

Article

Energy Efficiency Measures Applied to Heritage Retrofit Buildings: A Simulated Student Housing Case Study in Vienna

Essam Elnagar ^{1,*}, Simran Munde ² and Vincent Lemort ¹

- ¹ Thermodynamics Laboratory, Aerospace and Mechanical Engineering Department, Faculty of Applied Sciences, Université de Liège, 4000 Liège, Belgium; Vincent.Lemort@uliege.be
- ² Faculty of Engineering and Architectural Science, Ryerson University, Toronto, ON M5B 2K3, Canada; Simran.Munde@ryerson.ca
- * Correspondence: essam.elnagar@uliege.be

Abstract: One pavilion was selected for deep retrofitting from the Otto Wagner area situated in the west of Vienna. The retrofitting process involves sustainable and energy-efficient construction to improve the energy performance and energy production potential of the building while preserving the cultural heritage and significance. This four-story pavilion was re-designed according to the proposed regulations of a net positive energy university building to become a student residence. Architectural, building envelope, and engineering interventions along with various changes were simulated through the Sefaira tool in the SketchUp model. These included: optimization of the U-values of the roof, walls, and floor; the addition of different layers of sustainable energy-efficient insulation materials to decrease the overall energy demand. The specific energy demands for heating, cooling, and lighting were decreased in the proposed model to reduce the total energy use intensity from 248.9 kWh/(m² year) to 54.3 kWh/(m² year) resulting in a 78.2% reduction. The main goal of this study is to try and achieve a net positive energy status building as part of the Otto Wagner area by improving the building envelope and integrating renewable energies. A total of 22.5% of the annual energy consumption was generated by the designed PV system. The selected building achieved the passive house standards in Austria by optimizing the energy performance with the proposed energy efficiency measures.

Keywords: low energy buildings; energy efficiency; sustainable materials; renewable energies; heating demand; historical retrofit; historical preservation; integrated design process



Citation: 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*, 3919–3937. <https://doi.org/10.3390/heritage4040215>

Academic Editor: Tor Broström

Received: 10 September 2021

Accepted: 19 October 2021

Published: 22 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The preservation of the built cultural heritage has been an area of scientific research in European countries since the nineteenth century. Architects, engineers, building scientists, and heritage scientists rectify historic buildings by improving thermal and energy performance. In most European energy performance of buildings directive (EPBD) requirements, historic buildings are currently exempted, but there is a growing awareness of heritage protection and decreasing the gap between cultural heritage and energy efficiency. Heritage buildings usually have poor energy performance, and it might be sometimes impracticable to comply with energy performance regulations [1]. Historic buildings will only survive if there is an improvement in energy performance and thermal comfort by reducing energy consumption and carbon emissions. There are different factors apart from energy efficiency and heritage conservation such as costs, moisture conditions, human comfort, and other practical considerations that need to be considered [2]. Heritage buildings are a significant component of European architectural culture. In Europe, the percentage of historical buildings older than 1945 ranges from “6.1% (Turkey) to 47.4% (Luxemburg) with a mean value of 23.1%” of the total building stock of Europe [3]. In order to move forward and contribute to a sustainable future, it would be feasible to retrofit this existing building stock

to achieve a low-energy building. Demolishing and building new would not only require more embodied energy, but it would also eliminate the heritage character of the city.

The European Union developed various strategies to promote energy efficiency and to reduce CO₂ emissions, and, in buildings, the EU member states promoted different projects to reach the overall goal by constructing new efficient buildings and refurbishing old buildings without enough attention to heritage buildings [4].

Multiple conducted studies also support this notion of retrofitting existing buildings and show that it is possible to make a significant change in their energy consumption and potentially reach net-zero or net-positive operational energy with the incorporation of renewable energy sources. In fact, according to C. Cornaro et al., in this historical building, the intervention of insulating the exterior envelope and keeping windows closed significantly reduced energy by 38% while keeping the historic value intact [5]. Through a building performance simulation, the benefits of the retrofits can be analyzed. Additionally, the market value of the existing building after a retrofit is significantly higher than prior to the retrofit [6]. Another simulation-based study concluded that “performance-based retrofitting” for existing houses would reduce their heating demand from 312.2 kWh/(m² year) down to 23.0 kWh/(m² year) [7]. With changes made to the envelope of the building including updated windows and insulated walls and floors, another historic retrofit was able to reduce energy by 27.1% and CO₂ emissions by 32.1 tons while producing 107.9 MWh/year through a PV array [8]. A case study of a university campus building in Seoul, Korea found that through a proposed building energy retrofit package with transmittances of walls at 0.17 W/m²K or less, the roof at 0.15 W/m²K or less, and windows at 1.3 W/m²K or less, in addition, installing exterior shading with an integrated PV, could reduce the average energy consumption by 54.2% in winter, 42.6% in summer, and energy costs by 47.9% [9]. As pointed out by Cho, it is important to consider the hygrothermal performance and airtightness of historical buildings. For instance, an energy efficiency measure package proposed with added insulation, improving airtightness, and updated windows, lighting, and internal blinds reduced the heating demand by 72% and total energy use by 60% [10].

There is still a gap while studying energy efficiency measures in heritage buildings; this gap is due to the lack of an explicit analysis of the cultural values [2]. This paper takes a holistic approach in taking architecture, the building enclosure, and engineering into account to implement not only energy efficiency measures but also improved living quality and historical preservation as well. The current studies on energy efficiency measures and heritage values of built heritage are focused on developing decision-making tools and guidelines for assessing the energy performance of historic buildings [11], while the main focus of the paper is to integrate those heritage and energy efficiency measures in a real case study.

2. Methodology

2.1. Case Study-Pavillion 21

This paper focuses on how a potential net positive status may be achieved for a selected Pavilion in the Otto Wagner Areal (OWA) located about 10 km west of the center of Vienna, Austria. Designed by Otto Wagner, the OWA includes a church and a hospital complex with 55 pavilions, dating back to 1907, with a ground floor area of 173,100 m² [12]. In this study, the OWA was proposed to be the new net-positive campus for Central European University (CEU). Located in the southeast corner of the OWA complex, Pavilion 21 was selected to reach the net positive condition, as seen in Figure 1.



Figure 1. Selected Pavilion 21 highlighted on Otto Wagner Areal.

For the purpose of this paper, the focus is on Pavilion 21 as a student residence as seen in Figure 2. At the building level, there are many historical values which are significant to the building's historical preservation. The majority of these encompass visible characteristics from the exterior of the building such as the overall façade, deep plaster horizontal cornices, decorative window frames, exposed brick with plaster, and floors finished with "Mettlach Tiles" from Wienerberger [12].

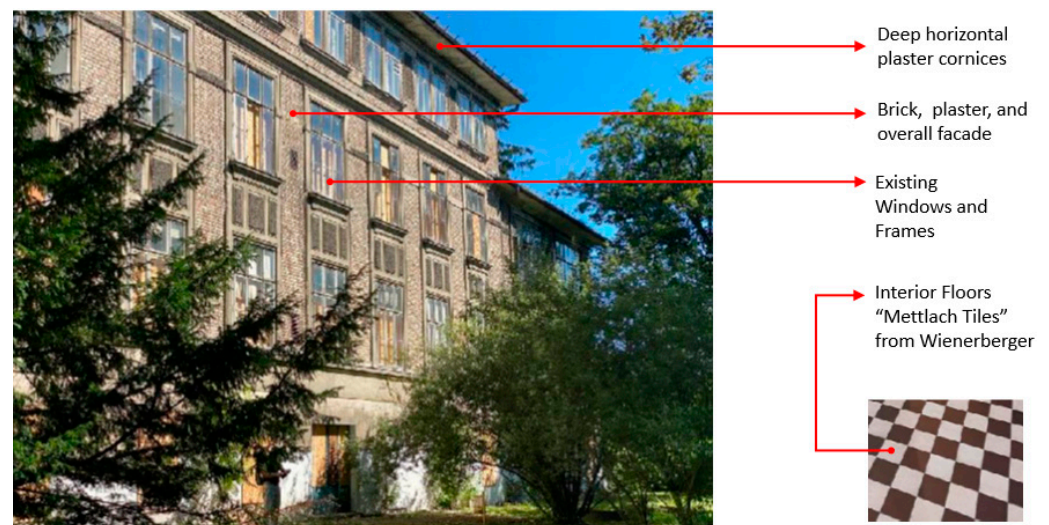


Figure 2. Selected Pavilion 21 at the Otto Wagner Areal (South Elevation).

The choice of selecting Pavilion 21 was made due to its proximity to public transit. Since most of the public buildings are located in the center of the site, the buildings on the far left and right, including Pavilion 21, were designated for student residence use. When designing the building, multiple goals were considered. These included creating a building with high comfort and a high quality of life for the students, striving for net-positive energy production, biophilia, and heritage protection. In order to achieve these goals, architectural, building enclosure/envelope, and mechanical interventions were all considered.

