energies

MDPI

Article

Improving the Energy Efficiency, Limiting Costs and Reducing CO_2 Emissions of a Museum Using Geothermal Energy and Energy Management Policies

Gianluca Cadelano [1,*], Francesco Cicolin [1], Giuseppe Emmi [2], Giulia Mezzasalma [3], Davide Poletto [4], Antonio Galgaro [5] and Adriana Bernardi [1]

1 Istituto per l'Atmosfera e il Clima, Consiglio Nazionale delle Ricerche, 35137 Padua, Italy
2 Dipartimento di Ingegneria Industriale, Università degli Studi di Padova, 35131 Padua, Italy
3 R.E.D. Srl, 35129 Padua, Italy
4 UNESCO Regional Office for Science and Culture in Europe-Science Unit, 30122 Venice, Italy
5 Dipartimento di Geoscienze, Università degli Studi di Padova, 35131 Padua, Italy
* Correspondence: gianluca.cadelano@itc.cnr.it

Received: 10 July 2019; Accepted: 7 August 2019; Published: 20 August 2019

check for updates

Abstract: Museums are major energy consumers amongst buildings, especially if they are housed in historical constructions. Museums usually present high energy demand for the air-conditioning due to their architectonical and structural characteristics, such as the presence of large exhibition rooms and open spaces. At the same time, temperature and humidity have to be strictly controlled in order to assure proper microclimate conditions for the conservation of the housed collections and adequate thermal comfort for visitors and personnel. Moreover, despite being subjected to architectural protection that limits most structural refurbishment interventions, these buildings must be adequate from an energy point of view to allow their reuse or continuity of use according to current quality standards, while retaining their heritage significance. In this awkward context, ground source heat pump working with high temperature terminals is proposed as a viable refurbishment solution. The use of shallow geothermal systems can improve the energy efficiency of the heating ventilation air-conditioning systems and, at the same time, increases the renewable energy source exploitation without affecting the indoor environmental conditions. However, after the interventions, the expected benefits and the sought-after limitation of energy consumption/cost may not occur for different reasons. In fact, even if the installed solution is working perfectly and properly designed, every effort will be in vain if adequate attention is not paid to the management of the plants during the operational phase. This document is meant to evaluate and compare the magnitude that invasive (i.e., technical interventions) and not invasive (i.e., energy management policies) actions respectively and their combined interaction, have on a museum. Through energy simulations it has been possible to quantify the effects that different interventions and energy management strategies had on an existing museum housed in an historical building, from energy consumption, energy costs and CO_2 emission standpoints.

Keywords: energy management; energy efficiency; geothermal energy; museum management; historical building; thermal comfort; cultural heritage conservation; indoor microclimate; energy saving; energy simulations; CO_2 emissions; sustainable energy

1. Introduction

Museums represent an interesting case in the field of energy efficiency among monumental buildings within the context of sustainable development and climate change mitigation measures. They have a high use of energy due to the air-conditioning of large exhibition rooms and space in general and to the high air-change rate because of the large numbers of visitors. Museums are habitually large energy consumers because of the need to provide tight humidity control, and additionally often have specific and/or different heating and cooling requirements for their artifacts and collections.

Historical and listed buildings, often hosting museums or art galleries, are a large part of the building stock in Europe, especially in countries such as Italy, both in terms of quantity and economic value [1].

These buildings, despite being subjected to architectural protection or strict indoor microclimate requirements, are required to comply with the current standards on energy performance, thermal comfort and safety, to allow their reuse or continuity of use, while retaining their heritage significance [2].

Buildings account for around 40% of energy consumption in the member states of the European Union. For this reason, the EU has sought to contain energy consumption and improve the efficiency performance of buildings with important provisions: Following the 2010 directive on energy consumption in buildings and the 2012 energy efficiency directive, recently, the 2018/844/EU provision was enacted, which came into force on 9 July 2018.

These regulations are applied through energy efficiency measures on the building envelope and systems, including technological solutions compatible with the exploitation of renewable energy sources. If properly planned, these interventions are suitable for the preservation of the collections and for their enhancement, making a historic building adapt for hosting visitors, thus allowing the continuity and recovery of a large part of the stock building.

The functional adaptation and the need to ensure the thermos-hygrometric conditions suitable for the conservation of work of arts and other museum objects, require a planning effort to correctly balance between the importance of conservative aspects and the choice in the installation of systems and technological solutions [3].

In fact, from a purely technical point of view, historic buildings always represent an unfavorable scenario, because of the different constraints they are subject to and which inevitably limit the use of energy solutions that are more efficient but impacting architecturally. Nevertheless, at the policy level, museums are required to keep pace with new societal, technological and cultural challenges [4].

2. Energy Efficiency Improvement in Historical Buildings and Museums

The special characteristics of the cultural heritage may make it necessary to proceed with special care during the installation of the systems in order to preserve the architectural and aesthetical value of the building itself, avoiding the presence of external units or devices that can modify landscape aspects of the building.

The most commonly and simple used intervention strategies of proven effectiveness for common energy demanding buildings [5] can hardly ever be applied in historical buildings. Moreover, historical buildings of special artistic or cultural value have to comply with the regulations about listed historical building, which prohibit or strongly limit many invasive interventions, including measures designed for improving building envelope efficiency (e.g., the reduction of thermal bridges and airtightness). In historical buildings, the overall level of insulation is typically poorer compared to recent and new buildings, but interventions such as window replacement or actions on the envelope to improve thermal insulation properties are often precluded, with some exceptions were special refurbishment designs or products were used [6]. Often even the replacement of Heating, Ventilation and Air Conditioning (HVAC) systems with more efficient and more environmentally friendly devices does not represent a viable solution. A common case is represented by the existing high temperature radiator units, which, if not replaceable with more efficient low or medium temperature terminal units (such as radiant floors or fan coils), also drastically limit the most important refurbishment strategies, such as the boiler choice.

A solution to these issues can be found by acting on the primary energy source. The use of renewable energy sources is often not feasible, because the installation of solar thermal collectors or photovoltaic panels on roofs and on external surfaces is not allowed. Nonetheless, a correct equilibrium point with conservation needs and aesthetical respect can be certainly achieved by using geothermal energy [7]. Compared to other solutions, this technology significantly limits the architectural and visual impacts, since most of the system is located underground.

An example of this approach of refurbishment of historical buildings is presented with a series of real case studies carried out within European projects that are underway (Cheap-GSHPs and GEO4CIVHIC [8,9]) funded within the Horizon 2020 European research program, which investigates and optimizes the practical applications of geothermal energy, with particular attention to the impacts on historic buildings and museums.

In particular, the integration of Cheap-GSHPs geothermal systems for heating and cooling purposes does not affect the aesthetic aspects of the historical building and are not invasive in the gardens because:

- The drilling methodologies are designed to limit the environmental impact during the installation;
- Most of the infrastructure is not visible because it is buried;
- Using the innovative ground source heat pump developed in Cheap-GSHPs (by Galletti Belgium/HiRef Spa) it is possible to maintain the existing terminal units, avoiding extra costs and issues for conservation constraints.

