Church heating: comparison of different strategies

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Abstract — **Church heating represents a challenging task because multiple goals have to be fulfilled simultaneously, such as the thermal comfort for the occupants and the optimal internal environmental conditions for the preservation of building components and artworks. In addition, current requirements for environmental and economic sustainability impose to make efforts to minimize the amount of energy needed and the consequent environmental/economic impact. In this context, the present work represents the assessment of the energy, environmental and economic impact of different strategies for church heating, including a novel technology based on the exploitation of renewable energies. The analysis was carried out in a real case-study building, represented by the Basilica di S. Maria di Collemaggio (L'Aquila, Italy), a church of worldwide relevance, currently under restoration.**

Index Terms - **Electric heating; sustainable church heating; friendly heating; cost analysis.**

I. Introduction

Heating historical buildings and, in particular, churches, during the winter has different purposes; first of all it aims to ensure an acceptable thermal comfort level to occupants and, secondly, to provide optimal indoor conditions to prevent the deterioration of building components and artworks [1]. However, conservation requirements and energy/running cost saving have hardly been considered while designing heating systems for historic churches. In fact, the low cost of fossil fuels before the 80' in many cases favored the installation of low-efficiency technical systems that currently determines very high specific primary energy consumption (i.e. kWh/m^2) and running costs [2, 3], even if the churches are commonly heated for few hours in a day/week. In facts, historic churches are typically characterized by very huge air volumes and high thermal mass, and results a significant thermal power and energy demand for heating.

In detail, considering the most widespread existing technical systems in churches, it can be stated that two main configurations can be usually found [4]:

1) Central heating, which is a configuration based on a main heat generator (i.e. a gas boiler), a distribution and an emission subsystem, designed to heat the whole church environment;

2) Local heating, which is typically composed by decentralized elements (i.e. infrared heaters) directly placed inside the church and mainly aimed to heat the churchgoers rather than the internal air.

Both the above-mentioned configurations can be coupled with two different operating strategies:

- Constant operation, which ensures that during the daytime or the whole opening period of the church the system is fully operated, typically with a thermostat control;
- Intermittent operation (on-demand), which implies to switch-on the heating system just in case of particular events such as the celebrations. In this case the control system is a timer.

Several research works demonstrated that central heating, specifically with intermittent operation, creates problems in historic churches [5, 6, 7]. In fact, this solution is frequently operated using an all-air system which determines strong fluctuations of air temperature and relative humidity, with consequent negative effects both on comfort and on artworks [8]. In some cases, the internal space is not heated uniformly resulting in sharp contrasts between warm-heated spaces and cold-unheated ones, leading to condensation and mold growth on cold wall surfaces.

Under an economic point of view, central heating is often based on outdated natural gas or diesel boilers with low efficiencies, coupled with air blowers, resulting in non-negligible energy costs.

In some cases, the operation of central heating could also be all-day-long in order to control the relative humidity and avoid abrupt changes in thermo-hygrometric conditions (conservation heating) but this solution usually implies huge running costs due to the high amount of required thermal energy.

On the contrary, local heating, which is more frequently coupled with intermittent operation, typically has a lower/negligible impact on the artworks and ensures competitive running costs [9, 10]. In facts, the variation in air temperature and relative humidity is limited to the areas occupied by churchgoers and usually the heating mechanism is mainly based on irradiation rather than convection, thus involving limited quantity of energy. The typical technical solutions are in fact infrared heaters (powered with natural gas or electricity) or radiant surfaces such as radiant footboards or pew-based heaters. In this sense, the solution developed within the EU project "Friendly Heating" represents a very interesting option for historic churches because it combines good local comfort levels with significant energy savings and

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low or no impact on the artworks and on the building structures [11, 12].

In general, it must be noted that in case of electric solutions based on the Joule-effect, in some contexts the installation and running expenditures can be non-negligible because of the high cost of both the electricity and the connection to the grid with an electric power that generally exceeds 20-25 kW also for small-medium size churches [13].