2.2. Proposed Interventions for Retrofit

There are many architectural, building envelope, and mechanical proposed changes made to achieve a low-energy building while maintaining its historical values and while using the passive house standard as a reference. Strategies to implement this included

improving the hygrothermal performance of the existing enclosure with insulation and including high-performance triple-pane windows.

Through this process, the specific heating demand, or the Thermal Energy Demand Intensity (TEDI), was reduced to 15.2 kWh/(m² year), and the Total Energy Use Intensity (TEUI) was reduced to 54.3 kWh/(m² year). Once reduced, the energy and hot water heating demands were met through a combination of photovoltaics and thermal hot water collectors inclined at a 25° angle and located on the roof of the building set back from the edge of the deep, historically prevalent cornice of the building in order to preserve its historical character. Additionally, a ground source heat pump as a highly efficient renewable energy source was connected to the existing energy system as well. Decarbonizing the heating sector is important for reducing CO₂ emissions. In Vienna, around 28% of the total CO₂ emissions are caused by the energy supply for buildings [13] and one of the most promising environmentally friendly technologies because of the potential of geothermal energy. In the last 15 years, the heating sector in Vienna has been moving towards more renewable energy sources with an increase of 34% in renewable energies. A combination of photovoltaic, solar collector array, and geothermal is used to supply energy for the proposed building to contribute to goal 7 in the sustainable development goals (SDGs) for affordable clean energy which is one of the main aspects of this study [14].

This section describes the various proposed interventions through sustainable architecture, building envelope and other simulated measures for energy efficiency, energy performance, and the energy production potential of the building.

2.2.1. Architecture

While keeping these main goals in mind, the interior layout was based on providing private and public areas in the building for the students based on their behavior. The goals mentioned in the previous section were achieved in different ways. During the schematic design, common facilities were introduced for the students in the center and on the lower ground floor of the building for easy access and comfort for the students. On the lower ground floor, these include the gym, yoga room, theater, art workshop, bike storage, and bike repair shop. On the other floors, the ground to second floors, there are communal kitchens, study spaces, and lounges as seen in Figure 3. These spaces promote a healthy, social, and high-quality lifestyle for the students. Outdoor common spaces were designed on the rooftop as well. This allowed for the student dorms to be placed on the wings of the building resulting in symmetry. This was advantageous since the south side of the building would provide passive solar gains during the winter for the common spaces in the building. The exterior of the building was not changed, and only some of the interior non-structural walls were demolished. Additionally, the existing windows were retained on the exterior, and high-performance windows were placed on the interior of the building. When considering the PV and thermal solar collectors, the angle and location of the panels were carefully considered so they would not be visible from the greenspace on the south side of the pavilion and compromise the existing heritage façade of the building. The exterior of the building was modified slightly in order to accommodate a wheelchair accessible entrance from the south side and a small patio for seasonal use. It was important to maintain the greenspace on the south of the building as existing since it includes mature trees. This allowed for the opportunity to introduce vegetation inside the building in order to implement biophilia. An atrium with a transparent PV array skylight was created in the middle of the building to provide solar exposure for the wintergarden as seen in Figure 3.



Figure 3. Proposed Interior Layout and Wintergarden Location in the building.

The wintergarden in conjunction with the passive cooling through natural ventilation during the summer creates a unique experience for the students in the building, improving occupant wellness and thermal comfort. Although there is increased humidity, and CO₂ levels, this can be removed during the summertime, but it would require additional mechanical ventilation during the wintertime.

In terms of the specific student units, there were two types of units proposed. Type 1 allows for the accommodation up to four people, and Type 2 allows up to two people as shown in Figure 3. Additionally, there were also units designed for wheelchair accessibility. Between these types, this pavilion can occupy 52 students.

2.2.2. Building Envelope

A series of changes were made to the original enclosure including the roof, ceiling, exterior walls, and underground floor and wall of the building. Based on the information made available during this study, the existing building envelope is mainly made up of load-bearing brick and concrete. The existing roof, interior floors, basement floors, and basement walls are made of an uninsulated assembly from only concrete. The existing exterior wall consists of load-bearing brick masonry. The existing building also has a district heating system with radiator distribution in the building as the heat is delivered by radiators in the different rooms. Heat is supplied to the pavilions via a district heating pipeline; the district heat is converted into superheated steam and distributed on the site via the high-temperature heating network. The pipes run along the pavilions. In any case, the entire existing heat pipe network no longer meets today's requirements and also has very poor energy efficiency. The thermal performance of the existing building was provided from the building archives and was found as shown in Table 1. These values are then improved resulting in lower U-values, also shown in Table 1.

Table 1. U-values of existing and U-values after proposed changes.

	Roof (W/m ² K)	Exterior Wall (W/m ² K)	Basement Floor (W/m ² K)	Underground Wall (W/m ² K)
Existing (U-value)	2.17	0.92	3.8	0.95
New (U-value)	0.175	0.345	0.22	0.19

To achieve such results, there were modifications made to the enclosure of the building. There were 2 types of insulations used throughout this enclosure. The majority of this

insulation is a rigid cellulose board which has a conductivity of 0.027 W/mK [15,16]. This insulation was chosen due the fact that it is permeable and will allow any trapped water vapor in the historic masonry walls to diffuse to the interior or exterior surface, thus improving its hygrothermal function. Additionally, there were also vacuum insulated panels (VIPs) used in small areas in order to achieve a low U-value without sacrificing the thickness of the assemblies. The conductivity of VIPs is also very low. For instance, it can be as low as 0.003 W/mK [17]. In combination with the cellulose rigid boards, VIPs were used only at the perimeter of the roof in order to maintain the original slender roof profile as shown in Figure 4a. The PV panels would be anchored down with thermally broken connectors to the concrete structure, and the VIP panels would be laid in afterwards. A vapor barrier was introduced in order to prevent moisture from entering into the existing concrete roof structure, and any opening in the vapor barrier would be required to be properly sealed to ensure continuity. In order to have additional insulation on the ceiling, a decorative plaster with corner detail was applied in order to blend with the existing historic building's character as seen in Figure 4a. The location of the vapor barrier in the roof allows for any moisture to dry towards the ceiling and the exterior wall, improving hygrothermal performance. After introducing a triple pane window on the interior side in addition to the existing exterior single pane window, the overall U-value was reduced to $0.8 \text{ W/m}^2\text{K}$ [18]. The interior wall insulation also turns in and terminates at the base of the new window frame, resulting in a thermally continuous plane as seen in Figure 4a,b. As seen in Figure 4b, moving onto the floor, a small portion of the perimeter of the floor is designed to be removed to allow the VIPs to be laid.

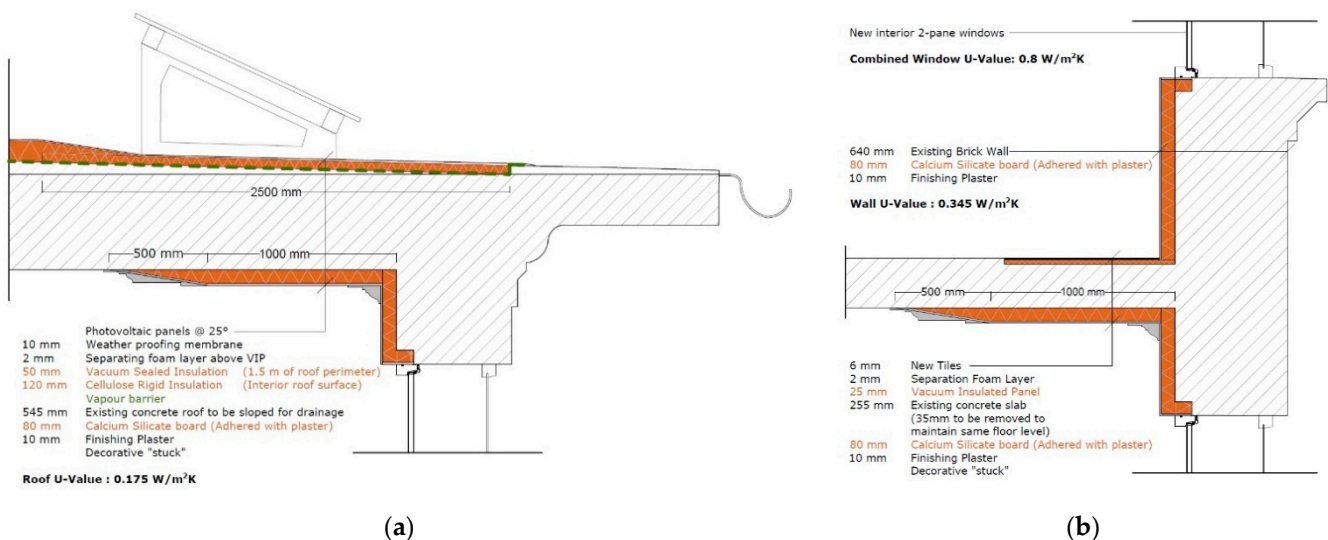


Figure 4. U-value of roof with proposed changes to the (a) Roof, (b) floor, and wall.