The new ground source heat pump developed within Cheap-GSHPs project blends well in the cultural heritage field because it can be easily combined with the terminals normally present in historical buildings, i.e., fan coils and conventional radiators. In fact, this heat pump provides water for heating at high temperatures (60/70 °C) as required by the kind of terminals often installed in heritage buildings without being penalized in performance efficiency. Due to that, the aesthetic impact of Cheap-GSHPs technologies on the building is negligible [10], mainly depending on the availability of a room of suitable dimensions that can be used as the plant room for housing the heat pump and the hydraulic connections (manifolds, etc.).

The retrofit interventions of historical buildings have direct and indirect impacts on the environment, due to the materials implemented to improve the energy demands [11] (i.e., insulation materials) or related to the source of primary energy respectively. Shallow geothermal systems have the potential to achieve remarkable results in terms of eco-sustainability and carbon footprint reduction, and therefore they are worthy of consideration when a retrofit intervention is planned on an historical building [12], especially if located in proper geological and climatic conditions [13,14].

3. Materials and Methods

3.1. Energy Management in Historical Buildings and Museums

Due to the previously mentioned limitations in applying energy saving solutions, a rational solution to the problem should be also sought in the non-invasive actions. The first choice for this purpose is acting on fine-tuning of the HVAC control system and applying a flexible approach in adjusting set point temperatures, especially taking into account specific needs for conservation conditions (i.e., considering the specificity of the housed collections) and variable heat loads due to visitors presence and weather conditions.

By intuition, each energy management policy is based on the concept that reducing energy use acts on potential monetary savings. For this reason, common energy management strategies rely on motivating people in order to change their habits toward more economically convenient (and consequently, energy conscious) behaviors. While it has been demonstrated in real case studies that energy consumption could be reduced by up to 20% through human behavior change only [15] in office spaces, in museum environments the human factor is strictly connected with the conservation requirements of the housed collections (i.e., microclimate/thermo-hygrometric requirements).

Museums hosting works of art, archaeological remains or other precious items have to prioritize the conservation, keeping the conditions that preserve the collections and do not deteriorate the cultural heritage. In such contexts, the energy management policy will take into account this aspect first, regardless of the needs of the people, and the choice of the indoor thermo-hygrometric conditions will depend almost entirely on the specific materials (e.g., temperature and humidity have different actions on metals, leather, paper, etc. thus different "safe zones" exist for each of them) and on other considerations based on conservational aspects. The microclimate condition should not necessarily be extended to the whole volume of the rooms: If there are not sensitive elements such as wooden furniture, wall paintings, tapestries, etc., inside. Thus, the indoor environment could be set in order to be comfortable for visitors and staff, as long as the delicate items are inside suitable air-conditioned showcases.

Some museums host collections or less sensitive or not extremely precious items that are less subject to deterioration (e.g., science and technology museums hosting airplanes, railway engines or other sturdy items). In these cases, the freedom of action is higher and it is of special interest to find the correct strategy to assess both conservation and comfort with regard to energy saving.

As a result, a rational energy management strategy in that kind of museum environment should take into account both human and heritage standpoints at once.

Many different standards, guidelines, recommendations and best practices have been proposed and applied in recent years in order to regulate the correct assessment of indoor thermo-hygrometric conditions for both conservation and comfort. The authors' intent with this document goes further beyond the determination of the best or the most appropriate microclimate management for each situation, leaving the discussion of such complex matter to the remarkably considerable published literature on that topic. For this reason, the proposed standards and microclimate conditions that will be addressed in the next paragraphs, despite being very reasonable and arguably appropriate for the museum context that has been taken into account in this study, have to be considered just functional for the discussion, and they do not necessarily represent the optimal environment for the conservation that could be applied for every kind of housed collection that could have specific requirements.

For the sake of keeping this study unbiased, two widely recognized ASHRAE standards are considered in order to define respectively thermal comfort and microclimate conditions: ANSI/ASHRAE Standard 55—thermal environmental conditions for human occupancy [16] (along with ISO 7730:2005 [17]) and the "Museums, Galleries, Archives and Libraries" chapter 21 in the American Society of Heating, Refrigeration, and Air Conditioning Engineers Inc. (ASHRAE) Handbook [18]. With regards to thermal comfort of people, it is an obvious assertion that the buildings do not need to be air conditioned for comfort in closure time when the visitors are not present. During the opening time, suitable thermo-hygrometric parameters (operative temperature, relative humidity, etc.) should take into account the results in terms of the predicted percentage dissatisfied (PPD) and predicted mean vote (PMV) indices that represent the expected comfort perceived by people at specific environmental conditions. Specifically, PPD is quite useful for a cost/benefit evaluation, in this case an optimization process that minimizes the energy cost while assuring a certain percentage of satisfied people (80% minimum, arbitrary 10% inferior than the common value chosen by HVAC engineers as best practice). ASHRAE's indoor climate classes of control for general museums, galleries, archives and libraries are well known: AA, A, B, C and D, in which AA decrees the most strict indoor climate, which include the concepts that set point may vary from the standard and provides the estimated risks for each class.

The classes of control are defined as specifications for allowed variations of indoor air temperature (T) and relative humidity (RH) over time. The following Table 1 shows the permitted ranges of T and RH of each class of control. The choice of the proper class should take into account the potential risks for the collections, which is summarized in Table 2.

Table 1. Description of the classes of control according to the American Society of Heating, Refrigeration, and Air Conditioning Engineers Inc. (ASHRAE) Handbook.

Class of Control	Set Point or Annual Average	Short Fluctuations Plus Space Gradients	Seasonal Adjustments in System Set Point
AA Precision control, no seasonal changes, with system failure fallback	50% RH (or historical average for permanent collections). Temperature set between 15 and 25 °C Note: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% RH, 21 °C, but sometimes 55% or 60% RH.	±5% RH, ±2 °C	RH no change Up 5 °C; down 5°C
A Precision control, some gradients or seasonal changes, not both, with system failure fallback		±5% RH, ±2 °C or ±10% RH, ±2 °C	Up 10% RH, down 10% RH Up 5 °C; down 10 °C or RH no change up 5 °C; down 10 °C
B Precision control, some gradients plus winter temperature setback		±10% RH, ±5 °C	Up 10% RH, down 10% RH, T up 10 °C, but not above 30 °C
C Control; prevent all high risk extremes.		Within range 25–75% RH year-round. Rarely over 30 °C, usually below 25 °C.	
D Control; prevent damp.		Reliably below 75% RH.	

Table 2. Collection risks for each class of control.

Class of Control	Collection Risks
AA	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% RH exceeds a critical RH. Chemically unstable objects are unusable within decades.
A	Small risk of mechanical damage to high vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs and books. Chemically unstable objects are unusable within decades.
B	Moderate risk of mechanical damage to high vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30 °C, but cold winter periods double life.
C	High risk of mechanical damage to high vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts and some books; and tiny risk to many artifacts and most books. Chemically unstable objects will become unusable within decades. Cold winter conditions may retard the rate of deterioration considerably.
D	High risk of sudden or cumulative mechanical damage to most artifacts and paintings (including objects of low vulnerability) due to low humidity fracture; however, high humidity delamination and deformations, especially in veneers, paintings, paper and photographs, will be avoided. Mold growth and rapid corrosion will be avoided. Chemically unstable objects will become unusable within decades. Cold winter conditions may retard the rate of deterioration considerably.

