosów Lacki (Poland) built between 1907–1924. The local parish was erected in 1425 and is one of the oldest in the region, as well the church is the largest in this part of the country. The GPS location of the building is 52.5963804N, 22.1475263E (the coordinates can be copied and pasted directly into a web browser). View of the temple is presented in Figure 1a.

Table 1. Comparison of the area and volume of the building

Building element	Area [m^2]	Gross volume [m^3]
Floor -1 (heating room)	27.60	59.34
Floor 0 (altair level)	1032.30	14997.01
Floor +1 (choir)	198.37	2090.86
Total	1258.27 m^2	17147.21 m^3

Table 2. List of building elements taken into account in the calculations

Building element	Total area [m^2]
Floor 0 (altair level)	1043.00
External walls without windows and doors	2627.00
Ceiling (vault)	1043.00
Windows (22 pieces)	301.00
Doors (5 pieces)	22

Building data

The church was built on a cross plan with dimensions of 34.47 × 60.15 m and a tower with a height of 53.13 m. The height of the vault inside the church is 17 m. Table 1 presents a list of all areas and volumes of the building.

Data used for the calculation

Table 2 presents the elements of the building and their areas considered in calculations of the heating power requirements and thermal energy demand. The list does not include all areas, such as Floor -1 (boiler room) and Floor +1 (choir), which is heated by the thermal energy penetrating from Floor 0 (altar level). Therefore, in the authors' opinion, the analysis of these areas are pointless. Only the data related to Stage 0 (floor) were used for the calculation.

Table 3 shows the structure and thickness of individual components of the floor. It contains the original elements made during the building construction over 100 years ago. During the renovation of the floor, additional thermal insulation was applied. The selected insulation material does not absorb water and is characterized by higher mechanical strength. The next layer of the floor is the underfloor heating pipes flooded with a layer of concrete. Last part of the floor is granite tiles.

Table 3. Floor components

Building element	Components	Thickness [cm]	Thermal conductivity [W/mK]
Floor	Granite tiles	1.5	1.05
	Concrete screed with underfloor heating	10	1.4
	Thermal insulation	5	0.045
	Original concrete screed on the ground	10	1.4

Table 4. External walls

Building element	Components	Thickness [cm]	Thermal conductivity [W/mK]
External walls	Cement-lime plaster	2	0.82
	Solid ceramic brick	75	1.05

Table 5. Ceiling elements (Vault)

Building element	Components	Thickness [cm]	Thermal conductivity [W/mK]
Ceiling (Vault)	Cement-lime plaster	2	0.82
	Profiled brick vault	20	1.7

The external walls presented in Table 4 are made of solid ceramic bricks with total thicknesses between 65–77 cm, depending on the measurement place. The thickness of the vast majority of walls is 75 cm, which was taken into account in the analyses. In addition, a cement-lime plaster was placed inside the building on the entire walls surface. The thickness of the plaster is 2 cm. It should be noted that external walls has no thermal insulation.Table 5 presents the structure of the ceiling (vault) inside the building. It is a profiled brick vault covered from the inside with cement-lime plaster.

Table 6 presents thermal conductivity coefficients of windows and doors used in the analysis. The values were determined according to literature review presented in this article. The building is equipped with interior double-glazed windows to reduce heat loss, which are unfortunately of low quality. Therefore, the combined thermal conductivity for exterior and interior windows was calculated at 2.2 W/mK. The thermal conductivity coefficient adopted for exterior doors was 3.0 W/mK.

Figure 2 presents photos of windows used in the building. There are two types of windows: "Window type 1" with dimensions of 1.75 × 7.76 m and "Window type 2" with dimensions of 2.60 × 9.92 m.

Table 6. Window and door heat transfer coefficients taken in the analysis

Building element	Thermal conductivity [W/mK]
External and internal windows	2.2
Door	3.0

Methodology for calculating the heat power demand

The demand for heating power of the building was carried out for following building elements, such as floor, external walls, ceiling and windows. The calculation method is presented below.

Heat transfer coefficient through the floor

To calculate this value, the equations presented below should be applied. The first coefficient determined is the "characteristic dimension of the floor" marked as B'.

$$B' = \frac{A}{0.5 \cdot P} \quad (1)$$

where: *B'* – characteristic dimension of the floor [m], *A* – floor area [m^2], *P* – Floor circumference [m].

Method of calculating the coefficient of the total "equivalent thickness" is presented in Formula 2:

$$d_t = w + \lambda(R_{si} + R_f + R_{se}) \quad (2)$$

where: d_t – total "equivalent thickness" [m], *w* – total thickness of external walls including all layers [m], *λ* – thermal conductivity via ground [W/mK], *Rsi* – input thermal resistance for downward heat flow [m^{2}K/W], *Rf* – thermal resistance of all floor layers [m^{2}K/W], *Rse* – output thermal resistance for downward heat flow [m^{2}K/W].

The analysed building does not have thermal edge insulation. Since there is a relationship where d_t < B', the heat transfer coefficient U is calculated using formula 3:

Figure 2. Types of windows in the church analysed: (a) Window type 1; (b) Window type 2

$$U_o = \frac{2\lambda}{\pi B' + d_t} ln\left(\frac{\pi B'}{d_t} + 1\right) \quad (3)$$

where: U_o – heat transfer coefficient of the analysed floor [W/m²K], λ – thermal conductivity via ground [W/mK], B' – characteristic dimension of the floor [m], d_t – total equivalent thickness [m].

Heat transfer through walls

The walls of a building consist of many layers of construction materials with thermal resistance R. The method of calculating this parameter is specified in Formula 4.

$$R = \frac{d}{\lambda} \quad (4)$$

where: R – thermal resistance [m²K/W], d – layer thickness [m], λ – thermal conductivity [W/mK].

