RE-USE OF HISTORIC BUILDINGS AND ENERGY REFURBISHMENT ANALYSIS VIA BUILDING PERFORMANCE SIMULATION
A Case Study

by

Nenad D. ŠEKULARAC[a]***, Dragoslav M. ŠUMARAC***[b]***,***
Jasna LJ. ČIKIĆ TOVAROVIĆ[a]***, Miloš M. ČOKIĆ***[c]***,***
and Jelena A. IVANOVIĆ-ŠEKULARAC[a*]

[a] Faculty of Architecture, University of Belgrade, Belgrade, Serbia
[b] Faculty of Civil Engineering, University of Belgrade, Belgrade, Serbia
[c] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

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This paper analyses the possibility to apply energy refurbishment measures in restored historic buildings in order to ensure reuse. The objective of the paper is to provide an appropriate methodology for the structural restoration of historic buildings, their re-use and sustainable energy refurbishment in accordance with current needs and conservation principles. The study provides the analysis and evaluation of the realized goals regarding energy refurbishment and energy efficiency. The presented historic buildings belong to Hilandar Monastery, Mount Athos, Greece. Mount Athos has been listed in UNESCO World Heritage Site for decades. The paper deals with the expert analysis of abandoned and devastated structures included in the Haybarn Complex. This paper provides a positive outcome of the performed restoration in terms of energy refurbishment and repurpose, since these buildings were turned into unique accommodation facilities for visitors. This accomplishment can be seen as a useful recommendation for improving energy efficiency of historic buildings during their restoration. All the undertaken methods are in accordance with the environmental protection requirements. This study is a practical observation and analysis of energy refurbishment in the field of restoration of listed buildings. This certainly is the most important contribution of this paper. All energy efficiency measures and renewable energy sources were carried out in compliance with conservation requirements and visual authenticity of historic structures. Assessment and analysis of energy efficient refurbishment via building performance simulation method and energy efficiency optimization was applied to several different models of restoration that was carried out in the Haybarn Complex.

Key words: *heritage conservation, UNESCO cultural heritage, sustainability, energy saving, renewable energy sources, heating and cooling*

Introduction

Restoration of historic buildings based on energy refurbishment and re-use principles is one of the most significant conditions for giving new life to a repurposed building, including indoor environment quality. This paper is primarily focused on restoration and

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[*] Corresponding author, e-mail: jelenais@orion.rs

reuse of the abandoned structures of the Haybarn Complex, the property of Hilandar Monastery on Mount Athos in Greece. The main objective is to improve energy efficiency, apply RES, preserve environmental protection and maintain authentic look and materialization. Assessment and analysis of energy refurbishment was carried out through simulation and analyses of five different restoration models via building performance simulation (BPS) method and energy efficiency optimization. The BPS is a powerful method and technique for predicting building's dynamic behavior, building's energy efficiency, and RES integration optimization. The BPS enables building's environmental technologies and sustainability harmonization [1].

Hypotheses of this paper are:

- appropriate construction methods, performed in accordance with conservation requirements, contribute to energy saving and energy efficiency during restoration of historic buildings, while at the same time maintain authentic look and harmony with the protected locality of Mount Athos and
- renewable energy is the most efficient source of energy supply for: heating, cooling, lighting, electrical appliances and hot water supply in this protected site.

The aim of the research is to:

- undertake functional exploration of the locality for the protection and conservation of historic buildings as well as locality management,
- increase the range of knowledge about the purpose and significance of architectural heritage, resources and restoration methods, in order to accomplish the goal of reusing historic buildings,
- determine construction methods for improving energy efficient restoration of historic buildings; these methods are to be applied along with RES in order to preserve environmental values of this isolated site, and
- systemize gathered knowledge about energy efficient restoration of historic buildings, provide recommendations for conservation, restoration and re-use of historic buildings and present research findings to academic community.

Construction workers used to have a long tradition of building in accordance with bioclimatic factors – their construction methods, use of local materials and appropriate location of their buildings indicate relying on natural lighting, ventilation, and natural sources of thermal energy. Therefore, one might conclude that environmentally friendly and energy saving measures used to be applied in that period. Bioclimatic design is a prevailing characteristic of historic and heritage buildings: it implies a typically resilient architectural structure and smart use of durable construction materials. When it comes to their endurance and durability measured by the hundreds and thousands of years, their sustainability is indisputable. As for the listed historic buildings with similar architectural elements, the concept of energy refurbishment is not what makes them different from other, unlisted buildings. Restoration methods depend on specific cultural heritage and adaptive reuse of a historic building. Restoration and energy refurbishment measures should not start until the analysis and evaluation of a historic building in terms of its current energy efficiency have been performed. Not only do energy improvement measures focus on potential energy savings, but also on the protection of the historic property, materials and features [2]. The key factor for successful energy refurbishment of historic buildings is to determine and analyze the existing energy efficient aspects of architectural heritage, preserve them and use them in future designs, along with the latest construction methods, in order to improve energy efficiency. Historic buildings are known to have very high heterogeneity and different protection level. So far, there have been no guidelines concerning the minimum level of energy performance for listed historic buildings [3].