Usually, museum staff aims for class AA, but from an energy saving standpoint, literature has proven that class A and B (the latter for poorly insulated building envelopes), while still considered precision controls thus mostly adequate for conservation purposes of many collections, are preferable for museums housed in historical buildings [19]. Specifically, A class of control allows short-term fluctuations of ±5% for relative humidity and ±2 °C for air temperature, with a seasonal change of ±10% for relative humidity and up 5 °C/down 10 °C for temperature.

Regardless of most recent guidelines, a more basic microclimate policy that represents the de facto situation on many museums, relies on maintaining a fixed set point that has been selected taking into account both conservation purposes (often quantitatively, according with one chosen standard) and the comfort of visitors (commonly only qualitatively addressed), but without any seasonal adjustments nor variations that depend on e.g., people occupancy or weather conditions. Such considerations lead to the deduction of two very simplistic but representative policies that could be implemented in the field of energy management in museums concerning different microclimatic and thermal comfort conducts, i.e., BASIC and ADVANCED, which are described in the following Table 3 and discussed in following Section 3.4. These two scenarios will be the reference for the following numerical simulations and the consequent discussion on energy savings:

Table 3. Description of BASIC and ADVANCED energy management policies.

	Microclimate Set Point Management Policy	**Thermal Comfort Management Policy**
BASIC energy management policy	Fixed set point T and RH	Occupancy schedule independent, PPD not considered
ADVANCED energy management policy	According to ASHRAE class A (minor fluctuations of T and RH and seasonal adjusting)	Occupancy schedule dependent, PPD ≤ 20%

3.2. Case Study: Technical Museum Nikola Tesla in Zagreb

The building that hosts the Technical Museum Nikola Tesla dates back to 1949 and was built as an extension of the Zagreb Fair, according to a project by the architect Marijan Haberle, and opened its exhibition space in 1963. The entire complex is enlisted within the National Register of Cultural Property, by decision of the Ministry of Culture of the Republic of Croatia (class UP-I-612-08/05-06/896, no. 532-04-01-1/4-05-2 of 28 April 2005) and it is located in the historic urban areas of the city of Zagreb, an urban zone abiding to a special regime of conservation and heritage protection. According to the provisions of the law on the Protection and Conservation of Cultural Goods, any structural works planned for the museum must be greenlighted by the Urban Office for the Protection of Cultural and Natural Monuments (GZZZSKP). For the purposes of this study, a limited part of the museum was considered and it was an exhibition room of 380 m^2 with a volume equals to 1463 m^3 mapped in Figure 1.

The original plant system consisted of only six electrical heaters originally used for heating and no devices for cooling are present. This had a serious impact on the environmental comfort of both visitors and personnel with a possible threat to the fire safety of the structure, which is made mainly of wood components both in its interiors and in exteriors.

The refurbishment intervention was approved by the museum and municipal authorities, and included the installation of a CO_2 heat pump with a capacity of 30 kW, in order to assure low global warming potential [20]. The installed heat pump is a prototype device, specifically designed to provide water at high temperature to terminals. This two-stage heat pump uses CO_2 refrigerant in the first stage and R1234ze(E) in the second stage. The Coefficient Of Performance (COP) considered for the simulations within this document was the average value between the summer and the winter period, and such values were calculated by means of measurements on field. For the purpose of cooling the heat pump we used only one of the two stages. This heat pump was now patent pending, thus no further specification could be provided at the moment because the technical data were currently embargoed.

The refurbishment also included the drilling of a geothermal field consisting of six 100 m deep ground heat exchangers in the garden, plus the relative hydraulic connections. In order to assure heating and cooling in the exhibition room of the museum, 10 fan coils were installed.

A model of the museum was created with the TRNSYS simulation tool to calculate the energy demand before and after the refurbishment intervention and taking into account different energy management strategies.

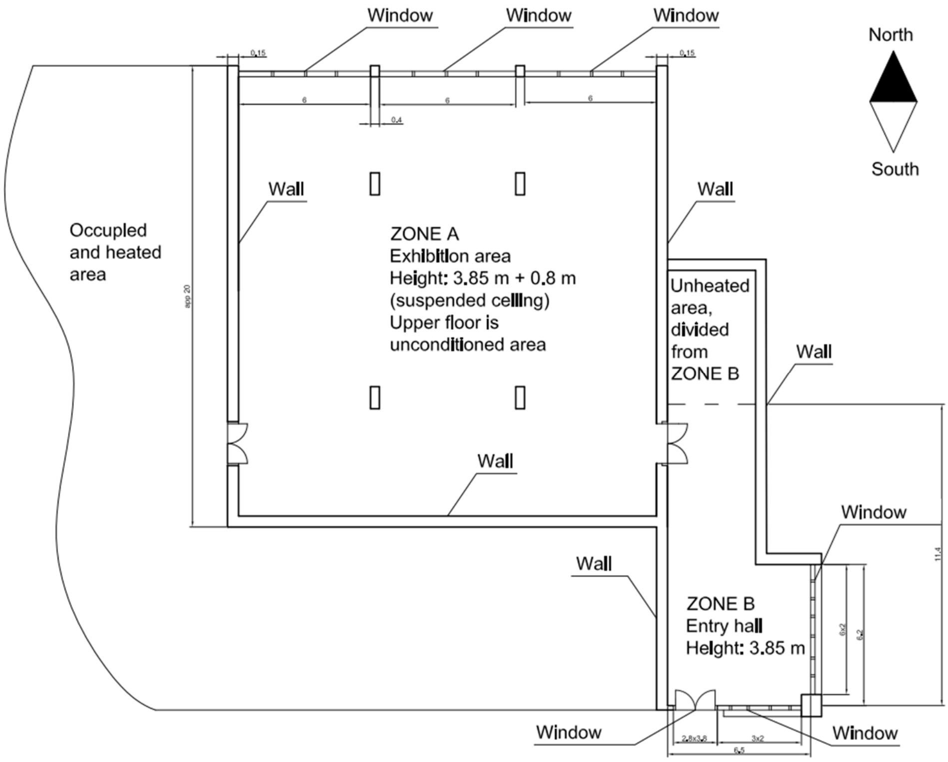

Figure 1. Plan of the exhibition room (ZONE A) of the Technical Museum Nikola Tesla in Zagreb (Croatia).

3.3. Evaluation of Microclimatic Conditions and Envelope Thermophisical Properties

Many methods exist and are commonly applied in order to gather the information on thermophysical properties of the materials constituting the envelope because external walls, roof and glazed surfaces play a key role in the calculation of the overall energy demand of a building, as much as the indoor microclimate conditions and thermal loads. However, the vast majority of such methods consist of spot measurements limited on space and time, and they could be misleading when the building is under dynamic thermal conditions [21,22], or if there are structural discontinuity in the walls e.g., due to numerous successive construction phases during the centuries, a quite common occurrence in historical buildings. The presented case study was relatively recent and its history was well documented, thus it was possible to assess the thermophysical properties needed for the mathematical simulation by analyzing the known configuration of the windows and the stratigraphy of the walls, by calculating the equivalent thermal resistance given by the layers of mortar, bricks, concrete, wood and other construction materials.

The stratigraphy of the external wall was brick and mortar without any added layer of thermal insulation (U = 2 W/m^{2}K). Double glazed windows with an aluminum frame covered the north wall almost completely (U = 2.9 W/m^{2}K). The ceiling and the floor were composed of concrete and wooden floors respectively ($U_{ceiling}$ = 2 W/m^{2}K, U_{floor} = 2.4 W/m^{2}K).