By summing up the thermal resistances of each layer of the building walls, the final thermal resistance of the wall can be calculated and is presented as R_t in Formula 5.

$$R_t = R_{si} + R1 + R2 + ... + R_n + R_{se} \quad (5)$$

where: R_t – total thermal resistance of the wall [m²K/W], R_{si} – input thermal resistance for horizontal heat flow [m²K/W], $R1$ – thermal resistance for the first layer of the wall [m²K/W], $R2$ – thermal resistance for the second layer of the wall [m²K/W], R_n – thermal resistance for the n-layer of the wall [m²K/W], R_{se} – output thermal resistance for horizontal heat flow [m²K/W].

The next step is calculation of the final heat transfer coefficient of the wall determined by the U parameter, which is shown in Formula 6:

$$U = \frac{1}{R_t} \quad (6)$$

where: U – total heat transfer coefficient [W/m²K], Rt – total thermal resistance [m²K/W].

The external and internal temperatures difference were taken in the next operation to calculate the thermal power losses through the wall determined by Formula 7:

$$P = U \cdot \Delta T \cdot S \quad (7)$$

where: P – demand for thermal power of the wall [W], ΔT – difference between outdoor and internal temperature [K], S – wall area [m²].

Heat transfer through the ceiling

The method of calculating the value of heat loses through the ceiling is identical to the walls of a building. The only difference concerns the values of the input and output heat resistances coefficients Rsi and Rse, which in the case of upward heat transfer are as follows: Rsi=0.1 m²K/W and Rse=0.04 m²K/W.

Calculations of energy consumed for heating

The calculation of the required energy in the heating period is presented in Formula 8.

$$E = \int_{t1}^{t2} P(t) \cdot dt \quad (8)$$

where: E – annual value of thermal energy [J], P – instantaneous values of required thermal power [W], $t1$ – Start of the heating period [s], $t2$ – End of the heating period [s].

Ventilation power loses

The calculation of the ventilation power loses is presented according to Formula 9.

$$P = \frac{c \cdot m \cdot \Delta T}{t} \quad (9)$$

where: c – specific heat of the air [J/kgK], m – mass of the air [kg], ΔT – difference in external and internal temperatures [K], t – ventilation time [s].

Distribution of external temperatures

Figure 3 presents the histogram of external temperatures. The most common temperatures are in the range between 0 °C and +1 °C for 723 hours. The lowest temperature values are in the range from -11 °C to -12 °C occurred for 2 h in the year, while the highest temperatures are in the range from 32 °C to 33 °C occurred only for 5 h in the year.

The average annual temperature from 1st January to 31st December was 7.95 °C, while the average temperature during the heating season between 13th December and 29th March (107 days) was 0.73 °C. It is worth mentioning that the building is located in the climatic zone, where the required design temperature for buildings is -20 °C.