Upon those, either the existing carefully removed tile can be placed back or new "Mettlach Tiles" from the same manufacturer, Wienerberger, can be placed. The existing basement floor was in poor condition based on on-site photographs and had to be replaced for structural stability by a new concrete slab. In this case, the structural integrity could not be compromised for historical preservation. This provides an opportunity to place cellulose rigid insulation and the vapor barrier under the slab as shown in Figure 5. The vapor barrier is continuous from under the concrete floor, then moves up to the underside of the finished tiles, then laps under the door frame, and moves towards the exterior insulation. For the underground wall, insulation was placed on the exterior, terminating under the door frame for thermal continuity.

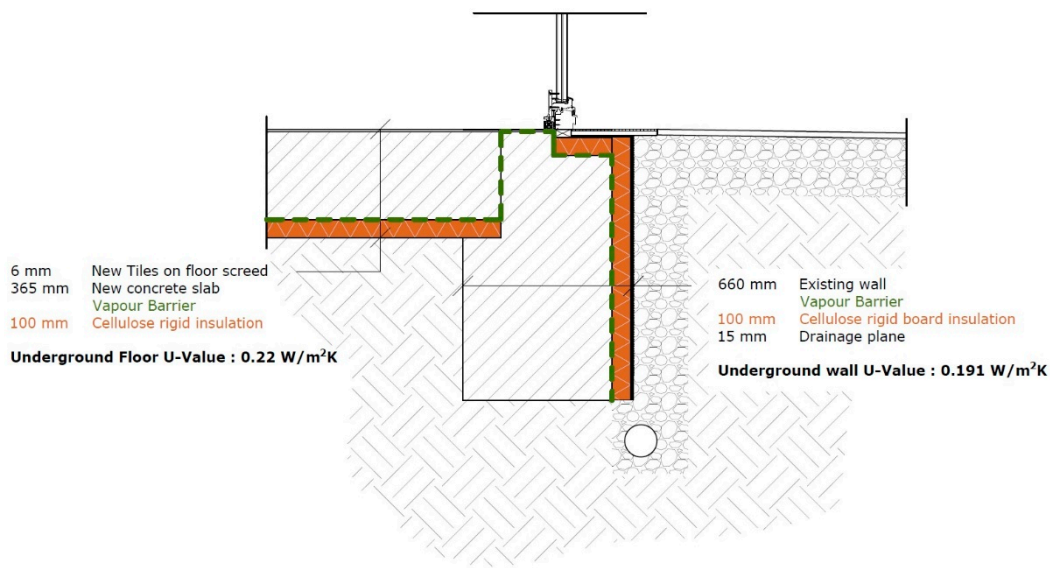


Figure 5. U-value of basement floor and wall with proposed changes.

Through an iterative design process, this solution provides minimal damage with maximum improvement in thermal performance while maintaining the historical integrity of this building. Overall, a decision was made to insulate the interior of the building since it would allow for the existing building’s exterior façade to remain as is for historical importance.

2.2.3. Energy Efficiency Measures

In order to simulate the energy use of this building, the Sefaira plugin in Sketchup and the online cloud tool was used in addition to Polysun [19,20]. Vienna, Austria is described to be warm and temperate with an average annual temperature of 10.9 °C. It also receives significant rainfall with 703 mm of precipitation annually. Throughout the year, temperatures in the summer can go up to 26 °C and can be as low as −3 °C in the winters. The average temperature in Vienna is 10.9 °C as shown in Figure 6 [21,22]. For the 2017 year, the heating degree days were 2683, and the cooling degree days were 386, indicating that it is a heating-dominated climate [23].

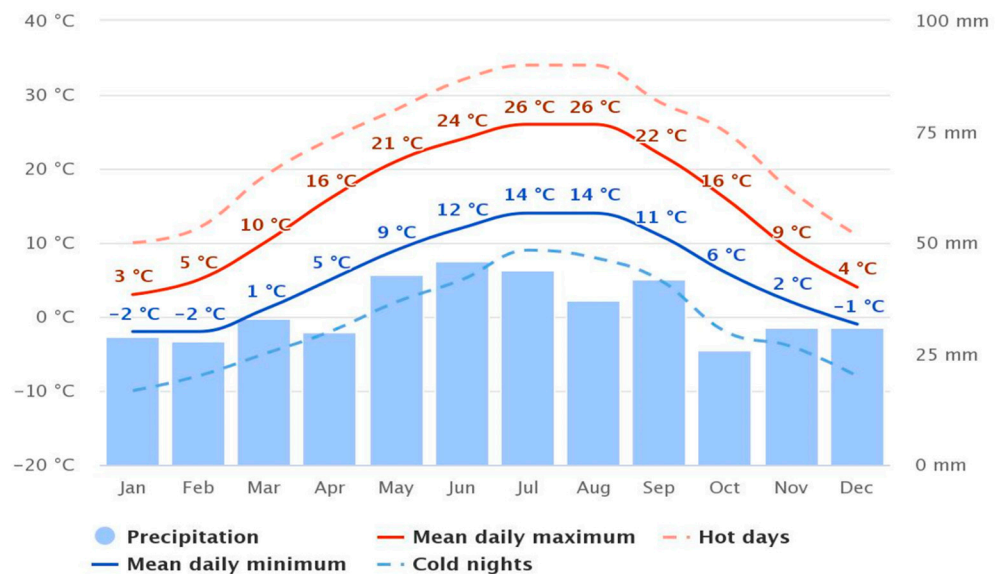


Figure 6. Average monthly temperature and rainfall precipitation in Vienna [22].

Through the Sefaira energy simulation model, an existing building baseline was established to which all iterations were compared. While simulating in Sefaira, a local weather file based in Vienna, Austria was used and kept constant through all simulations. Any parameters not mentioned were kept as default. Unfortunately, the building's consumption data were not made available during this project for a more accurate calibration in the energy simulation. The different iterations were used to assess different parameters in order to determine which ones contribute to reduced energy consumption. One of these parameters includes different levels of added insulation to the building enclosure. It should be noted that the building enclosure assemblies were being designed simultaneously, while the energy simulation was being conducted as a true iterative exercise incorporating the integrated design process.

The values mentioned in Table 1 represent the final proposed building enclosure U-values. In addition to the building enclosure assembly U-values, other parameters including the Solar Heat Gain Coefficient (SGHC), infiltration, interior shading, occupant density, equipment density, lighting density, the setpoint temperature for cooling and heating, natural ventilation, and the heat recovery ventilator were explored. With internal shading, both blinds and venetian blinds were simulated, but exterior shading was not considered due to its impact on the historical façade of the building.

In Table 2 below, the vertical and horizontal shading represents the depth between the exterior face of the window and the exterior face of the exterior wall in meters. This impacts the light entering the windows and is modeled in Sefaira as shading. Initially, the lighting density was reduced to 2.5 W/m² to reduce energy; however, it was not sufficient lighting for the program within the space. Thus, this was increased to 10 W/m² as per ASHRAE guidelines [24]. The different iterations which were tried in the software are shown in Table 2 below. The dashes on Table 2 represent no change compared to the previous iteration, and only changes are shown.

Table 2. Changes made between different iterations for Sefaira simulation.

	Proposed Simulated Iterations in Sefaira							
	1 (Baseline)	2	3	4	5	6	7	8
Envelope								
Façade Glazing U-value (W/m ² K)	2.5	0.8	-	-	-	-	-	-
Walls U-value (W/m ² K)	0.92	0.345	-	-	-	-	-	-
Floors (W/m ² K)	2.17	-	0.35	-	0.22	-	-	-
Infiltration type and amount	Crack Infiltration (2.0 L/sm)	1 ACH	-	1 m ³ /m ² ·h @ 50 Pa (Façade Area)				
Roof Glazing U-value (W/m ² K)	2.4	-	0.8	0.85	0.8	-	-	-
Roof Glazing (SHGC)	0.6	-	-	-	-	-	-	-
Roof U-value (W/m ² K)	2.17	0.35	-	-	0.175	-	-	-
Shading								
3D model shading	Yes	-	-	-	-	-	-	-
Horizontal shading (m)	0.64	-	-	-	-	-	-	-
Vertical Shading (m)	0.64	-	-	-	-	-	-	-
Automated Blinds and shades	No	-	-	-	-	Yes	No	-
Space Use								
Occupant density (m ² /people)	5	-	-	28	22	-	-	-
Equipment Power Density (W/m ²)	8	-	-	1.5	2.5	-	-	-
Lighting power density (W/m ²)	3	-	-	2.5	10	-	-	-
Setpoint temp (Heating) (°C)	21	-	-	20	-	-	-	-
Setpoint temp (Cooling) (°C)	25	-	-	26	-	-	-	-
Setback temp (Heating) (°C)	18	-	-	-	-	-	-	-
Setback temp (Cooling) (°C)	28	-	-	-	-	-	-	-
Outside air rate/person (L/s)	3.5	-	-	10	8.3	-	-	-
Natural Ventilation								
HRV (Heat Recovery Ventilator) efficiency	Off	-	-	-	-	-	-	On
	50%	-	-	-	-	-	90%	-

Using Polysun, a space heating system with seasonal storage and a PVT (Photovoltaic-Thermal Solar) collector combined with a borehole heat exchanger as a source of geothermal energy were designed as shown in Figure 7 in the energy system schematic. This type of collector consists of a combination of a solar-thermal collector and a PV module. The PVT system is designed using 160 modules tilted by 25° with a collector aperture area of 264 m². The performance ratio of the PVT collector is 86.2%. The performance ratio measures the overall effect of losses on the rated output of the system; it is the percentage between the specific annual energy yield and average daily peak sun-hours [25].