Concerning the indoor air conditions, it was much more complex and unreliable deducing the needed yearly trends of T and RH without direct measurements on site. In order to provide reliable real data to set up the energy simulation and to validate the mathematical model, microclimate monitoring of the exhibition room was carried out during the cooling (summer 2017 and 2018) and the heating season (winter 2017 and 2018) before and after the actual refurbishment of the Technical Museum Nikola Tesla.

The specifications of the temperature and relative humidity measurement system are shown in the following Tables 4 and 5 respectively.

An example of temperature and relative humidity trends in summer is shown in Figures 2 and 3 respectively. Outdoor thermo-hygrometric parameters are given as reference.

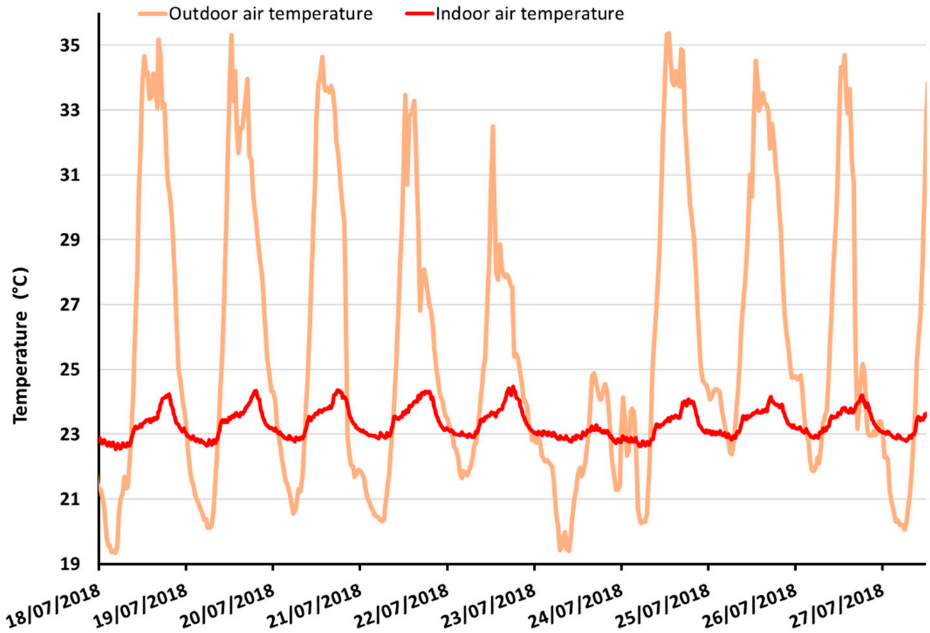

Figure 2. Air temperature trend inside the exhibition room—cooling season.

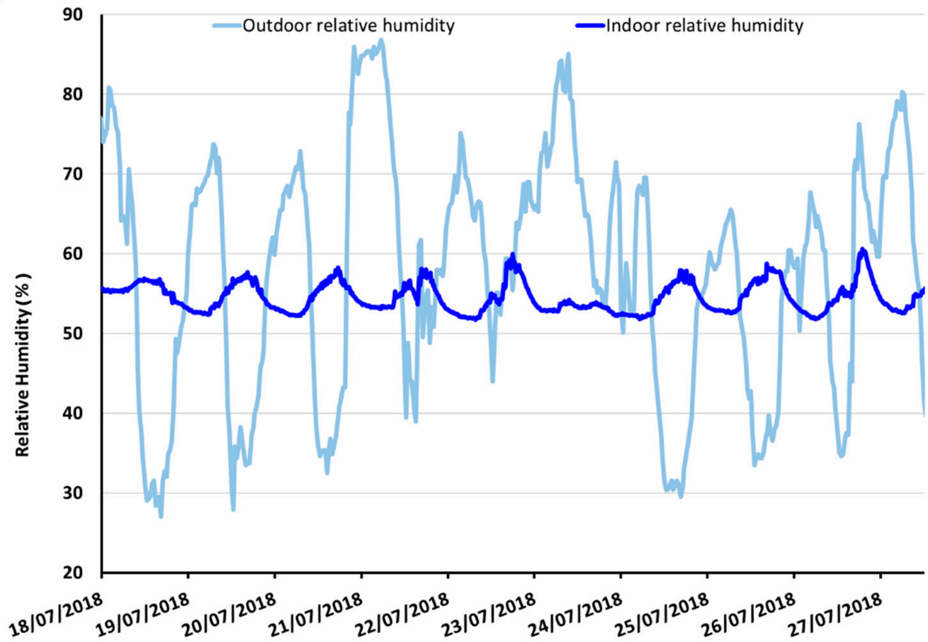

Figure 3. Relative humidity trend inside the exhibition room—cooling season.

Table 4. Technical specifications of temperature probe used in indoor monitoring of the exhibition room.

Temperature	
Reading range	−25 °C to +85 °C
Sensor type	10 K NTC Thermistor
Response time	25 min to 90% FSD in moving air
Reading resolution	0.01 °C or better
Accuracy	<0.5 °C within the measured temperature range

Table 5. Technical specifications of relative humidity probe used in indoor monitoring of the exhibition room.

Relative Humidity	
Reading range	0% to 100% RH
Sensor type	Capacitive
Response time	40 s to 90% FSD
Reading resolution	Better than 0.3% RH
Accuracy	±3.0% RH at 25 °C

According to the ASHRAE Handbook, the HVAC system succeeded in assuring stable conditions that are mostly in compliancy with the class of control A rating.

3.4. Calculation of the Optimized Dynamic Set Point of T and Rh for Conservation, Thermal Comfort and Energy Saving

The energy simulations that were discussed in the next subchapter were required to keep the indoor thermal conditions equal to the BASIC or the ADVANCED energy management policies in order to compare the outcomes of such HVAC control strategies.

This required the creation of yearly trends of T and RH based on one hour resolution, calculated by algorithms coded in MATLAB® [23] software (Matlab R2018a, The MathWorks, Inc., Natick, MA, USA) environment.

The data collected on site was taken into account for assuming the set point conditions for indoor air T and RH, respectively equal to T = 23 °C and RH = 50%. While the average measured temperature value was in within the range of the ASHRAE recommendations (set point T ranging from 15 to 25 °C), the RH value was marginally adjusted to fulfill the requirements for precision control classes (set point RH = 50%).

Such values were considered fixed over the whole year for defining the BASIC energy management policy conditions.

The code implemented for the calculation of the trends of T and RH of the ADVANCED energy policy was much more complex because it describes an unsteady condition and it takes into account interdependently many factors such as: The outdoor air conditions of Zagreb, the ASHRAE class of controls specifications (both gradients and fluctuations over time), the occupancy schedule of the museum and the thermal comfort requirements. Being a step optimization algorithm, each variable was represented by lookup tables (occupancy schedule, outdoor air conditions and clothing insulation of visitors) or by an analytical formula derived from physical observations (i.e., psycrometic formulae) or described by standards (thermal comfort and microclimate for the conservation), and all of them were interconnected.