In such context, the present work represents the prosecution of a previous research [14, 15] carried out on the same case-study, the Basilica di Collemaggio, where different heating strategies were compared under the energy and environmental point of view. In particular, the aim of this work is to assess also the economic impact of each solution by means of a global-cost analysis and to demonstrate the cost-effectiveness of a novel hydronic pew-based heating system coupled with a geothermal heat pump. The latter solution was in fact selected as the best option and is currently being installed in the church.

II. Description of the case-study

The Basilica di S. Maria di Collemaggio, L'Aquila has a rectangular floorplan (26 m × 95 m) with a maximum height of 21 m. The floor surface of the church is about 2,120 m^2 and its net volume is about 34,800 m^3. The total thermal dispersing surface is 8,380 m^2 and the S/V value is 0.24. The walls have a high thermal mass (limestone with a variable thickness from 1 m to 2.6 m) while the roof is made by construction wood, covered with roofing tiles. The church was damaged by the earthquake that struck L'Aquila in 2009 and is currently under a deep restoration. Considering the cold climatic condition of L'Aquila (2,514 heating degree day) the restoration project included also the installation of a heating system to ensure acceptable thermal comfort conditions during the celebrations in wintertime. For such reason, a detailed dynamic energy simulation was carried out to assess the behavior in free-floating conditions [14]. In particular, it was observed that the church's indoor air temperature during the heating season (October-April) ranges between 7.4°C and 12.4°C, with an average value of 9.9°C.

The same energy model was used to assess the thermal energy demand considering continuous heating, which is equal to 562 MWh/year, corresponding to approximately 265 kWh/m^2year. The maximum thermal power in design day conditions has been evaluated equal to approximately 500 kW.

The Church's usage profile considered for all the energy and cost analyses is: opening hours from 9.00 to 19:00 every day, 1 celebration per day from Monday to Saturday and 2 celebrations per day on Sunday. Each celebration lasts one hour and a maximum capacity of 500 persons (300 seated and 200 standing) for each celebration was assumed.

III. Technical description of the heating strategies and calculation of the investment cost

In the present section, the different heating strategies that were considered actually feasible in the specific context of the Basilica are described under the technical point of view. For each solution, the real constraints of the church were carefully examined to size the components and estimate the installation works; additional technical details can be found in [14].

In addition, a cost-analysis was carried out considering the current market price of all the required components and labor for each configuration. The single cost items were mainly derived from reference price lists for public works in Italy [16,17] and verified, where feasible, with average literature values [18]; the final expenditures summarized hereafter should be considered as turnkey costs excluding VAT.

Moreover, it must be noted that when constant operation was assumed, it was considered to heat the Basilica during the whole daytime opening-period, while for intermittent operation just the scheduled celebrations were taken into account as heating periods.

<u>Solution 1 – All-air system (daytime operation)</u>

The system is constituted by a hot-air generator equipped with a natural gas condensing boiler. Both the boiler and the ventilating blowers can be continuously modulated to fit the operation conditions with the thermal loads of the church. The air is supplied to the indoor space through air ducts and high induction diffusers. The exhaust air flows back through ducts to the hot-air generator and can be recirculated or discharged through a heat recovery unit to pre-heat the fresh air. The gas boiler has a nominal power of 550 kW and the maximum air flow rate is 35,000 m^3/h. About 150 m of air ducts are required for the supply and the exhaust air.

The reference costs of the system are summarized in the following table.

TABLE I
Cost items for the all-air system with daytime operation

Item	Costs [€]
Hot-air generator including the gas boiler	35,000
Supply and exhaust air ducts	30,000
Inlet air diffusers and exhaust air grills	12,000
Dampers, control and management system, fittings	15,400
Total	**92,400**

<u>Solution 2 – All-air system (on demand operation)</u>

The system is constituted by two hot-air generators equipped with natural gas condensing boilers. Also in this case the air is supplied to the indoor space through ducts and high induction diffusers, which are sized to face a higher flow rate compared to Solution 1, in order to quickly heat the air volume. The exhaust air flows back through ducts to the hot-air generator and can be recirculated or discharged through a heat recovery unit to pre-heat the fresh air.

Each boiler has a nominal thermal power of 350 kW and the maximum air flow rate is 28,000 m^3/h. About 200 m of air ducts are required for supply and exhaust air.