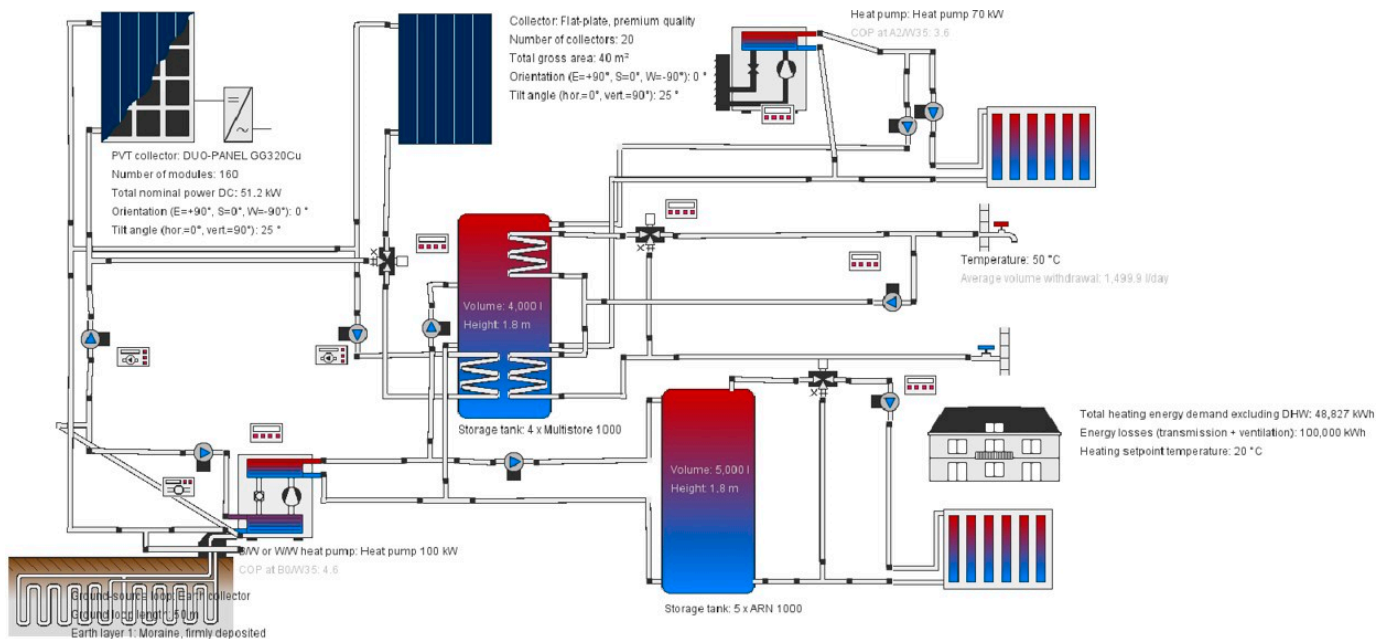


Figure 7. Energy system schematic (space heating with seasonal storage with PVT collector).

The solar thermal energy system is designed using 20 flat-plate collectors with an overall gross area of 40 m² to cover a daily consumption of hot water of 1500 L/day for 52 students. The average specific water consumption amounted to 26.6 L per student per day for full-time-studies students [26]. The geothermal borehole field is designed using 4 boreholes, with a depth of 50 m each. The building specifications are shown in Table 3; the heating setpoint temperature is 20 °C, and the estimated annual specific heating energy demand is 16 kWh/(m² year) to cover the required specific heating energy demand of the passive house standard in Austria of 15 kWh/(m² year) [27].

Table 3. Building Specifications.

Building	-	-
Heated/air-conditioned living area	m ²	3051
Heating setpoint temperature	°C	20
Heating energy demand excluding DHW (Qdem)	kWh	48,827
Estimated Annual specific heating energy demand	kWh/m ² /a	16
Useful heat gain	kWh	52,285

3. Results

These results incorporate the architectural and building envelope methodology as it was simulated through the Sefaira and Polysun simulation tools.

3.1. Simulation: Sefaira

Based on the changes made between each iteration mentioned in the previous section, there were varying results. Since the focus of this study is to reduce energy consumption, the Thermal Energy Demand Intensity (TEDI) and Total Energy Use Intensity (TEUI) were the main criteria examined to form the results. These results of all the iterations can be seen in Table 4 below.

Table 4. Results from proposed iterations in Sefaira.

	1 (Baseline)	2	3	4	5	6	7	8
TEUI (kWh/(m ² year))	248.9	199.8	130.9	61.3	54.6	55.1	54.3	69.9
TEDI (kWh/(m ² year))	149.2	104.0	53.4	30.1	15.6	16.1	15.2	43.1

Based on these results, making changes to the envelope of the building significantly reduced the consumption, and once the appropriate occupant density and other space use parameters were applied based on the new use of the building, this resulted in even lower consumption. It should be noted that the interior blinds and venetian shading system slightly increased the energy use likely due to reduced passive solar gain in this heating-dominated building. Since there is reduced passive solar gain, the heating demand increases directly. After applying a high-efficiency HRV (Heat Recovery Ventilator) into the building system, the energy consumption was reduced even further, resulting in the lowest simulated iteration, iteration 7.

For further exploration, natural ventilation was modeled; however, it is difficult to model the multi-story atrium and stairwells accurately through Sefaira, and these results are likely simplified. A more accurate representation would need to be conducted with the aid of CFD, computational fluid dynamics, software to determine its impact on the overall energy consumption and TEDI.

In Figure 8 below, the breakdown of the different components that make up the energy use can be seen as compared with the different iterations in relation to iteration 7. The percentages in red indicate how much higher the energy use is compared to iteration 7. A significant makeup of the energy is heating, and once that is reduced, the other components such as lighting and equipment create a larger ratio of the whole, so all small changes can make an impact on the whole energy consumption. Elnagar E. and Köhler B. show that passive approaches could minimize the energy demand of buildings (mainly heating and cooling, but also lighting) and can have a large impact on the specific and overall energy demand [28].

Based on the results, iteration 7 was selected. The results indicate that the existing building used 704,193 kWh/year which is 248.9 kWh/(m² year), as seen in Figures A3 and A4 in Appendix A, and the proposed building based on iteration 7 used only 165,490 kWh/year which is 54.3 kWh/(m² year), as seen in Figure A5 in Appendix A and Figure 8.

It can be seen that the majority of the energy is consumed for heating, lighting, and equipment in Figure 9; however, the specific heating demand was reduced from 149.2 kWh/(m² year) down to 15.2 kWh/(m² year) which is close to the passive house standard of 15 kWh/(m² year) [27]. Similarly, the interior loads, lighting, and equipment were reduced from 48 kWh/(m² year) down to 21 kWh/(m² year).

Annual Energy Use - Comparison

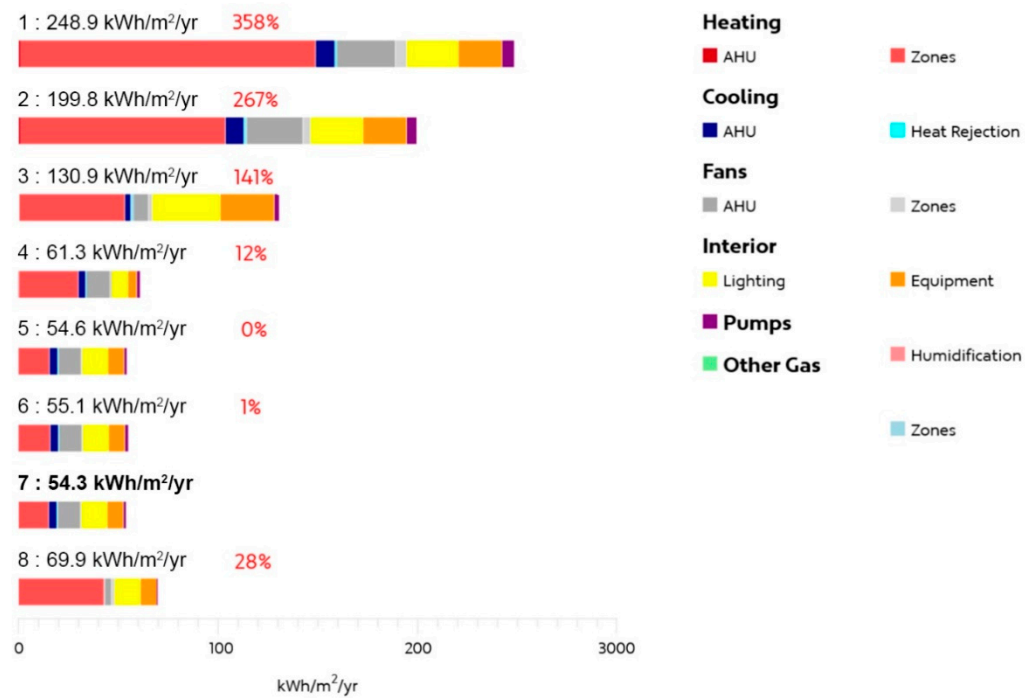


Figure 8. Total Energy Use Intensity (TEUI) breakdown and comparison between iteration 7 and others.