As previously stated, for the determination of the indoor conditions T and RH to be used as input parameters for the mathematical simulations of the ADVANCED management policy, A class of control (which was selected after the on site measurements, the building envelope transmittance and considering the general conservation needs of this museum) was implemented as an algorithm that considered the following aspects in descending priority order: Conservation, thermal comfort and energy saving. The indoor conditions change during the year within the allowed ranges of A class of control, but also minimizing the difference between indoor and outdoor values of T and RH in order to reduce the effort of the air conditioning systems, thus limiting the energy consumption as much as possible without compromising the conservation. RH was estimated using the empiric formulae based on the vapor pressure ratio of the wet and dry bulb.

The schedule of occupancy was implemented, and it played a key role because it governs the periods while the indoor conditions have to be proper for the comfort of the people, reaching the target value PPD ≤20%. As a consequence, the target PPD value has to be accomplished all days from 10 am to 7 pm, except Saturday and Sunday (10 am to 5 pm), and Monday (closing day).

According to the ADVANCED energy management policy, temperature has been adjusted by diverging from the A class of control as much as needed in order to get a PPD <20% during the opening time of the museum. The resulting variations of temperature between opening and closing time are because during the opening times of the museum the indoor conditions have to fulfill not only the A class of control requirements, but also the thermal comfort necessities for people. During the closing time, only the conservation needs and the energy saving issues were considered.

Due to climatic conditions, in some periods of the year these conditions are quite different from the average set points, especially in the heating season, so an effort was required from the HVAC system that significantly impacts the energy consumption of the building. The variation of indoor conditions was thus affected during the opening times of the museum by the target PPD by means of reiterative step calculations of T, RH and PMV, to obtain the minimum difference from the average setpoint.

The thermal comfort parameters PMV, which is an estimate of the expected average vote of a panel of evaluators for a given thermal environment and PPD, which is the percentage that quantifies the expected dissatisfied people in a given thermal environment, were calculated by the method developed by Fanger [24] taking into account the following values:

- M: Metabolic rate: Considered as constant and equal to 1 met = 58.2 W/m^2, which corresponds to the energy produced per unit surface area of an average person while at rest. The surface area of an average person is 1.8 m^2.
- Clo: Clothing insulation: The clothes act as thermal insulation when worn by a person and that has a substantial impact on thermal comfort. In order to consider the fact that the typical clothing variability during the year, this value was adjusted on a daily basis and ranged from 1 Clo = 0.155 m^2·K/W down to 0.5 Clo, linear, dependent on the average outdoor temperature. These limit values correspond to trousers, a long sleeved shirt and a jacket (Clo = 1), and knee-length trousers and short-sleeved shirt (Clo = 0.5) to replicate winter and summer indoor clothing.
- W: Rate of mechanical work equals to 0 W (W/m^2).
- Var: Air velocity <0.1 m/s, constant value and representative of indoor conditions without any mechanical ventilation not relevant embrasures such as windows, vents or significant air leakages.

Such a method consists of a model of correlation between the subjective human perception (PMV) on a scale ranging from −3 (very cold) to +3 (very hot), and the ratio between the heat generated and released by the human body. The formula used to calculate PMV is deeply described by Fanger [24].

The following Figures 4 and 5 show respectively the T and RH conditions over a year period at the Technical Museum Nikola Tesla in Zagreb, to be used as input data for the energy model meant to compare BASIC and ADVANCED energy management policies.

Temperature trends are shown in Figure 4, and it was possible to observe that the ADVANCED trend (in blue) was fluctuating on a daily basis, within the allowed short-term limits, every week from Tuesday to Saturday, due to the day/night alternation during the opening days. This happened when the system was adjusting the set point to match the minimum requirements of thermal comfort. The values were always within the boundaries of class of control A (green band) and the average value diverged from the fixed setpoint (i.e., 23 °C) because it exploited the seasonal adjustment that allowed it to get closer to the external air temperature (in red). The trend representing the BASIC temperature (in pink) was constant during the year at the imposed set point, and the temperature was higher than the ADVANCED ones.

Relative humidity (RH) trends are shown in Figure 5, as it can be seen the ADVANCED trend (in blue), contrariwise the related temperature shown in Figure 4, was not fluctuating on a daily basis because it was assumed that a humidity control system was always on.

The seasonal adjustment was observable during the summer period when the RH diverged from the fixed setpoint (i.e., 50%), but within the short-term limits. The values were always within the boundaries of class of control A (green band). The trend representing the BASIC RH (in pink) was constant during the year at the imposed set point, and it was lower than the ADVANCED ones from June to September, which implied a major effort for the dehumidifier in summer.

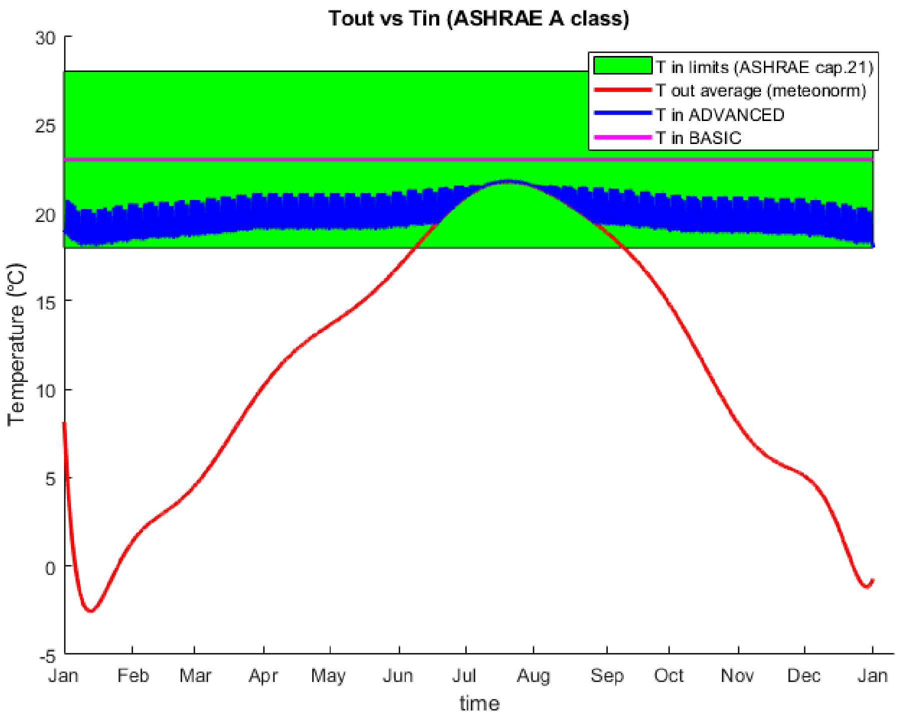

Figure 4. Indoor and outdoor air temperature yearly trends.