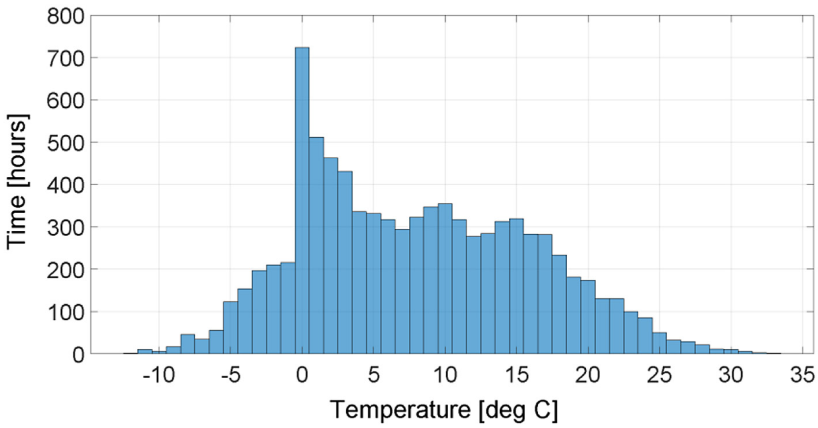

Figure 3. Histogram of the most common external temperatures

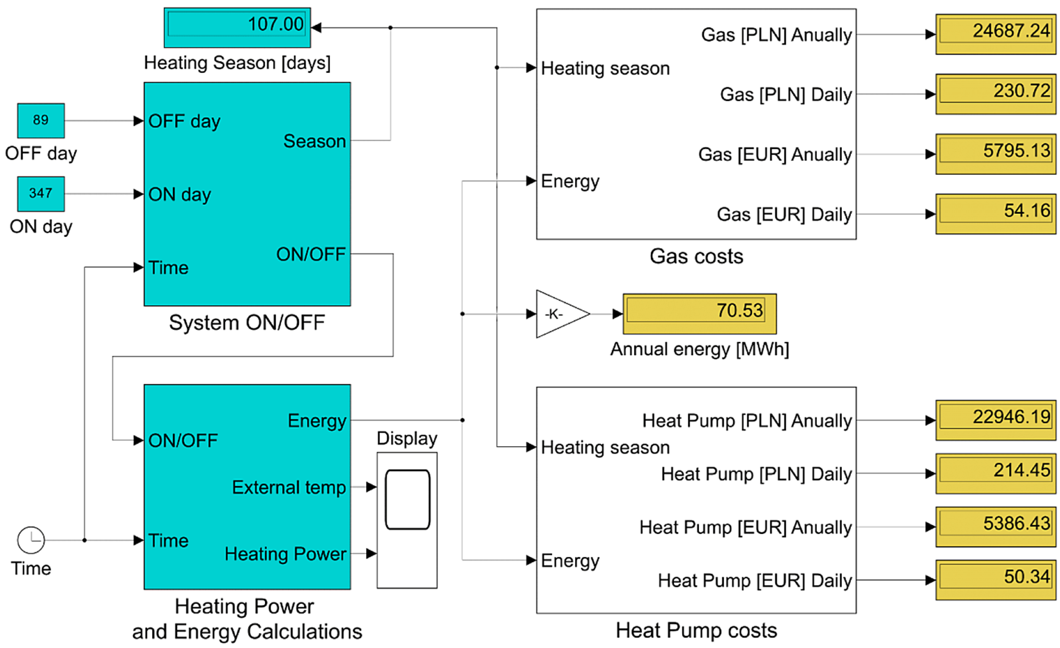

Figure 4. View of the simulation model in Matlab-Simulink 2022b

Simulation model

Figure 4 presents the simulation model created in Matlab Simulink 2022b. This simulation platform was selected for satisfactory method of implementation of mathematical formulas describing the tested object and easy conducting necessary calculations.

The main purpose of the model was calculation of the maximum required heating power, the annual energy demand, the annual costs of energy carriers and the annual value of CO_2 emission in the case of heating with gas and ground source heat pump.

The simulation model includes the mathematical formulas presented in the previous chapter where temporary values of the required parameters were calculated. Values are obtained for the external temperature range from -20 °C to +12 °C and from -20 °C to +7 °C according to the calculation variant described in next chapters. The first value is the minimum temperature in accordance to mentioned III Heating Zone in Poland, were building is located. The second value is the external temperature when the heating system is turned off.

The simulation model includes three control and computational blocks, where the input signals interact with other parameters, allowing the required values to be obtained. The first unit, the "System ON/OFF", is responsible for switching the heating system on and off according to the heating period. The second block "Heating Power and Energy Calculations" provides the instantaneous values of the required heating power and annual heating energy consumption. On the basis of these parameters, the annual value of CO_2 emissions is obtained. Last two blocks calculate energy costs of heat sources used in simulations. All values have been calculated in 1-hour steps throughout the year.

RESULTS

This chapter presents the results of the research. Required heating parameters for all variants of insulated and non-insulated building were presented. A method of determining power losses for ventilation has been proposed. Finally annual costs of energy carriers and CO_2 emission were estimated.

Results of peak power and thermal energy demand

As it was mentioned before, the building is located in the climatic zone, where, the minimum required calculation temperature for buildings is -20 °C. The results of required peak thermal power and energy demand for the variants differing in the values of internal temperature and the building insulation level:

- Variant 1 – building without thermal insulation. Indoor temperature +12 °C,
- Variant 2 – building without thermal insulation. Indoor temperature +7 °C,
- Variant 3 – building with thermal insulation. Indoor temperature +12 °C,
- Variant 4 – building with thermal insulation. Indoor temperature +7 °C.

Table 7 presents the results for Variant 1 (building without thermal insulation). The external temperature is -20 °C, and the internal temperature is +12 °C.

Table 8 presents the results for Variant 2 (building without thermal insulation). The external temperature is -20 °C, and the internal temperature is +7 °C.

Variants 3 and 4 refers to building with thermal insulation. The scope of insulation concerns:

Replacement of all internal windows with those that meet the requirements of the

Table 7. Analysis results for Variant 1

Variant calculations	External temperature [°C]	Internal temperature [°C]	Building element	Power losses [kW]
Variant 1	-20	+12	Floor 0 (altar)	7.62
			Building walls	92.51
			Ceiling (vault)	118.96
			Windows	21.19
			Entrance doors	2.11
			Building ventilation	11.33
Required power [kW]				241.73
Annual thermal energy consumption [MWh]				227.03

Table 8. Analysis results for Variant 2

Variant calculations	Temperature external [°C]	Temperature internal [°C]	Building element	Power losses [kW]
Variant 2	-20	+7	Floor 0 (altar)	6.43
			Building walls	78.06
			Ceiling (vault)	90.25
			Windows	17.88
			Entrance doors	1.78
			Building ventilation	9.56
Required Power [kW]				203.96
Annual thermal energy consumption [MWh]				123.08

current standards of total heat transfer coefficient through windows, at the level of 0.9 W/m²K or less. External windows remain unchanged. Thermal modernization of the ceiling (vault) should be performed from the attic side, because of easy access to areas that need to be insulated.

The thermal insulation used in the analysis specifies a heat transfer coefficient at the value of 0.026 W/m²K and a thickness of 15 cm. Using an insulation material with different heat transfer coefficient is possible, but requires recalculation of material thickness.

The building floor does not require thermal modernization, because underfloor water heating system was installed with proper thermal insulation from the ground. This element of the building has significantly the lowest heat losses. The main door to the building requires carpentry renovation only because of cracks caused by atmospheric conditions. The building interior is separated by vestibules with another internal door that reduces heat losses. The external walls are characterized by significant heat losses. According to the requirements of the Conservator's Office, thermal insulation is not possible to apply. Hence, this element must be unchanged.