Annual Energy Use

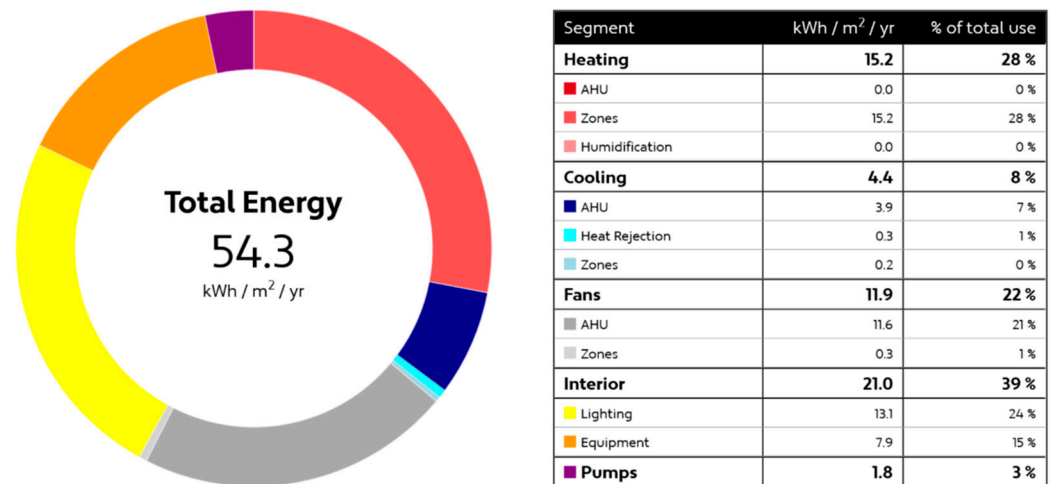


Figure 9. Overall energy breakdown of the proposed design.

When analyzing the annual trend of this selected iteration, as seen in Figure A6 in Appendix A, the energy use of the lighting, equipment, and fans are relatively the same throughout the year; however, the cooling and heating energy use fluctuates from winter to summer. This reduced operational energy value results in less energy required to be produced onsite. The results indicate a reduction in TEUI and TEDI by about 78.2% and 89.8%, respectively.

3.2. Simulation: Polysun

The energy system was designed to cover the total heating demand of 48,820 kWh_{th} excluding the DHW demand; the designed system covers the estimated heating demand by Sefaira (46,293 kWh_{th}); the space heating system is powered by radiators. The annual electricity consumption is 82,740 kWh (sum of the electricity consumption from profiles and thermal components); the value of 65,000 kWh_e is the electricity consumption of the building hourly profiles (Epcs), and 17,740 kWh_{th} are consumed by the thermal components (Ethcs) as shown in Table 5, and the total energy consumption is 65,956 kWh. The PVT system produced 60,312 kWh_e with a self-consumption fraction (Rocs) of 30.8%, as only 18,560 kWh_e from the generated amount were consumed, as the system was designed without batteries. The self-consumption fraction (Rocs) equals the relation between self-consumption and self-production.

Table 5. Building electricity consumption.

Electric Consumers	-	-
Electricity consumption (Ecs); (Ecs = Epcs + Ethcs)	kWh	82,740
Electricity consumption of the profiles (Epcs)	kWh	65,000
Electricity consumption of the thermal components (Ethcs)	kWh	17,740
Self-consumption (Eocs)	kWh	18,563
Self-consumption fraction (Rocs)	%	30.8

Table 5 shows a breakdown of the electricity consumption in the selected building. The daily maximum temperature of the PVT collector is shown in Figure A1 in Appendix A. The hot water energy demand is 24,220 kWh; 61% of the hot water demand is produced by the solar thermal collectors as shown in Figure 10. Figure A2 in Appendix A shows the daily maximum temperature for the solar thermal collectors. As shown in Figure 10, during the summer months, the fraction of solar energy to the system is high. The ground-coupled heat pump generated 36,509 kWh, with an inflow temperature of 10.4 °C and an outflow temperature of 9.3 °C.

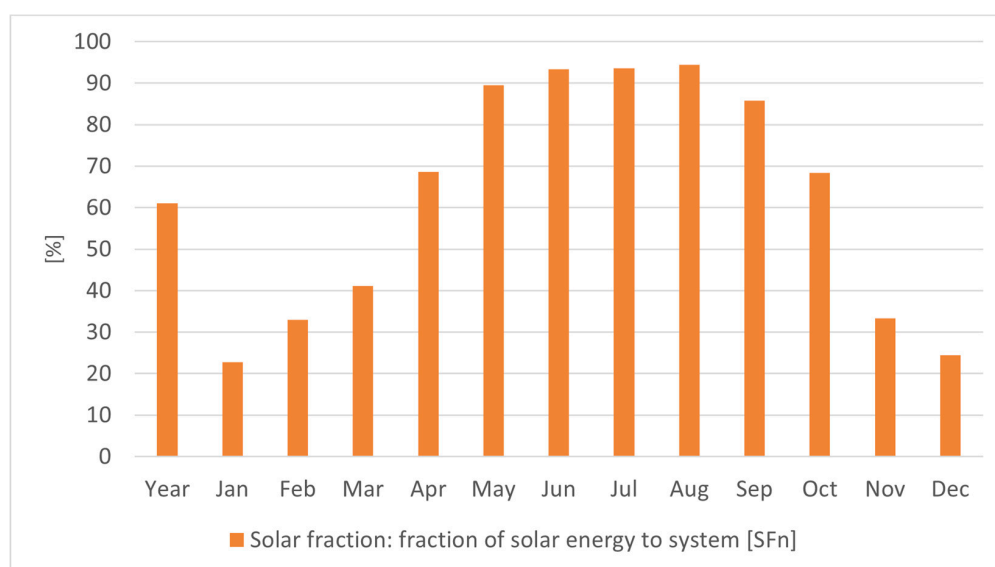


Figure 10. Fraction of solar energy to the system.

The energy flow diagram is shown in Figure 11; it shows the energy inflows on the left-hand side and its distribution on the right-hand side. On the inflow side, heat is generated to the system, e.g., from the solar collector field. On the distribution side, there are demands and losses of the system. Both thermal energy and electrical energy are considered. The annual balance is shown with a precision of 72.27%.

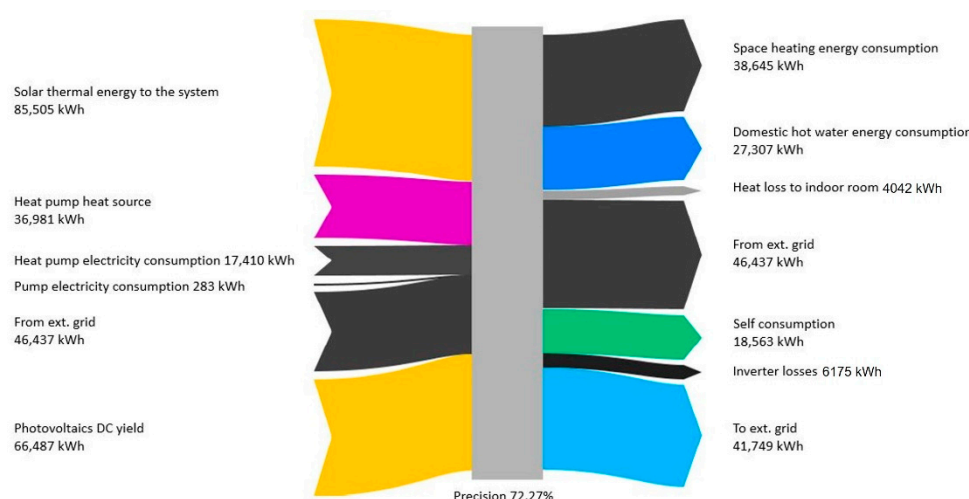


Figure 11. Energy flow diagram (annual balance).