The reference costs of the system are summarized in the table II.

TABLE II
COST ITEMS FOR THE ALL-AIR SYSTEM WITH ON DEMAND OPERATION

Item	Costs [€]
Hot-air generators including the gas boilers (2 units)	58,000
Supply and exhaust air ducts	40,000
Inlet air diffusers and exhaust air grills	16,000
Dampers, control and management system, fittings	22,800
Total	**136,800**

Solution 3 – Gas-fired infrared heaters (on demand operation)

The system in constituted by 20 gas-fired infrared heaters installed at medium-height in the occupied zones of the church and equipped with low-NO_X (class 5) ceramic plates. Only the occupied zone is radiated. The ceramic plates are designed to quickly reach their operation temperature (900°C). The natural gas supply pipes must be installed in order to reach each heater. The exhaust gases can be discharged outside the church through small ducts. The thermal power of each generator is 20 kW.

The reference costs of the system are summarized in the following table.

TABLE III
COST ITEMS FOR GAS-FIRED INFRARED HEATERS

Item	Costs [€]
Gas-fired infrared heaters (20 units)	60,000
Natural gas supply network	9,000
Control and management system, fittings	10,350
Total	**79,350**

Solution 4 – Electric infrared heaters (on demand operation)

The system is constituted by 140 electric infrared heaters installed in the same zone and at the same height of the gas-fired heaters described for the Solution 3. The heaters are equipped with electric resistances with an operating temperature of 900°C, managed by an electronic system for temperature controls. Each heater has a nominal power of 3 kW. The needed wirings and power supply equipment have to be provided for each unit.

The reference costs of the system are summarized in the following table.

TABLE IV
COST ITEMS FOR ELECTRIC INFRARED HEATERS

Item	Costs [€]
Electric infrared heaters (140 units)	53,900
Wirings and power supply equipment	21,000
Main electric board, control system	14,000
Total	**88,900**

It must be noted that the abovementioned costs don't consider the possible need of realizing a medium-voltage electric supply, which could be required for the considerable electric power requested.

Solution 5 – Pew-based electric heating (on demand operation)

The system is constituted by electric radiant plates to be directly installed on the church's wooden pews. The main component of the system are the following.

- Support panel;
- Insulating panel;
- Heating film;
- Protection and heat diffusing film;
- Wooden topcoat.

The heating film has a support panel on which carbon conductive stripes are deposited. The heating power of the system depends on the topcoat and for wooden foil is equal to 220 W/m^2. In the present case, due to the geometry of each pew, a total radiant surface of 1.8 m^2 and a related power of 400 W per pew was estimated.

The reference costs of the system are summarized in table V.

TABLE V
COST ITEMS FOR PEW-BASED ELECTRIC HEATERS

Item	Costs [€]
Electric infrared heaters (per pew)	700
Wirings and power supply equipment (per pew)	200
Main electric board, control and management system (per pew)	150
Total (60 pews)	**63,000**

Considering a total of 60 pews, an electric power of 24 kW is needed, thus the power supply can be done in low-voltage with the existing church infrastructure.

Solution 6 – Pew based hydronic heating (on demand operation)

The system is constituted by hydronic radiant plates integrated in each wooden pew. The plates are realized with extruded aluminium profiles, provided with internal ducts with circular section, where the heat transfer fluid flows, and can directly be covered with a thin layer of wood as a finishing. The heat generator is a geothermal water-to-water heat pump with a nominal power of 30 kW (water-glycol temperature at 0°C, and supply water temperature at 40 °C) and a seasonal coefficient of performance (SCOP) equal to 4. The heat exchange with the ground is based on four, 150 m deep, boreholes, placed on the back of the Basilica. The system includes also a water tank both for peak loads management and acting as an interface element between the primary circuit (heat pump) and the secondary one (supply to the pew-based heating elements). Variable-speed circulation pumps, equipped with inverter, are used in the hydronic circuits realized with plastic multilayer pipes mainly placed above the floor. The whole system is managed by the control unit integrated in the heat pump and for the specific case-study it is designed to work with an inlet water flow temperature in the pews equal to 35°C. The same radiant surface (1.8 m^2 per pew) of the Solution 5 was assumed.