Table 9 presents the results for Variant 3 (building with thermally insulated ceiling and

Table 9. Analysis results for Variant 3

Variant calculations	Temperature external [°C]	Temperature internal [°C]	Building element	Power losses [kW]
Variant 3	-20	+12	Floor 0 (Altar)	7.62
			Building walls	92.51
			Ceiling (vault)	5.49
			Windows	8.67
			Entrance doors	2.11
			Building ventilation	11.33
Required power [kW]				127.73
Annual heat consumption [MWh]				125.05

Table 10. Analysis results for Variant 4

Variant calculations	Temperature external [°C]	Temperature internal [°C]	Building element	Power losses [kW]
Variant 4	-20	+7	Floor 0 (altar)	6.43
			Building walls	78.06
			Ceiling (vault)	4.63
			Windows	7.32
			Entrance doors	1.78
			Building ventilation	9.56
Required power [kW]				107.78
Annual heat consumption [MWh]				70.53

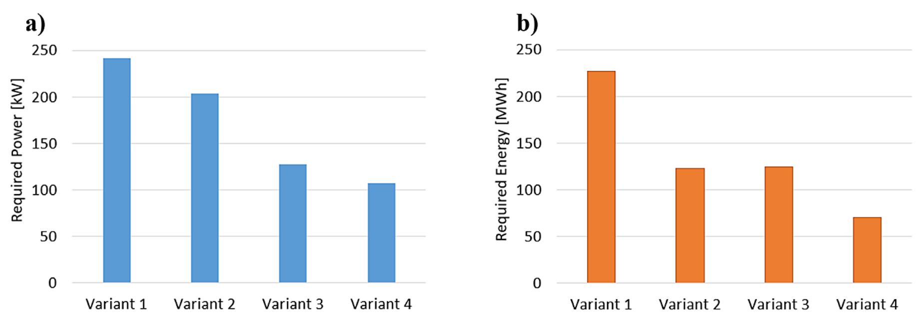

Figure 5. Results of the heating analysis: (a) values of required maximum power; (b) required annual energy

Table 11. Proposed ventilation parameters

Analyzed element	Value
Number of breaths by 1 person	65 breaths/min → 3900 breaths/h
Average lungs capacity	5 dm^3 = 0.005 m^3
Number of visitors	300
Total volume of humid air from lungs	97.5 m^3/min → 5850 m^3/h
Ratio of humid air volume to the building volume	34.11%
Suggested ventilation air flow and mass of the air	1000 m^3/h → 1250 kg/h
Ventilation time	5.85 h
Specific heat of the air	1020 J/kgK
Temperature difference (ext. -22 °C, int. +12 °C)	34 °C
Heat power loss	12.04 kW

windows). The external temperature is -20 °C, and the internal temperature is +12 °C.

Table 10 presents the results for Variant 4 (building with thermally insulated ceiling and windows). The external temperature is -20 °C, and the internal temperature is +7 °C.

Figures 5a and 5b presents graphically calculated values of the required power and annual energy for the analyzed Variants 1 to 4.

Building ventilation

Building ventilation power losses are crucial to maintaining proper indoor climate parameters. Table 11 contains calculated values of ventilation heat losses.

Air exchange requirement according to the present standards (twice per hour) results in significant power and energy losses. In the case of historic buildings with significant volumes, large spaces and etc., the authors of this article proposed an individual approach to this problem.

It was assumed that visitors in the number of 300 persons spent 1 h in the temple, where all the emitted moisture is accumulated inside the building and then removed by forced ventilation.

During this time, the volume of humid air increases to 5850 m^3, which equals to 34.11% of the total volume of the building. Using a 1000 m^3/h fan, it is possible to remove moisture in less than 6 hours, which results in a power losses at the value about 12 kW

Energy prices taken in analysis

Table 12 presents the costs of electric energy and gas in Poland and are calculated on the basis of bills. Electric energy is used to supply power to compressors of the ground source heat pumps, while gas is used as fuel for gas boilers. Prices are presented in PLN and EUR.

Verification of the simulation model

An important element of this research is the verification of the accuracy of the simulation model. Therefore, analyses results of the electric energy costs for supply power to the currently exploited, low quality ground heat pump were conducted. The devices operate in cascade mode with 25 kW of heating power. The required parameters are presented in Table 13.

Table 12. Prices of energy carriers taken in the analysis

Energy carrier	Energy quantity	Gross price [PLN]	Exchange rate PLN/EUR	Gross price [EUR]
Electrical energy	1 kWh	1.285	4.26	0.3016
Gas		0.350		0.0821

Table 13. Parameters of the current heating system and electric energy costs

Heating power system [kW]	Compressor electric power [kW]	COP [-]	Annual electric energy cost [PLN]		Electric energy costs error [%]
			Electric energy bills	Simulation model	
25.00	12.22	2.05	47 762	46 557	2.58

The obtained error was 2.58%. On the basis of the simulations, a satisfactory convergence of the calculated costs with the value of actual electric energy bills was reached.

Results of the analysis of thermal power and energy demand

This stage of the analysis is the determination of the energy carriers costs used for heating. For this purpose, the parameters of the ground heat pump with a heating capacity of 132 kW were used in the research. Detailed parameters of the device were described in the datasheet presented in [44]. The key parameter used in the analysis is the Seasonal Coefficient of Performance. The value of SCOP = 3.95 was taken in analysis.

Figure 6a presents the results of the most energy-efficient Variant 4 obtained from the simulation. It contains the external temperature and temporary heating power time waveforms obtained in 1 h step during a year. The histogram presented in Figure 6b describes the most frequent values of heating power applied to the building during heating season. The highest values of the operation time was 34345 min (23.8 day) for the heating power range between 30–35 kW. On the other hand the highest heating power 75–80 kW was reached for 436 min (7.3 h).

Annual CO_2 emissions

Table 14 presents the CO_2 emission values for the analysed heating methods of the building Variants 1–4. In Polish power system, the CO_2 emission cost is covered by energy producer (power plant), not by end user. This cost is not included in analysis, but is presented for comparison.

Table 15 presents the CO_2 emission factors and costs of emissions from natural gas and electric energy generated in the Polish power system.

Estimation of heating costs in PLN

Tables 16 and 17 presents four variants of the heating costs with a ground source heat pump with SCOP = 3.95 and natural gas. Cost of CO_2 emission for electric energy for user is zero, as mentioned in last chapter. In the case of gas, emission cost must be paid by the user.