4. Discussion

The architectural interventions proposed in this case study provide a balance of private, public, and semi-public areas for the students. However, some difficulties may arise during the actual construction process with unknown issues due to the age of the building. For example, more interior walls may be required than anticipated in order to ensure structural safety. Since PV and thermal solar collectors are proposed to be the dominant method of producing energy on-site, this would require approval from municipal authorities. Further on-site investigation and testing would be required in order to determine if any of the proposed interventions may cause problems in reality. Since this is an existing building, the air infiltration will not be as low as a newly constructed building. This would increase the actual heat loss in comparison to this virtual study conducted. It would also be difficult to predict other challenges which may take place on-site during renovation since this is an old building existing from the early 1900s. It becomes very difficult to simulate these unforeseen challenges which may compromise the building's thermal performance. For more accuracy, a blower door test can be conducted, and building consumption data can be used to calibrate the building energy simulations. Although not the focus of this study, further steps can be taken to analyze the hygrothermal performance of the proposed building envelope assemblies through a condensation risk analysis and the effects of point and linear thermal bridging through software such as WUFI and THERM.

Overall, in order to achieve a low-energy building, reducing the initial consumption as much as possible is an essential first step. Working with this building's historic restrictions, the changes were made to allow the maintenance of the existing building as much as possible while incorporating an improved thermal resistance. Based on the proposed measure, the specific characteristics of historical value were preserved. From the exterior, the façade including the windows, cornice, and exposed brick/stone/plaster all remain unchanged. From the interior, the plaster finish over the insulation would maintain the interior finish as per the existing design as well. Only a small portion of the original floor tiles would be removed and can be replaced by the original supplier. Additionally, the tilt angle of the PV array is also designed not to be seen from people walking up to the pavilion. As a result, the historic values of the building are preserved. Some of these changes are summarized in Figure 12 below.

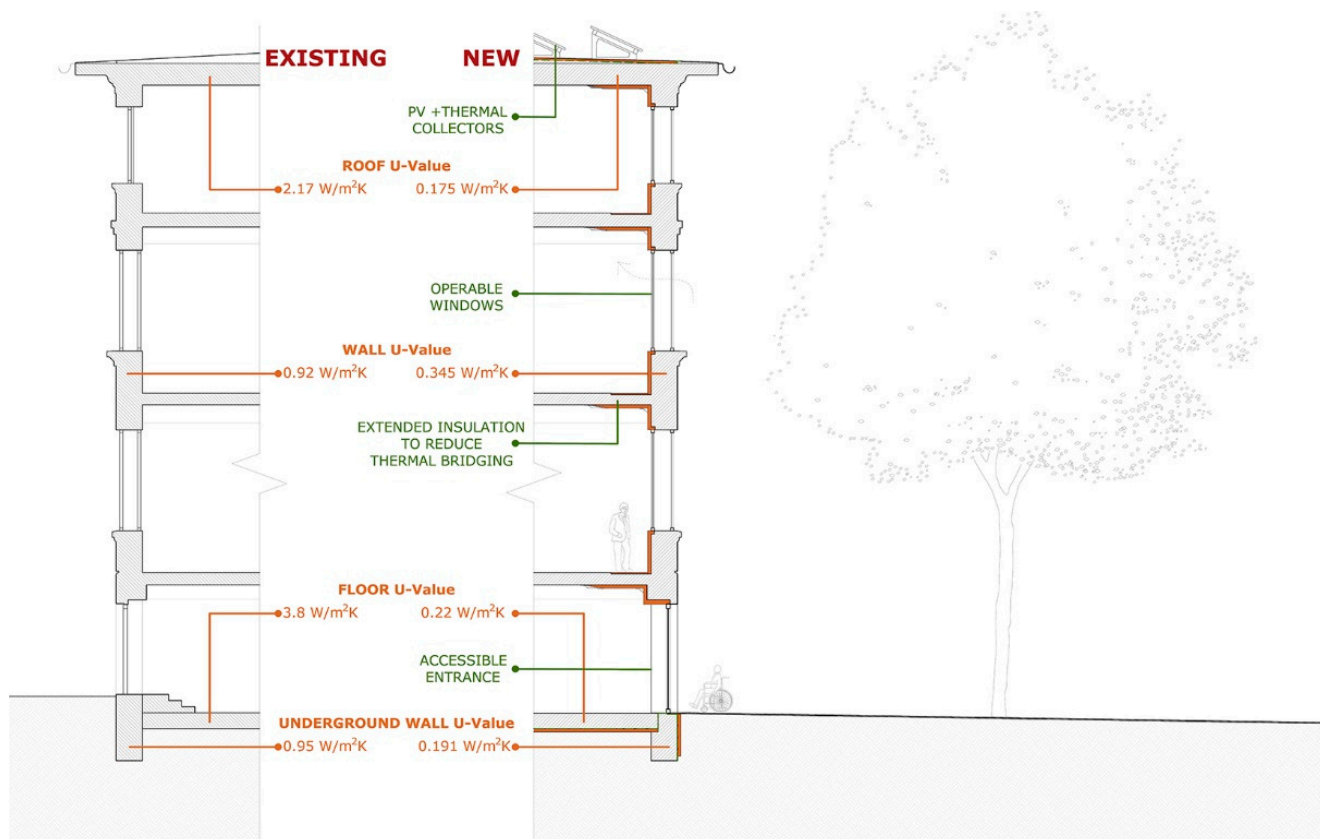


Figure 12. Summary Graphic of major changes made for improved energy efficiency.

Future Climate Change Implications

The effect of climate change on historical buildings was examined previously. Climate change will result in an increase in temperature and a change in the pattern of rainfall. The energy use, indoor climate, and humidity dynamics of historic buildings can be changed along with retrofit solutions [29]. Overheating is already a growing concern with regard to the internal climate. The combined effect of internal insulation and increased outdoor temperatures may increase the energy demand for cooling and encourages the implementation of cooling and ventilation systems for historical buildings. The impact of the changing climate for Pavilion 21 would be much less compared to buildings located in the dense city's center. Since the OWA is located outside of central Vienna, there is a lower impact of the Urban Heat Island effect (UHI), resulting in a lower cooling demand in the summer. Since passive cooling with natural cross ventilation is proposed by taking advantage of north prevailing winds on-site, this may be sufficient to accommodate for the changing climate in the future but would require further modeling with future weather files to be certain. Additionally, there is a large greenspace towards the north and large mature trees around the site and complex which were kept as existing as shown in Figure 2; E. Elnagar et al. show the building with the greenspaces in a wider view [30]. Therefore, through the process of evapotranspiration, the surrounding area is further cooled to reduce the summer cooling load. Since the proposed changes made to the building result in interior insulation, during the summertime, this may be problematic. Although the proposed insulation is vapor permeable, during the summertime, the sun would drive the moisture towards the interior surface of the envelope. This may lead to insulation degradation or reduced performance if the moisture within the wall is not able to dry out towards the interior quickly.

5. Conclusions

In conclusion, multiple aspects are required to retrofit an existing historical building in order to achieve a net-positive energy status. Architectural interventions were incorporated in order to preserve heritage, improve quality of life, create opportunities for biophilia with a wintergarden, and design with sustainability. The flexible room typologies allow for wheelchair accessibility and can accommodate up to 52 students. The solutions presented in this paper include improving the thermal performance of the enclosure while maintaining the historical character of the building through the use of VIPs and cellulose rigid board insulation. This resulted in the overall energy demand of the building to be reduced to 54.3 kWh/(m² year) from 248.9 kWh/(m² year), showing a 78.2% reduction.

Although it is difficult to anticipate on-site conditions and simulate the existing airtightness levels, the proposed changes provide a good starting point for retrofits for historical buildings in the European context where the majority of the cities are already built. If applied to the whole Otto Wagner Areal, this can develop an innovative infrastructure and encourage other campuses to integrate these strategies as well to contribute to reduced carbon emissions. There were some constraints to be taken into consideration while designing the PV system, as the aperture area of 264 m² was the accessible hidden area for the PV system modules, as the priority is the historical preservation of the building. In addition to the PV system, a geothermal system was considered which led to 36,981 kWh energy savings annually (75.7% of the heating energy demand excluding DHW demand was provided by the geothermal system).

These strategies can be applied to contribute towards the sustainable development goals, and four SDGs are explored in this study. Moving towards providing clean and affordable energy, as outlined in goal 7, is demonstrated in this study with the use of PV, solar hot water collectors, and a ground source heat pump to power the building after reducing the energy demand as much as possible, resulting in significantly reduced energy bills. In addition to this, cellulose insulation was selected since it is an organic material to contribute towards goal 9 for industry, innovation, and infrastructure.

This study also encourages students to bike and to use the gym and yoga room, thus contributing towards goal 3 regarding good health and well-being [5]. Factors included in this design also contribute to goal 11 for sustainable cities and communities [5,30]. Moving forward, these strategies in combination with others pave the way for a sustainable future for retrofitting historical buildings.