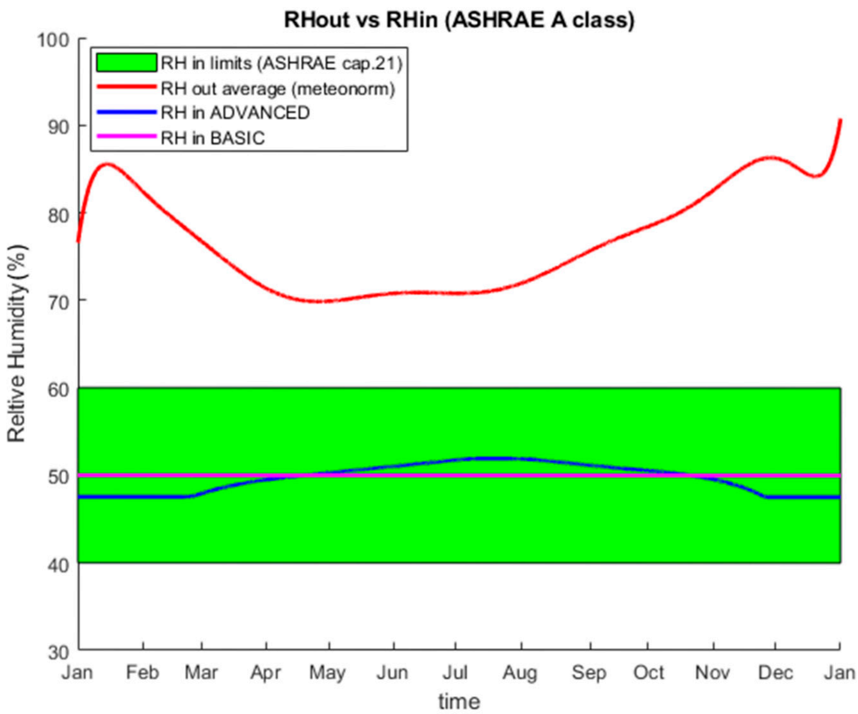

Figure 5. Indoor and outdoor relative humidity yearly trends.

3.5. Simulation of Energy Performance and Consumption

Several simulation strategies are available to model the thermal behavior of a building. In this work the Technical Museum Nikola Tesla was studied using the software TRNSYS® [25]. TRNSYS 18, a Transient Simulation Program, Solar Energy Laboratory, University of Wisconsin: Madison, WI, USA.

This software was chosen for the easy and reliable implementation and comparison of different energy savings measures. The creation of the model was based on a geometrical model, with respect to the sizes and orientations of building envelope elements, and on the thermal properties of the walls according to literature and actual wall stratigraphy. When data could not be obtained directly, typical values derived from the literature were used. The TRNSYS software was used to determine hourly values of heating demand over one year of simulation. The weather data for the city of Zagreb were selected from the standard weather libraries [26].

The boundary conditions for this evaluation were:

1. Climate data from the Meteonorm database (T, RH, solar radiation, etc.).
2. Opening time of the exhibition room for three months in winter (December, January and February) and for three months in summer (June, July and August): Tuesday–Friday from 10.00 a.m. to 7.00 p.m., Saturday–Sunday from 10.00 a.m. to 5.00 p.m.
3. Internal gain (considered during the opening time of the room): Lighting devices:
    a) 60 pieces of halogen light 100 W/12 V.
    b) A daily presence of 160 people split up as summarized in Table 6.
4. A conjectural device assuring continuous humidity control was supposed inside the museum (not existing in the actual museum).
5. No ventilation.
6. Infiltration: 0.5 vol/h.
7. Heating power limit: 30 kW.
8. Cooling power limit: 25 kW.

Table 6. Opening and closing times of the museum (daily basis, 24 h format).

Opening Hours	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19
Monday	Close	Close	Close	Close	Close	Close	Close	Close	Close
Tuesday to Friday	10	20	20	10	20	20	20	20	10
Saturday and Sunday	20	30	20	20	20	30	20	Close	Close

The results in terms of monthly energy demand of the exhibition room are summarized in Tables 7 and 8, where the sign means whether the heat is absorbed or released.

Table 7. Monthly energy demand of the exhibition room with the BASIC energy management policy.

	Before Refurbishment		After Refurbishment	
	Heating (kWh)	**Dehumidification (kWh)**	**Heating (kWh)**	**Cooling and Dehumidification (kWh)**
January	21805	0	21805	0
February	17843	0	17843	0
March	14950	0	14950	0
April	9550	73	9550	73
May	5365	189	5402	341
June	2706	882	2864	1844
July	1121	1374	1409	3094
August	1747	1397	1992	2561
September	4633	493	4698	661
October	10115	140	10115	140
November	14942	5	14942	5
December	21147	0	21147	0

Table 8. Monthly energy demand of the exhibition room with the ADVANCED energy management policy.

	Before Refurbishment		After Refurbishment	
	Heating (kWh)	**Dehumidification (kWh)**	**Heating (kWh)**	**Cooling and Dehumidification (kWh)**
January	18044	2	18044	2
February	14843	2	14843	2
March	12209	16	12209	16
April	7009	248	7009	248
May	2952	449	2994	695
June	992	1213	1053	2561
July	517	1531	661	3177
August	659	1677	730	3274
September	2457	807	2501	1169
October	7336	347	7336	347
November	12223	94	12223	94
December	17606	5	17606	5

The reference simulation of the building is for a BASIC energy management policy, where the indoor environmental conditions considered were:

- 23 °C for the indoor temperature (except in pre-refurbishment scenario, where this value was maintained only during heating periods due to electrical heaters, as detailed in Section 4);
- 50% for the RH.

A second simulation was made for an ADVANCED energy management policy, where the indoor conditions used were the results of the mathematical model for ASHRAE A class of control showed in the previous section.

4. Results

The summary of the simulations is shown in Table 9 concerning the energy demand of the building.

Table 9. Yearly energy demand of the museum with the BASIC and ADVANCED energy management policy.

Energy Demand	**Before Refurbishment (kWh) (kWh/m²)**		**After Refurbishment (kWh) (kWh/m²)**	
	Heating	**Dehumidification**	**Heating**	**Cooling and Dehumidification**
BASIC energy management policy	125923 (331)	4553 (12)	126717 (333)	8720 (23)
ADVANCED energy management policy	87043 (229)	5653 (15)	87591 (231)	14649 (39)

The use of geothermal solution installed in the museum does not affect the possible reduction of the thermal energy demand of the building (that could be reach with interventions on the envelope for example). In fact, the reduction in thermal energy demand is related to the energy requirements of the building envelope side. Thus, only interventions on the envelope (i.e., installation of thermal insulation to reduce the U-Value, replacing embrasures with airtight doors and windows to reduce heat losses, etc.), and not on the plant, allowed us to reach a saving in terms of energy demand of the building.

In this case, in particular, the energy demand after the refurbishment interventions, as can be seen in Table 9, became higher than the situation before. This strange result is easy to explain: The system initially installed, as described previously, was composed by six electrical heaters, which could not provide cooling; on the contrary, after the refurbishment, the building was equipped with a heat pump used not only for heating but also for cooling.

Thus, while in the heating season the set point temperature of 23 °C was always guaranteed, in the cooling season for the BASIC energy management policy with electrical heaters only the relative humidity, set to 50%, was controlled. For this purpose, the electrical demand for the operation of a dehumidification system with an Energy Efficiency Ratio (EER) of 2.5 was taken into account in the simulation. On the other hand, the energy demand for the humidification process in heating period was neglected. The simulations showed that for both the BASIC and the ADVANCED energy management policy the indoor temperature in the exhibition room was regularly in the 23 ± 5 °C range, in accordance with class of control A.

On the contrary, considering the operating principle of a heat pump, it allows us to obtain significant primary energy saving. In fact, with the previous electrical heaters installed, the energy transformation can be considered 1 kWh_t = 1 kWh_e, while with the geothermal system the conversion become 1 kWh_t. = 1/COP kWh_e. From data collected on field, basing on an average between summer and winter, a COP = 2.5 was used for the calculation of primary energy consumptions in the following calculations.