Table 14. Annual emission of CO_2

Variant number	Ground heat pump [tonnes]	Natural gas [tonnes]
Variant 1 (241.73 kW)	166.41	62.89
Variant 2 (203.96 kW)	90.80	34.31
Variant 3 (127.73 kW)	91.65	34.64
Variant 4 (107.78 kW)	51.70	19.54

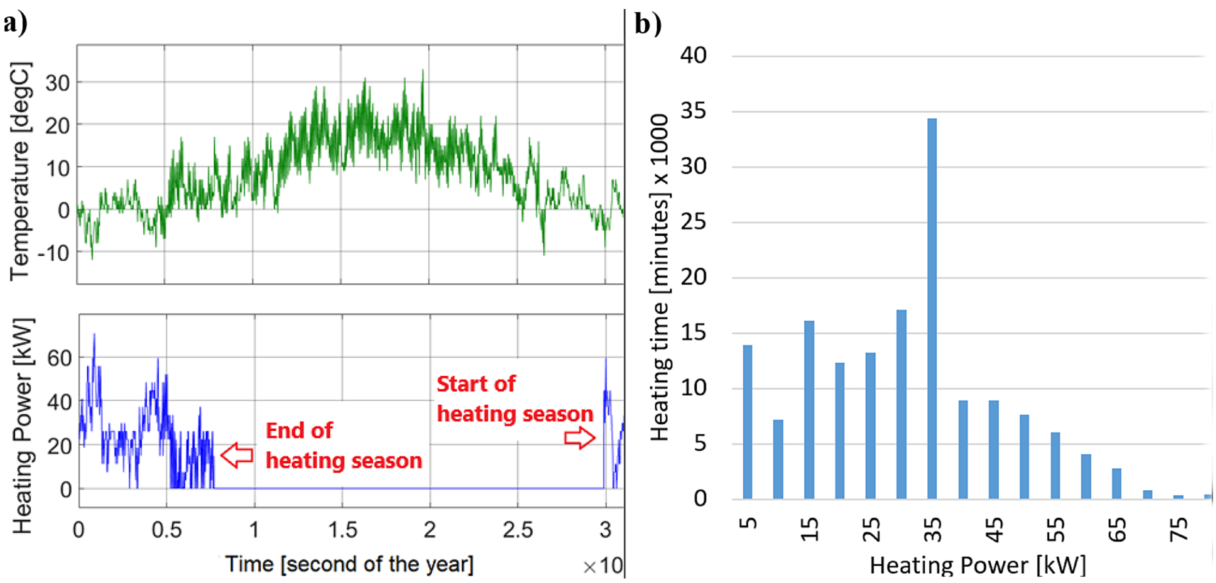

Figure 6. Results of Variant 4 obtained during research: (a) Selected waveforms of the temperature and heating power variation during a year; (b) Histogram of the heating power applied to the building

Table 15. The CO_2 emissions factors [45] and emission cost per 1000 kg [46]

Energy carrier	CO_2 emission factor [kg/kWh]	Cost of 1000 kg of CO_2 emission [EUR]
Electrical energy	0.733	65.45
Gas	0.227	

Table 16. Annual costs of ground source heat pump in PLN

Variant number	Electric energy cost	CO_2 emission cost	Total annual costs
Variant 1 (241.73 kW)	73 858	0	73 858
Variant 2 (203.96 kW)	40 295	0	40 295
Variant 3 (127.73 kW)	40 679	0	40 679
Variant 4 (107.78 kW)	22 946	0	22 946

Table 17. Annual costs of gas in PLN

Variant number	Gas cost	CO_2 emission cost	Total annual costs
Variant 1 (241.73 kW)	79 462	17 534	96 996
Variant 2 (203.96 kW)	43 353	9 567	52 920
Variant 3 (127.73 kW)	43 765	9 657	53 422
Variant 4 (107.78 kW)	24 687	5 447	30 134

Table 18. Annual costs of ground heat pump in EUR

Variant number	Electric energy cost	CO_2 emission cost	Total annual costs
Variant 1 (241.73 kW)	17 337	0	17 337
Variant 2 (203.96 kW)	9 459	0	9 459
Variant 3 (127.73 kW)	9 549	0	9 549
Variant 4 (107.78 kW)	5 386	0	5 386

Table 19. Annual costs of gas in EUR

Variant number	Electric energy cost	CO_2 emission cost	Total annual costs
Variant 1 (241.73 kW)	18 653	4 117	22 770
Variant 2 (203.96 kW)	10 176	2 246	12 422
Variant 3 (127.73 kW)	10 273	2 267	12 540
Variant 4 (107.78 kW)	5 795	1 279	7 071

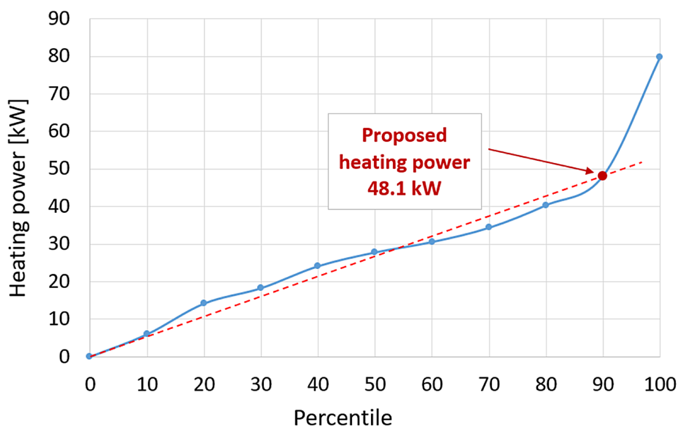

Figure 7. Percentile values of heating power

Table 20. Annual total costs of heating in PLN

Variant number	Ground heat pump	Gas heating
Variant 4 (107.78 kW)	24 687	30 595
Variant 5 (48.1 kW)	22 946	29 151
Difference	7.5%	4.9%

Table 21. Annual total costs of heating in EUR

Variant number	Ground heat pump	Gas heating
Variant 4 (107.78 kW)	5 795	7 181
Variant 5 (48.1 kW)	5 386	6 842
Difference	7.5%	4.9%

Estimation of heating costs in EUR

Tables 18 and 19 presents the costs calculated in EUR.