Author Contributions: Conceptualization, E.E. and S.M.; methodology, E.E. and S.M.; software, E.E. and S.M.; validation, E.E., S.M. and V.L.; formal analysis, E.E., S.M. and V.L.; investigation, E.E. and S.M.; resources, E.E. and S.M.; data curation, E.E.; writing—original draft preparation, E.E.; writing—review and editing, E.E., S.M. and V.L.; supervision, V.L.; project administration E.E., S.M. and V.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Karin Stieldorf from TU Wien, Georg Reinberg from Reinberg Architekten ZT, as well as the Green.Building.Solutions (GBS) Summer University for their valuable input and assistance during the participation in the summer university. The authors also thank Marcello Turrini from the GBS team for the paper's internal review and feedback, and Karina Rafailov for her input in the architectural development for this project during the summer university program.

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

Appendix A

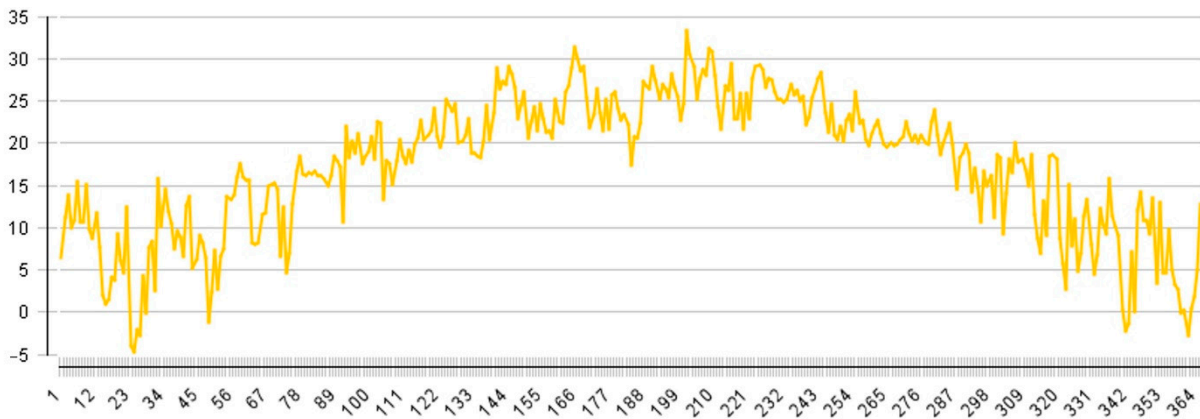


Figure A1. Daily maximum temperature (°C) for the PVT collector.

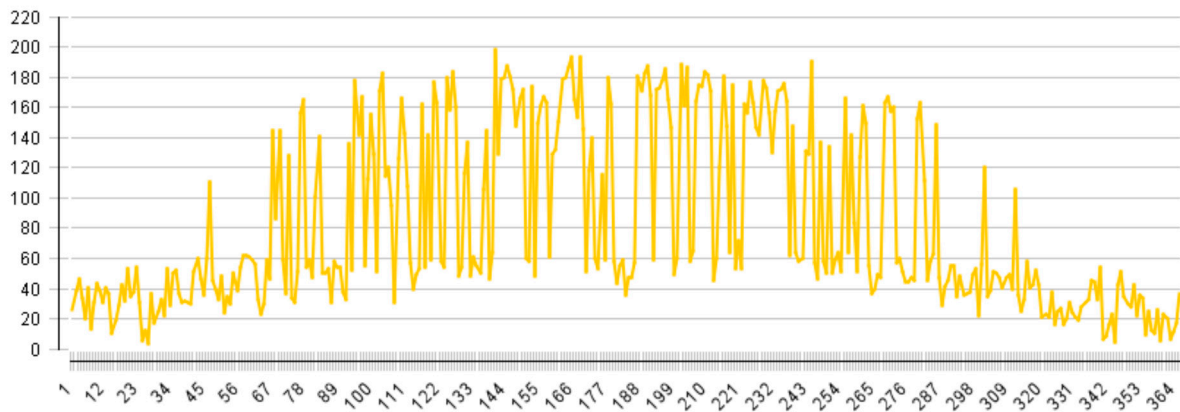
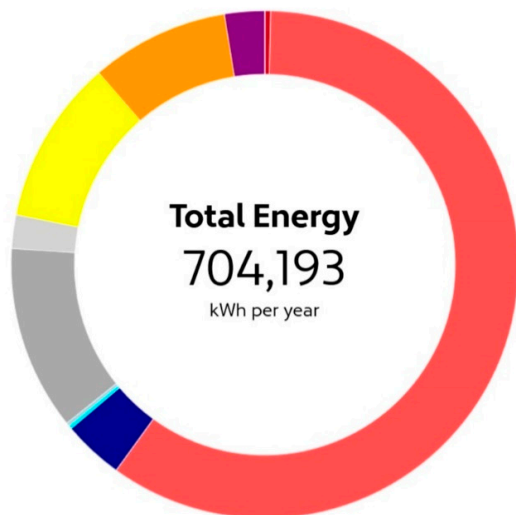


Figure A2. Daily maximum temperature (°C) for the solar thermal collector.

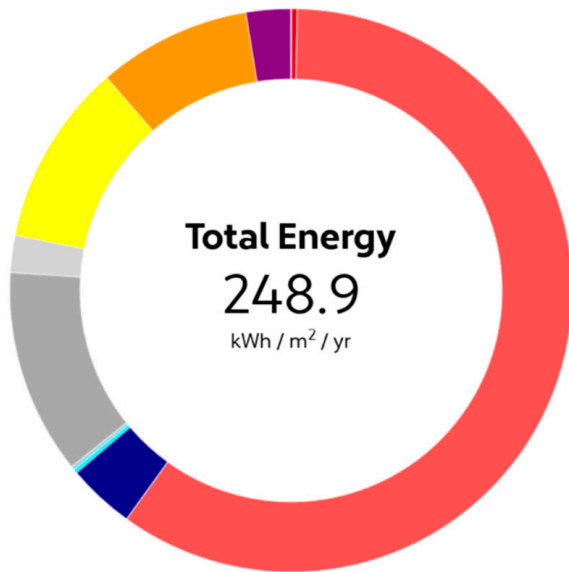
Annual Energy Use



Segment	kWh per year	% of total use
Heating	422,277	60 %
■ AHU	2 608	0 %
■ Zones	419,669	60 %
■ Humidification	0	0 %
Cooling	30,240	4 %
■ AHU	27,171	4 %
■ Heat Rejection	1 444	0 %
■ Zones	1 625	0 %
Fans	97,797	14 %
■ AHU	82,797	12 %
■ Zones	15,000	2 %
Interior	135,886	19 %
■ Lighting	73,886	10 %
■ Equipment	62,000	9 %
■ Pumps	17,993	3 %

Figure A3. Annual energy use in the existing building.

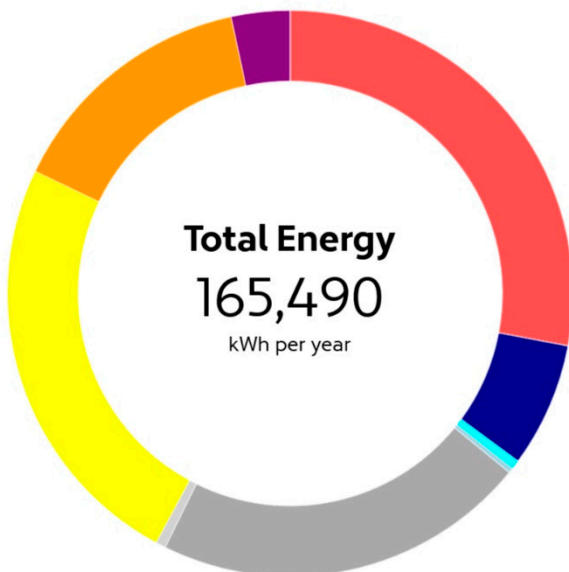
Annual Energy Use



Segment	kWh / m ² / yr	% of total use
Heating	149.2	60 %
■ AHU	0.9	0 %
■ Zones	148.3	60 %
■ Humidification	0.0	0 %
Cooling	10.7	4 %
■ AHU	9.6	4 %
■ Heat Rejection	0.5	0 %
■ Zones	0.6	0 %
Fans	34.6	14 %
■ AHU	29.3	12 %
■ Zones	5.3	2 %
Interior	48.0	19 %
■ Lighting	26.1	10 %
■ Equipment	21.9	9 %
■ Pumps	6.4	3 %

Figure A4. Annual specific energy use in the existing building.