Just for comparison, an alternative solution for the renovation of the heating system was evaluated in the present document. One of the most used alternatives in the actual market, in fact, is usually the natural gas boiler. Hereunder it is evaluated this third possibility, although must be taken into account that this solution requires the construction of a flue, not easy to install in a historical building.

Both the geothermal and gas boiler solution, differently from the reference solution, require the use of circulators for the pumping of the heat carrier fluid in the geothermal field and in the terminal units' loop. In these case studies, several assumptions were done in order to consider this aspect. In particular, for the geothermal solution and of the natural gas boiler the water circulation pump for the fan coils loop was assumed to have an electrical absorption of 100 W_e. Moreover, for the geothermal heat pump it was necessary to evaluate also the energy needed by the pump to the geothermal field loop, estimated in 200 W_e for the high temperature heat pump installed in the museum. It was, instead, not evaluated the electrical demand for the fans of the terminal units by the fact that it is a common energy requirement for all the evaluated solutions and it was considered similar.

For the natural gas boiler, considering the high temperature terminals, it was decided to use an efficiency of 90%.

The evaluation of the primary energy demand is summarized in Table 10. The analysis was carried out considering a primary energy factor (PEF) of 2.5 for the electrical energy vector, which is approximately the medium value for Europe.

Table 10. Primary energy demand of the museum with the BASIC and ADVANCED energy management policy.

Primary Energy Demand	Before Refurbishment (kWh)	After Refurbishment (kWh)	
	Electrical Heaters	Natural Gas Boiler	Geothermal Heat Pump
BASIC energy management policy	319361	146475	142007
ADVANCED energy management policy	224911	109589	108810

The production of electrical energy is different for each country, depending on its underground resources and national policy. For this reason, every country has different CO_2 emissions, based on the systems it uses for the generation of energy. For Croatia the share of energy from non-renewable sources considering that the energy coming from renewable sources is 27.3% of the gross final energy consumption [27]. The actual share of energy from non-renewable sources in respect to each analyzed solution (e.g., the electric energy needed by the geothermal heat pump) is presented in the Table 11 hereunder.

Table 11. Energy coming from non-renewable sources for the museum with the BASIC and ADVANCED energy management policy.

Energy from Non-Renewable Sources	Before Refurbishment (kWh)	After Refurbishment (kWh)	
	Electrical Heaters	Natural Gas Boiler	Geothermal Heat Pump
BASIC energy management policy	92870	147112	41296
ADVANCED energy management policy	65404	110226	31642

For the evaluation of the energy cost, Croatian national prices of primary energy including taxes [28] (natural gas and electric power) were taken into account as shown in Table 12.

Table 12. Electric energy and natural gas prices for household consumers (taxes included).

	Primary Energy Price (Croatia-2018) (Eurocents/kWh)
Electric energy	13.11
Natural gas	3.68

The role of the energy management policy is decisive especially considering the effect on the energy cost reduction, as shown in Table 13, because it could drastically reduce the energy consumptions.

Table 13. Energy costs of the museum with the BASIC and ADVANCED energy management policy.

Energy Costs	Before Refurbishment (€)	After Refurbishment (€)	
	Electrical Heaters	Natural Gas Boiler	Geothermal Heat Pump
BASIC energy management policy	16747	5425	7447
ADVANCED energy management policy	11794	4067	5706

Results show an economic advantage in the use of natural gas for the refurbishment of the museum compared to the geothermal solution. For Croatia, in fact, as can be seen in the previous table, the cost of natural gas was really low at the moment. However, it is important to consider that this situation could change in the next years, becoming similar to the western European countries, making the geothermal system profitable. Another issue to bear in mind, as written previously, is that the natural gas boiler needs the construction of a flue, which could become a problem when applied to historical buildings.

Considering the different energy consumption and the primary energy origin, CO_2 emissions have been evaluated for each of the simulated cases, and the outcomes are presented in Table 14.

Table 14. Tonnes of CO_2 emissions per year of the museum with the BASIC and ADVANCED energy management policy.

CO_2 Emissions per Year	Before Refurbishment ($t\ CO_2$)	After Refurbishment ($t\ CO_2$)	
	Electrical Heaters	**Natural Gas Boiler**	**Geothermal Heat Pump**
BASIC energy management policy	25.4	30.5	11.3
ADVANCED energy management policy	17.9	22.7	8.7

The calculations were made starting from the primary energy consumptions of the different solutions, calculated in Table 10, and then considering the Croatian emissions in grams of CO_2 equivalent deriving from the production of energy. The present evaluation considered an emission of 199.1 g CO_2/kWh for the electrical system [29] and of 210 g CO_2/kWh for the boiler [30].

Results show the enormous advantage in the use of a geothermal solution for the environment due to the fact that, as explained before, just a little part of the energy demand of the building comes from electrical energy for this system, which accounts for about 42% considering the COP = 2.5.

Previous tables show the benefits in the use of an advanced energy management policy, decided to be ADVANCED for the museum, in comparison with a basic energy management policy. An improved management of the museum leads to almost 24% savings in terms of energy, costs and CO_2 emissions.

5. Discussion

The study of an energy retrofit to a historical building is a complex task, that should take into account both technological and management measures together with the conservation issues. This work showed how proper energy management associated with the use of innovative renewable energy solutions could be successfully applied to limit the energy costs and the environmental footprint, while taking into consideration both the conservation requirements and the thermal comfort of people.

A model of a real museum hosted in an historical building was created with TRNSYS software to calculate the energy consumption and the environmental footprint before and after a refurbishment intervention, where the energy source was replaced with a ground source heat pump working with high temperature terminals. By means of simulations, also the effect of different energy management policies during the operational phase was evaluated. The results show the benefits of the geothermal systems with respect to the baseline conditions, which determined approximately a 48% reduction on the energy cost. The impact that energy management policies also have on the energy consumption was not negligible, potentially reducing the energy cost by up to 24%.

The most effective approach to energy efficiency is ultimately represented by the combination of both technical (ground source heat pump) and not technical (proper energy management) measures, which determines a reduction of the energy cost up to 66% with respect to the baseline conditions.

The resulting extra 10.8% that could be reached coupling a proper energy management policy to the technical intervention is of interest because reducing the energy consumption as much as possible during the operational phase also lowers the CO_2 emissions further and strongly reduces the payback time of the intervention, i.e., makes the geothermal energy systems more economically attractive, thus allowing a more widespread diffusion of this solution.

Author Contributions: Conceptualization, G.C.; methodology, G.C., F.C. and A.B.; software, G.C., F.C. and G.M.; validation, G.E., A.B., A.G. and D.P.; formal analysis, G.C., F.C. and G.E.; investigation, G.C., F.C., G.M. and A.B.; resources, G.M., D.P. and A.B.; data curation, G.C. and F.C.; writing—original draft preparation, G.C. and F.C.; writing—review and editing, G.C., F.C., G.E., G.M., A.G., A.B. and D.P.; visualization, G.C. and F.C.; supervision, G.C., F.C. and A.B.; project administration, A.B.; funding acquisition, A.B.

Funding: Cheap-GSHPs project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 657982. GE4CIVHIC project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 792355.