The reference costs of the system are summarized in the following table.

TABLE VI

COST ITEMS FOR PEW-BASED HYDRONIC HEATERS

Item	Costs [€]
Hydronic radiant plates with hydraulic connections (per pew)	850
Boreholes (4 units, 150 m. deep each)	23,000
Heat pump and water tank	22,000
Primary and secondary hydronic circuits, pumps and valves.	6,500
Control and management system	1,500
Total (60 pews)	**104,000**

IV. GLOBAL-COST ANALYSIS

In order to evaluate the cost-effectiveness of each proposed solution, the global cost (C_G) during a reference lifetime was calculated for all the analysed options. In general, C_G accounts the initial investment cost and the annual operation costs, by means of a present worth analysis to construct the cumulative cash flow (year by year) and is calculated according to the following formula [19]:

$$C_G(t)=C_I+\sum_{i=1}^{t}\frac{C_{a,i}}{(1+r)^i}-V_{f,t} \qquad (1)$$

where:
C_I: initial investment cost, as calculated in section III (€);
$C_{a,i}$: the annual running cost during each year i, which is the cost of the energy (electricity and/or natural gas) and the maintenance cost (€);
t is the length of the calculation period (years);
r: is the real interest rate (-);
$V_{f,t}$: is the residual value of the components at the end of the calculation period (€).

To estimate the annual running cost $C_{a,i}$, the total annual demand of electricity and/or natural gas for each solution was assumed as calculated in [14] and summarized in the following table.

TABLE VII

ANNUAL DEMAND OF PRIMARY ENERGY, NATURAL GAS AND ELECTRIC ENERGY

System	Primary Energy	Natural Gas	Elect. Energy
	MWh	*MWh*	*MWh*
1) All-air daytime	410	380	13.8
2) All-air on demand	145	140	2.3
3) Gas-fired IR on demand	78	78	0,0
4) Electric IR on demand	168.5	0	77.3
5) Electric pew-based on dem.	22.73	0	10.4
6) Hydronic pew-based on dem.	6.7	0	3.1

Furthermore, the prices of electricity and natural gas were derived considering the mean tariffs in Europe for household sector [20]. The average maintenance cost and the expected lifetime for each main component (e.g. hot-air generator, heat pump, etc.) were instead considered as a percentage of the investment cost, according to the values reported in the EN 15459 and summarized below.

TABLE VIII

REFERENCE LIFESPAN AND ANNUAL MAINTENANCE

Main component	Average Lifespan	Average annual maintenance in % of the initial investment
Hot-air generators	17.5	3
Gas boilers/burners	20	1.5
Electric heaters	22.5	1
Electric radiant panels	30	2
Hydronic radiant panels	30	2
Heat pumps	17.5	3
Fans	17.5	4
Air ducts and diffuser	30	2
Pipes/wires	40	1

The reference calculation period was set equal to 30 years, which is a reasonable value commonly used for cost-optimal assessments of technical systems and energy saving measures [21]. Consequently, considering the above-reported average lifespans, the replacement cost was accounted when necessary. To simplify the evaluation, the residual value of the components at the end of the calculation period $V_{f,,t}$ is supposed equal to 0 in all cases. The global cost C_G was therefore obtained adding up the initial investment cost C_I and the annual running cost $C_{a,I}$, actualized for each year of the calculation period.

The other fundamental assumptions for the calculation of the actualized $C_{a,i}$ are summarized in the following table.

TABLE IX

REFERENCE PARAMETERS FOR THE ECONOMIC ANALYSIS

Parameter	Unit	Value
Electricity cost	€/MWh	20
Natural gas cost	€/MWh	70
Rate of annual increase of energy cost	%	2.0
Real investment rate (r)	%	3.0

The global cost $C_G(30)$ for each heating solution is thus reported in Figure 1.

In order to allow an economic and environmental assessment, also the expected CO_2 emissions of each scenario were reported in the graph, considering a primary energy factor equal to 1 for natural gas and 2.18 for electricity.