Possibilities of additional reduction of heating power and final installation costs

Visitors usually spends 1h in religious buildings. According to the opinion of the article authors, there is no need to use the maximum calculated above peak power to achieve the required internal temperature during the heating season. By agreeing to temporarily reduce the internal temperature, it is possible to significantly decrease the required heating power, and the final cost of the heating installation.

Figure 7 presents the percentile distribution of the heating power calculated for Variant 4. It presents that in the range between 0–90th percentile, the required heating power increases linearly and above the 90th percentile heating power increase significantly. The dotted line indicates that a heating power of 48.1 kW is the optimal value. Tables 20 and 21 present the annual heating costs for Variant 4 and the new Variant 5.

The calculated costs differences are 7.5% for electric energy and 4.9% for gas, while the installation power is reduced to 48.1 kW, which is 44.6% of the nominal power for Variant 4. Such a solution significantly reduces the heat source costs and heating installation final costs. According to the analysis, some disadvantages occur as well. For 10.7 days, the heating power will be lower than required, which should not be a problem for a building used 2–4 hours daily, especially in weekends during daytime.

CONCLUSIONS

The calculations of heating energy demand for historical sacral buildings is a multifaceted issue. This problem involves implementation of analyses related to building elements heat losses and require individual procedures to reduce them. Such knowledge is important due to possible changes in operation schedule of current heat sources or replacing them with new cost-efficient ones.According to the simulation model developed in this research, the annual heating costs with a ground source heat pump and a gas boiler for an insulated and non-insulated building were determined for two internal temperatures +12 °C and +7 °C. The results obtained from the simulations were compared with real energy bills for heating purposes. An error of 2.58% was obtained, indicating the high accuracy in calculation methodology. A similar approach to this topic has not been found in the literature review, so this is one of this article goalsOn the basis of the research, thermo-modernization of the building is key in reduction of the heating costs. The highest heat losses occurs through the ceiling and according to simulation results 95% of the energy can be saved. Another elements that need improvement are windows, were additional internal energy-efficient glazes with heat transfer coefficient at the level of 0.9 W/m^{2}K or less are recommended to install. According to simulation results, 60% of the heat losses through windows can be saved.

According to Variant 1 (current state of the building without thermal insulation) with internal temperature at the value of +12 °C required peak thermal power is 241.73 kW and annual energy consumption is equal to 227.03 MWh. Total heating cost during 107 days of heating period for ground heating pump is 73,858 PLN (17,337 EUR) and 96,966 PLN (22,770 EUR) for gas heating including CO_2 emission. In the author's opinion final costs are not acceptable.

According to Variant 4 (building with thermal insulation) with internal temperature at the value of +7 °C required peak thermal power is 107.78kW, and annual energy consumption is equal to 70.53 MWh. Total heating cost during 107 days of heating period for ground heating pump is 22,946 PLN (5386 EUR) and 30,134 PLN (7071 EUR) for gas heating including CO_2 emission. In the author's opinion final costs are still discussable.

Variant 5 presents the possibility of additional reduction of maximum heating power. According to research additional 7.5% of cost reduction can be achieved for ground heat pump and 4.9% for gas heating. The annual heating cost is ca. 25% lower for ground source heat pump and depends on temporary electric energy prices. The Polish Power System is mainly based on coal, were energy costs depends on CO_2 emissions in accordance with the ETS Directive. From 1.01.2027, a new ETS2 Directive will be implemented to the market, were the costs of CO_2 emissions from buildings will be included in the final energy bills. According to the report presented in [51], estimated price of 1000 kg of CO_2 emission to the beginning of 2027 is zero. Between 2027 and 2030 the emissions cost remains almost constant at the value of 220 PLN (52 EUR) per 1000 kg. After 2030, the cost is planned to increase significantly, which will affect to final gas prices.

Taking into account the above issues, many users face a difficult decision regarding the type of heat source choice. It seems that the proper solution are heat pumps and other renewable energy sources. Due to the high installation costs especially in old buildings, as well as costs of the complex thermal modernization and the high cost of electric energy, end users are still waiting to make a final decision. Therefore, gas is still a popular source of heat.

Acknowledgements

The article's authors would like to express their gratitude to Father Paweł Anusiewicz, the parish priest of Kosów Lacki (Poland), for providing the required documents for conducting this research.