Annual Energy Use



Segment	kWh per year	% of total use
Heating	46,293	28 %
■ AHU	6	0 %
■ Zones	46,287	28 %
■ Humidification	0	0 %
Cooling	13,119	8 %
■ AHU	11,778	7 %
■ Heat Rejection	851	1 %
■ Zones	490	0 %
Fans	36,354	22 %
■ AHU	35,406	21 %
■ Zones	948	1 %
Interior	64,167	39 %
■ Lighting	40,104	24 %
■ Equipment	24,063	15 %
■ Pumps	5 557	3 %

Figure A5. Annual energy use based on iteration 7 (Final proposed iteration).

Monthly Energy Use

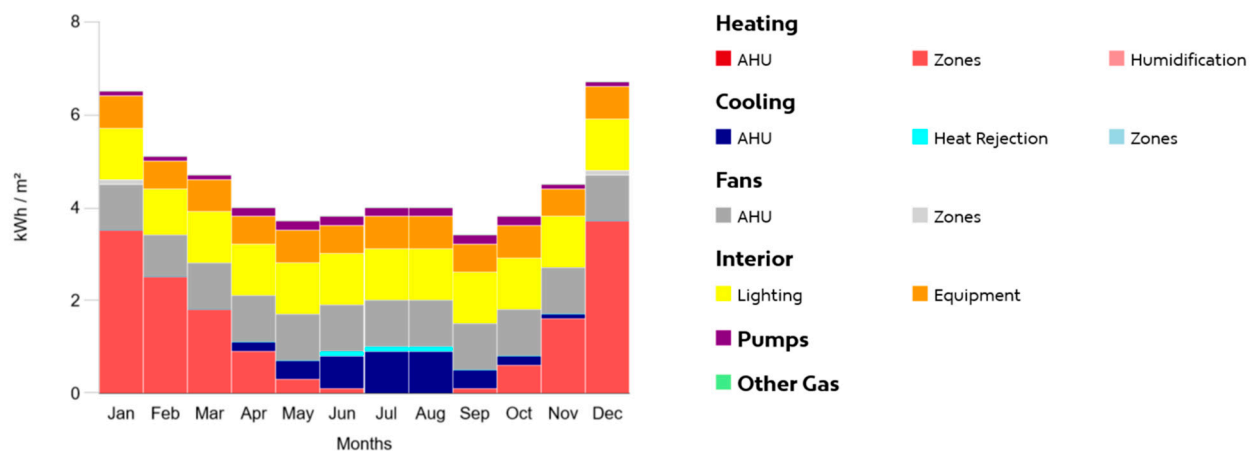


Figure A6. Monthly Energy use breakdown based on iteration 7 (Final proposed iteration).

References

- Young, B.; Right, W. Energy Efficiency of Heritage Buildings. Fact Sheet. Available online: https://epbd-ca.eu/wp-content/uploads/2018/04/02-CT2_Factsheet-Heritage.pdf (accessed on 15 August 2021).
- Lidelöw, S.; Örn, T.; Luciani, A.; Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. *Sustain. Cities Soc.* **2019**, *45*, 231–242. [CrossRef]
- Effesus, Deliverable D1.1: European Building and Urban Stock Data Collection—Energy Efficiency for EU Historic Districts Sustainability. 2013. Available online: http://www.effesus.eu/wp-content/uploads/2016/01/D-1.1_European-building-and-urban-stock-data-collection.pdf (accessed on 15 August 2021).
- Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.-L. Energy efficiency and thermal comfort in historic buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [CrossRef]
- Cornaro, C.; Puggioni, V.A.; Strollo, R.M. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study. *J. Build. Eng.* **2016**, *6*, 17–28. [CrossRef]
- Filippi, M. Remarks on the green retrofitting of historic buildings in Italy. *Energy Build.* **2015**, *95*, 15–22. [CrossRef]
- Leardini, P.; Manfredini, M.; Callau, M. Energy upgrade to Passive House standard for historic public housing in New Zealand. *Energy Build.* **2015**, *95*, 211–218. [CrossRef]
- Bellia, L.; Alfano, F.R.D.; Giordano, J.; Ianniello, E.; Riccio, G. Energy requalification of a historical building: A case study. *Energy Build.* **2015**, *95*, 184–189. [CrossRef]
- Cho, H.M.; Yun, B.Y.; Yang, S.; Wi, S.; Chang, S.J.; Kim, S. Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building. *Appl. Energy* **2020**, *275*, 115313. [CrossRef]
- Cho, H.M.; Yang, S.; Wi, S.; Chang, S.J.; Kim, S. Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: A cultural properties case study. *Energy* **2020**, *201*, 117607. [CrossRef]
- Fouseki, K.; Cassar, M. Energy Efficiency in Heritage Buildings—Future Challenges and Research Needs. *Hist. Environ. Policy Pract.* **2014**, *5*, 95–100. [CrossRef]
- Stieldorf, K.; Turrini, M. Otto Wagner Areal Plus—Green Building Solutions 2020 Design Projects—OeAD Student Housing. Available online: https://issuu.com/barbara.mayr/docs/owa_booklet_complete_20210121_final (accessed on 16 August 2021).
- Tissen, C.; Menberg, K.; Benz, S.A.; Bayer, P.; Steiner, C.; Götzl, G.; Blum, P. Identifying key locations for shallow geothermal use in Vienna. *Renew. Energy* **2021**, *167*, 1–19. [CrossRef]
- The 17 Goals. Sustainable Development. Available online: <https://sdgs.un.org/goals> (accessed on 16 August 2021).
- Wang, P.; Aliheidari, N.; Zhang, X.; Ameli, A. Strong ultralight foams based on nanocrystalline cellulose for high-performance insulation. *Carbohydr. Polym.* **2019**, *218*, 103–111. [CrossRef] [PubMed]
- Pierson, B. Cellulose Rigid Foam Board Insulation, Environmentally-Friendly Styrofoam Alternative. Available online: <https://www.ecohome.net/news/1465/cellulose-foam-insulation-boards/> (accessed on 16 August 2021).
- Capozzoli, A.; Fantucci, S.; Favoino, F.; Perino, M. Vacuum Insulation Panels: Analysis of the Thermal Performance of Both Single Panel and Multilayer Boards. *Energies* **2015**, *8*, 2528–2547. [CrossRef]
- Rustic Profile Wood Windows Custom Built with Glazing Bars. Neuffer-Windows.ca. Available online: <https://www.neuffer-windows.ca/wood-window-rustic.php> (accessed on 4 January 2021).
- Mads, J.; Peter, K. Sefaira. Timble. Available online: <https://www.sketchup.com/products/sefaira> (accessed on 3 October 2021).
- Polysun—Simulation Software for Energy Systems. Polysun. Available online: <https://www.velasolaris.com/software/?lang=en> (accessed on 4 October 2021).

21. Vienna climate: Average Temperature, Weather by Month, Vienna Weather Averages—Climate-Data.org. Available online: <https://en.climate-data.org/europe/austria/vienna/vienna-41/> (accessed on 3 October 2021).
22. Meteoblue. Climate Vienna. Available online: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/vienna_austria_2761369 (accessed on 15 October 2021).
23. Ashrae Climatic Design Conditions 2009/2013/2017. Available online: http://ashrae-meteo.info/v2.0/index.php?lat=48.200&lng=16.367&place=%27%27&wmo=110340&ashrae_version=2017 (accessed on 3 October 2021).
24. Ashrae Special Publications, Ansi/Ashrae Standard 90.1-2010 (SI). Ashrae. 2010. Available online: <https://www.ashrae.org/technical-resources/bookstore/standard-90-1> (accessed on 3 October 2021).
25. Abdul-Ganiyu, S.; Quansah, D.A.; Ramde, E.W.; Seidu, R.; Adaramola, M.S. Investigation of Solar Photovoltaic-Thermal (PVT) and Solar Photovoltaic (PV) Performance: A Case Study in Ghana. *Energies* **2020**, *13*, 2701. [[CrossRef](#)]
26. Wichowski, P.; Rutkowska, G.; Kamiński, N.; Trach, Y. Analysis of Water Consumption in the Campus of Warsaw University of Life Sciences—SGGW in Years 2012–2016. *J. Ecol. Eng.* **2019**, *20*, 193–202. [[CrossRef](#)]
27. Passivhaus Institut. Available online: https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm (accessed on 16 August 2021).
28. Elnagar, E.; Köhler, B. Reduction of the Energy Demand with Passive Approaches in Multifamily Nearly Zero-Energy Buildings Under Different Climate Conditions. *Front. Energy Res.* **2020**, *8*, 224. [[CrossRef](#)]
29. Hao, L.; Herrera-Avellanosa, D.; del Pero, C.; Troi, A. What Are the Implications of Climate Change for Retrofitted Historic Buildings? A Literature Review. *Sustainability* **2020**, *12*, 7557. [[CrossRef](#)]
30. El Nagar, E.; Munde, S.; Lemort, V. Refurbishment concepts for a student housing at the Otto Wagner Areal in Vienna under the aspects of sustainability, energy efficiency and heritage protection. In Proceedings of the SBE21 Sustainable Built Heritage, Bolzano, Italy, 14–16 April 2021; p. 10.