From the above-reported results, it can be observed that the incidence of running expenditures on the final global cost is considerably relevant for the solutions from 1 to 4. On the contrary, both pew-based solutions have very low running costs, with particular reference to the hydronic one. The latter requires a slightly higher investment compared to that of the electric pew-based system but is the solution which minimize the overall CO_2 emission thanks to the capability to exploit the geothermal renewable energy. Thus, such solution can be considered the best under the economic and environmental point of view.

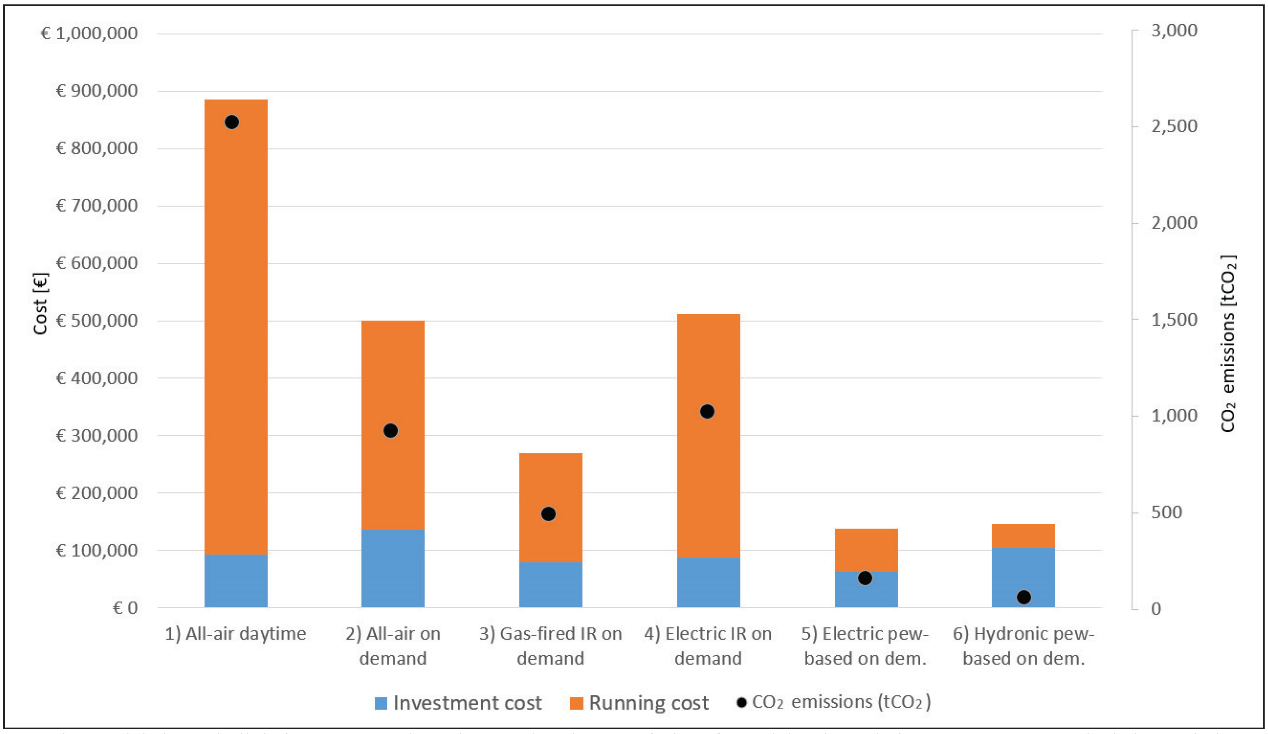

Fig. 1. Global cost (spilt in investment and running costs) and CO_2 emissions for each heating solution over a 30-years calculation period

V. Conclusions

The present work represents the assessment of the energy, environmental and economic impact of different strategies for church heating. The feasible solutions for the Basilica di S. Maria di Collemaggio were analysed, including a novel pew-based hydronic system for local comfort. The obtained result in terms of global cost demonstrated that pew-based systems (electric or hydronic), which are the most suitable in terms of comfort and artworks preservation, achieve also the best cost-effectiveness on a reference period of 30 years. Furthermore, the hydronic version also minimizes the amount of CO_2 emission and enables the exploitation of renewable energy.

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