Acknowledgments: The authors thank many people that contributed, participated and supported this work. In particular our partners Fabio Poletto and Andrea Tarabotti (HiRef Spa), and Michele De Carli (UNIPD). For the work performed at the Technical Museum Nikola Tesla in Zagreb, the director Franulić and Eng. Branimir Prgomet, Davor Trupoković, Assistant Minister, Ministry of Culture of Croatia, Vladimir Soldo, Faculty of Mechanical Engineering and Naval Architecture University of Zagreb, Eng. Ante Pokupčić and Arch. Željko Kovačić, designer of the technical room, heat pump installer Eng. Franjo Banić, Trojanović local REHAU staff, Veljko Mihalić, Ines Franov Beoković, Narcisa Vrdoljak and Jasna Šćavničar Ivković, Municipality and City office of Zagreb, Vesna Drasal from E-kolektor services, Miljenko Sedlar, Deputy Principal of Department for project implementation, Rut Carek, Secretary General, Croatian Commission for UNESCO.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mazzarella, L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy Build.* **2015**, *95*, 23–31. [CrossRef]
2. Bernardi, A. *Microclimate inside Cultural Heritage Buildings*; Il Prato: Padova, Italy, 2008; p. 171.
3. Comite Europeen de Normalisation. *EN 16883: Conservation of Cultural Heritage—Guidelines for Improving the Energy Performance of Historic Buildings*; Comite Europeen de Normalisation: Brussels, Belgium, 2017.
4. Mairesse, F. Recommendation on the Protection and Promotion of Museums and Collections, their Diversity and their role in Society, UNESCO General Conference (17 November 2015). In *Museums, Ethics and Cultural Heritage*; Routledge: Abingdon, UK, 2016.
5. Ballarini, I.; De Luca, G.; Paragamyan, A.; Pellegrino, A.; Corrado, V. Transformation of an Office Building into a Nearly Zero Energy Building (nZEB): Implications for Thermal and Visual Comfort and Energy Performance. *Energies* **2019**, *12*, 895. [CrossRef]
6. Hartman, V.; Kirac, M.; Zanki, V.; Grozdek, M.; Poletto, D.; Ronchini, D. *Energy Efficiency and Energy Management in Cultural Heritage, Case Studies Guidebook*; UNPD and UNESCO: Zagreb, Croatia, 2013.
7. Perry, T.; Jay, C.A. Sustainable Solutions for Historical Buildings: Geothermal Heat Pumps in Heritage Preservation. *APT Bull.* **2009**, *40*, 21–28.
8. Cheap-GSHPs EU Project. Available online: www.cheap-gshp.eu (accessed on 10 May 2019).
9. GEO4CIVHIC EU Project. Available online: www.geo4civhic.eu (accessed on 10 May 2019).
10. Cadelano, G.; Pasquali, R.; O'Neill, N.; Alessandrini, D.; Di Tuccio, M. Environmental Risk Assessment Study for Each of the Case Study Locations. Cheap-GSHPs Deliverable D7.4. 2018. Available online: www.cheap-gshp.eu (accessed on 10 May 2019).
11. Bortolin, A.; Bison, P.; Cadelano, G.; Ferrarini, G.; Fortuna, S. Measurement of thermophysical properties coupled with LCA assessment for the optimization of a historical building retrofit. *J. Phys. Conf. Ser.* **2015**, *655*, 012011. [CrossRef]
12. 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. *Energy Procedia* **2017**, *133*, 183–194. [CrossRef]
13. De Carli, M.; Bernardi, A.; Cultrera, M.; Dalla Santa, G.; Di Bella, A.; Emmi, G.; Galgaro, A.; Graci, S.; Mendrinos, D.; Mezzasalma, G.; et al. A database for climatic conditions around Europe for promoting GSHP solutions. *Geosciences* **2018**, *8*, 71. [CrossRef]
14. Carnieletto, L.; Badenes, B.; Belliardi, M.; Bernardi, A.; Graci, S.; Emmi, G.; Urchueguía, J.F.; Zarrella, A.; Di Bella, A.; Dalla Santa, G.; et al. An European database for standardized energy profiles for heating and cooling of buildings with ground source heat pumps. *Energies* **2019**, *12*, 2496. [CrossRef]
15. Mulville, M.; Jones, K.; Huebner, G. The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Archit. Eng. Des. Manag.* **2014**, *10*, 79–90. [CrossRef]
16. The American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ANSI/ASHRAE Standard 55—Thermal Environmental Conditions for Human Occupancy*; ASHRAE: Atlanta, GA, USA, 2017.
17. The International Organization for Standardization. *ISO 7730:2005—Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*; ISO: Geneva, Switzerland, 2005.
18. Bruno, F.; Belusko, M.; Halawa, E. CO_2 Refrigeration and Heat Pump Systems—A Comprehensive Review. *Energies* **2019**, *12*, 2959. [CrossRef]

19. The American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook—HVAC Applications Chapter 21: Museums, Galleries, Archives, and Libraries*; ASHRAE: Atlanta, GA, USA, 2011.
20. Kramer, R.; Schellen, H.; van Schijndel, J. Energy impact of ASHRAE's museum climate classes: A simulation study on four museums with different quality of envelopes. *Energy Procedia* **2015**, *78*, 1317–1322. [CrossRef]
21. Ferrarini, G.; Bison, P.; Bortolin, A.; Cadelano, G.; De Carli, M. Thermographic measurement of thermal bridges in buildings under dynamic behavior. In *Thermosense: Thermal Infrared Applications XXXVIII*; International Society for Optics and Photonics: Bellingham, WA, USA, 2016; p. 98610V.
22. Ferrarini, G.; Bison, P.; Bortolin, A.; Cadelano, G. Thermal response measurement of building insulating materials by infrared thermography. *Energy Build.* **2016**, *133*, 559–564. [CrossRef]
23. Matlab R2018a. The MathWorks, Inc.: Natick, MA, USA. Available online: www.mathworks.com/ (accessed on 10 May 2019).
24. Fanger, P.O. Assessment of man's thermal comfort in practice. *Br. J. Ind. Med.* **1973**, *30*, 313–324. [CrossRef] [PubMed]
25. Klein, S.A.; Duffie, J.A.; Mitchell, J.C.; Kummer, J.P.; Bechkman, W.A.; Duffie, N.A. *TRNSYS, A Transient Simulation Program*; Solar Energy Laboratory, University of Wisconsin: Madison, WI, USA, 1994. Available online: http://www.trnsys.com/ (accessed on 10 May 2019).
26. Meteonorm Global Meteorological Database. Available online: https://meteonorm.com (accessed on 10 May 2019).
27. Share of Renewable Energy in the EU. Available online: https://ec.europa.eu/eurostat/documents/2995521/9571695/8-12022019-AP-EN.pdf (accessed on 10 May 2019).
28. Electricity Prices for Household Consumers (Taxes Included), First Half 2018 (EUR per kWh). Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php (accessed on 10 May 2019).
29. Fattori di Emissione Atmosferica di Gas a Effetto Serra nel Settore Elettrico Nazionale e nei Principali Paesi Europei. Available online: http://www.isprambiente.gov.it/files2019/pubblicazioni/rapporti/R_303_19_gas_serra_settore_elettrico.pdf (accessed on 10 May 2019).
30. Poteri Calorifici Inferiori dei Combustibili e Fattori di Emissione Della CO_2. Available online: http://www.efficienzaenergetica.enea.it/regioni/siape/poteri-calorifici-inferiori-dei-combustibili-e-fattori-di-emissione-della-co2 (accessed on 10 May 2019).