REFERENCES

1. Talbot, R.; Hashemi, A.; Ashton, P.; Picco, M. Identifying Heating Technologies Suitable for Historic Churches, Taking into Account Heating Strategy and Conservation through Pairwise Analysis. In: Proceedings of the E3S Web of Conferences; 2021; Vol. 246.
2. Santamouris, M.; Vasilakopoulou, K. Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation. *e-Prime - Advances in Electrical Engineering, Electronics and Energy* 2021, *1*, 100002, https://doi.org/10.1016/j.prime.2021.100002.
3. Repelewicz, A. Rational increasing of energy efficiency of sacral buildings. *Management Systems in Production Engineering* 2017, *25*, https://doi.org/10.1515/mspe-2017-0018.
4. Talbot, R.; Hashemi, A.; Ashton, P.; Picco, M. Assessing Occupant Comfort in Historic Churches When Using Localised Heating Systems. In: Proceedings of the Building Simulation Conference Proceedings; 2023; Vol. 18.
5. Cai, Y.K.; Xie, H.R.; Ma, Y.; Hokoi, S.; Li, Y.H. Active Environmental Control Strategies for Brick Historical Buildings, Combining Heritage Conservation and Thermal Comfort. In: Proceedings of the Journal of Physics: Conference Series; 2021; Vol. 2069.
6. Zhang, Y.; Olofsson, T.; Nair, G.; Zhao, C.; Yang, B.; Li, A. Cold Windows Induced Airflow Effects on the Thermal Environment for a Large Single-Zone Building. In: Proceedings of the E3S Web of Conferences; 2020; Vol. 172.
7. Broström, T.; Wessberg, M. The Power from above - A Novel Church Heating System. In: Proceedings of the IOP Conference Series: Earth and Environmental Science; 2021; Vol. 863.
8. Aste, N.; Torre, S. Della; Adhikari, R.S.; Buzzetti, M.; Del Pero, C.; Leonforte, F.; Manfren, M. Sustainable church heating: The basilica Di Collemaggio case-study. *Energy Build* 2016, *116*, https://doi.org/10.1016/j.enbuild.2016.01.008.
9. Massarotti, N.; Mauro, A.; Normino, G.; Vanoli, L.; Verde, C.; Allocca, V.; Calcaterra, D.; Coda, S.; de Vita, P.; Forzano, C.; et al. Innovative solutions to use ground-coupled heat pumps in historical buildings: a test case in the city of Napoli, southern Italy. *Energies (Basel)* 2020, *14*, https://doi.org/10.3390/en14020296.
10. Napp, M.; Kalamees, T. Energy Use and indoor climate of conservation heating, dehumidification and adaptive ventilation for the climate control of a mediaeval church in a cold climate. *Energy Build* 2015, *108*, https://doi.org/10.1016/j.enbuild.2015.08.013.
11. Khalid, Y.; Ngwaka, U.; Papworth, J.; Ling-Chin, J.; Smallbone, A. Evaluation of decarbonisation options for heritage church buildings. *Journal of Building Engineering* 2023, *77*, https://doi.org/10.1016/j.jobe.2023.107462.
12. Pisello, A.L.; Petrozzi, A.; Castaldo, V.L.; Cotana, F. Energy Refurbishment of Historical Buildings with Public Function: Pilot Case Study. In: Proceedings of the Energy Procedia; 2014; Vol. 61.
13. Branca, I.-C. Considerations regarding the solutions for heating and cooling of cult buildings. *Bulletin of the Polytechnic Institute of Iași. Construction. Architecture Section* 2021, *67*, https://doi.org/10.2478/bipca-2021-0014.
14. Metals, M.; Lesinskis, A.; Turauskis, K. Control

of Indoor Climate of Historical Cult Buildings. In: Proceedings of the E3S Web of Conferences; 2021; Vol. 246.

15. Semprini, G.; Galli, C.; Farina, S. Reuse of an Ancient Church: Thermal Aspect for Integrated Solutions. In: Proceedings of the Energy Procedia; 2017; Vol. 133.
16. Marinosci, C.; Morini, G.L.; Semprini, G.; Garai, M. Preliminary Energy Audit of the Historical Building of the School of Engineering and Architecture of Bologna. In: Proceedings of the Energy Procedia; 2015; Vol. 81.
17. Zhang, Y.; Zhao, C.; Olofsson, T.; Nair, G.; Yang, B.; Li, A. 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 Build* 2022, *255*, https://doi.org/10.1016/j.enbuild.2021.111646.
18. Aste, N.; Torre, S. Della; Adhikari, R.S.; Buzzetti, M.; Del Pero, C.; Leonforte, F.; Cardenas, H.E.H. CFD Comfort Analysis of a Sustainable Solution for Church Heating. In: Proceedings of the Energy Procedia; 2017; Vol. 105.
19. Obstawski Paweł and Tomczuk, K. High-temperature two-stage subcritical heat pump running on environmentally friendly refrigerants. *Advances in Science and Technology Research Journal* 2024, *18*, 369–381, https://doi.org/10.12913/22998624/187103.
20. Tomczuk, K.; Obstawski, P. Analysis of the cooperation of a compressor heat pump with a PV system. *Sustainability* 2024, *16*, https://doi.org/10.3390/su16093797.
21. Muñoz González, C.M.; León Rodríguez, A.L.; Suárez Medina, R.; Ruiz Jaramillo, J. Effects of future climate change on the preservation of artworks, thermal comfort and energy consumption in historic buildings. *Appl Energy* 2020, *276*, 115483, https://doi.org/10.1016/j.apenergy.2020.115483.
22. Sesana, E.; Bertolin, C.; Gagnon, A.S.; Hughes, J.J. Mitigating Climate Change in the Cultural Built Heritage Sector. *Climate* 2019, *7*, https://doi.org/10.3390/cli7070090.
23. Cabeza, L.F.; de Gracia, A.; Pisello, A.L. Integration of Renewable Technologies in Historical and Heritage Buildings: A Review. *Energy Build* 2018, *177*, 96–111, https://doi.org/10.1016/j.enbuild.2018.07.058.
24. Wessberg, M.; Broström, T.; Vyhlidal, T. A Method to Determine Heating Power and Heat up Time for Intermittent Heating of Churches. *Energy Procedia* 2017, *132*, 915–920, https://doi.org/10.1016/j.egypro.2017.09.720.
25. Malaguti, V.; Lodi, C.; Tartarini, P. Dynamic analysis of the role of thermal inertia in the heating system control of historical and monumental buildings. *Tecnica Italiana-Italian Journal of Engineering Science* 2019, *63*, https://doi.org/10.18280/ti-ijes.632-430.
26. Vallati, A.; Di Matteo, M.; Fiorini, C.V. Retrofit proposals for energy efficiency and thermal comfort in historic public buildings: The case of the engineering faculty's seat of Sapienza University. *Energies (Basel)* 2023, *16*, https://doi.org/10.3390/en16010151.
27. Resuli, P.; Dervishi, S. Thermal Performance of Cultural Heritage Italian Housing in Albania. In: Proceedings of the Energy Procedia; 2015; Vol. 78.
28. Saio, C.; Nocentini, K.; Tagliafico, L.A.; Biwole, P.H.; Achard, P. Application of advanced insulating materials in historical buildings. *International Journal of Heat and Technology* 2017, *35*, https://doi.org/10.18280/ijht.35Sp0147.
29. Webb, A.L. Energy Retrofits in historic and traditional buildings: A review of problems and methods. *Renewable and Sustainable Energy Reviews* 2017, *77*.
30. Ceroni, F.; Ascione, F.; Masi, R.F. De; Rossi, F. De; Pecce, M.R. Multidisciplinary Approach to Structural/Energy Diagnosis of Historical Buildings: A Case Study. In: Proceedings of the Energy Procedia; 2015; Vol. 75.
31. Magrini, A.; Franco, G.; Guerrini, M. The Impact of the Energy Performance Improvement of Historic Buildings on the Environmental Sustainability. In: Proceedings of the Energy Procedia; 2015; Vol. 75.
32. Melin, C.B.; Legnér, M. The relationship between heating energy and cumulative damage to painted wood in historic churches. *Journal of the Institute of Conservation* 2014, *37*, https://doi.org/10.1080/19455224.2014.939096.
33. Aparicio-Fernández, C.; Torner, M.E.; Cañada-Soriano, M.; Vivancos, J.L. Analysis of the energy performance strategies in a historical building used as a music school. *Developments in the Built Environment* 2023, *15*, https://doi.org/10.1016/j.dibe.2023.100195.
34. Emmi, G.; Zarrella, A.; De Carli, M.; Moretto, S.; Galgaro, A.; Cultrera, M.; Di Tuccio, M.; Bernardi, A. Ground source heat pump systems in historical buildings: Two italian case studies. In: Proceedings of the Energy Procedia; 2017; Vol. 133.
35. Baborska-Narożny, M.; Laska, M.; Fidrów-Kaprawy, N.; Małyszko, M. Circadian Winter Thermal Profiles and Thermal Comfort in Historical Housing - Field Study. In: Proceedings of the Journal of Physics: Conference Series; 2021; Vol. 2069.
36. Marina Domingo, A.M.; Rey-Hernández, J.M.; San José Alonso, J.F.; Crespo, R.M.; Rey Martínez, F.J. Energy efficiency analysis carried out by installing district heating on a university campus. A case study in Spain. *Energies (Basel)* 2018, *11*, https://doi.org/10.3390/en11102826.
37. Elnagar, E.; Munde, S.; Lemort, V. Energy efficiency

measures applied to heritage retrofit buildings: A simulated student housing case study in Vienna. *Heritage* 2021, *4*, https://doi.org/10.3390/heritage4040215.

38. Staffell, I.; Pfenninger, S.; Johnson, N. A Global model of hourly space heating and cooling demand at multiple spatial scales. *Nat Energy* 2023, *8*, https://doi.org/10.1038/s41560-023-01341-5.
39. Basińska M. The use of multi-criteria optimization to choose solutions for energy-efficient buildings. *Bulletin of Polish Academy of Sciences Technical Sciences* 2017, *65*, 815–824.
40. VargovÁ, A.; Ingeli, R. Assessment of the energy demands for heating in an historic building. case study: renewal of a functionalist building of the infectious diseases pavilion in Topoľčany, Slovakia. *Slovak Journal of Civil Engineering* 2021, *29*, 29–36, https://doi.org/10.2478/sjce-2021-0025.
41. Zulgowska-Zgrzywa, M.; Piechurski, K.; Stefanowicz, E.; Baborska-Narożny, M. Multi-criteria assessment of the scenarios of changing the heating system in apartments in historical buildings in Wroclaw (Poland) – Case study. *Energy Build* 2022, *254*, 111611, https://doi.org/10.1016/j.enbuild.2021.111611.
42. Miasto i Gmina Kosów Lacki City of Kosów Lacki Web Site Available online: https://kosowlacki.pl/page/zabytki (accessed on 13 September 2024).
43. Wikipedia Józef Pius Dziekoński Available online: https://pl.wikipedia.org/wiki/J%C3%B3zef_Pius_Dzieko%C5%84ski (accessed on 13 September 2024).
44. Viessmann Vitocal Datasheet Available online: https://viessmanndirect.co.uk/files/499b1238-03e0-4b0c-b7d5-adda016de3ff/Technical%20Guide.pdf?srsltid=AfmBOorEGF3bS1fJo5ZPgGS6eMQcWZtrnvx-2YwDxySoRSdUiWF364Ut (accessed on 26 September 2024).
45. Wytyczne Dotyczące Konwersji - Emisje Gazów Cieplarnianych Available online: https://www.parp.gov.pl/storage/grants/documents/105/Wytyczne-dotyczce-konwersji-emisje-gazw-cieplarnianych_20200225.pdf (accessed on 27 September 2024).
46. CO2 Emission Allowances Price in EU ETS System.
47. Adamczewski T.; Kleinschmidt P. Budynki w pułapce gazowej. Available online: https://www.forum-energii.eu/download/pobierz/budynki-w-pulapce-gazowej (accessed on 2 December 2024).