Generally speaking, restoration and rehabilitation of buildings must include the following procedures in order to create energy efficient buildings of high quality [4]:

- analyses of location, orientation and form of buildings,
- high-level thermal insulation on outer coating of buildings; thermal bridges are to be avoided,
- using solar power; protection from excessive sunlight, and
- further exploitation is to include the implementation of energy efficient heating systems as well as cooling and ventilation systems along with renewable energy resources.

This can not be applied to historic buildings since it could affect their authentic look. The understanding of authenticity plays a fundamental role in cultural heritage investigations [5], conservation projects and inscriptions on the list of World Heritage Sites. Sustainability model is established through the process of preservation of buildings, as authentic cultural monuments, and their original function or a new one, along with comfort increase and energy consumption reduction. Restoration of historic buildings and sustainability are inextricably linked. Thermal insulation for the entire building envelope must be avoided, because the loss of authenticity would be an irreparable damage, and potential energy saving is not worth such loss. Not only does this method protect the authentic look of a historic building, it also protects the construction method itself [6].

Methodology

Research methodology consists of:

- on-site observation – the analysis and evaluation of historic buildings and their remains specified the building to be protected,
- case study investigations of restoration and energy refurbishment of the Haybarn Complex, Hilandar Monastery, Mount Athos, in order to provide scientific findings,
- design and specification criteria for constructional protection based on previous analyses of location conditions and chosen methods of restoration and re-use,
- restoration of historic buildings in compliance with conservation requirements: keeping authentic structural elements (façade walls, roof structure), materialization and authentic look of a historic building,
- design elaboration on the restoration of historic buildings; design and realization of restoration in order to improve energy efficiency and energy saving,
- all the interventions, performed for the purpose of restoration, re-use or energy efficiency improvement, are reversible and are carried out in accordance with the conservation requirements,
- analysis and evaluation of the achieved results of restoration, in terms of energy refurbishment, reusability and application of RES meant for energy supply and environmental protection, and
- analyses of potential improving the already restored buildings by performing specific interventions in order to increase energy efficiency and energy saving, applying various models and testing via BPS method and simulations that have been performed using Bentley AECOsim Energy simulator [7], which is fully integrated with EnergyPlus energy simulation software [8].

Case study – the Haybarn Complex, Hilandar Monastery

Specific characteristics of the site

Mount Athos is situated on a secluded, inaccessible peninsula, Chalkidiki, the northern part of Greece. There is no land route and it is accessible only by ferry, over the surrounding sea. Mount Athos is a unique monastic country in the whole world. Its autonomy is granted by the Constitution of Greece and Mount Athos Statute. Its autonomous status aims to protect spiritual and religious values, measured by hundreds and thousands of years of being the most important cultural and religious center for the entire Eastern Orthodox Church. According to the UNESCO decision, Mount Athos and its monasteries have been on the list of the World Heritage Sites since 1988. Hilandar Monastery is one of the most important testaments of the Serbian architectural heritage. It was founded in 1198, on the remains of the old and abandoned monastery of Helandariy, built at the end on the 10th century [9]. The property was given to Saint Sava and his father, Saint Simeon, to found a new monastery accommodation for the Serbian monks.

Restoration of the Haybarn Complex

The Haybarn Complex was once used to shelter monastery animals and their food (hay). These abandoned and dilapidated buildings were built in the first part of the 19th century, outside the monastery walls but still close to them.

Before the restoration in 2006, the Haybarn Complex, fig. 1, consisted of [10]:
- the Stable - a building for keeping mules,
- the Mulekeepers' House - a building for the people taking care of the mules, and
- the Haybarn - a huge building for hay storage, hence the name for the entire complex.

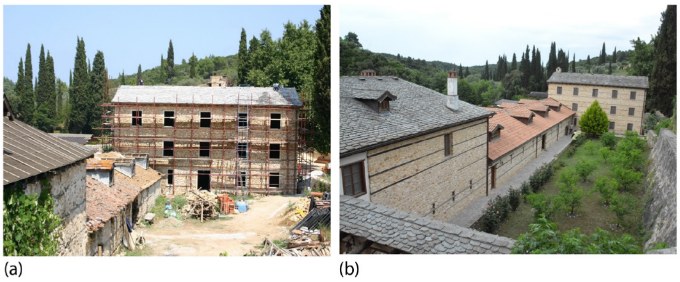
(a) (b)

Figure 1. The Haybarn Complex: Mulekeepers' House, Stable, Haybarn (from left to right): (a) former appearance, (b) after the restoration (photos taken by the author)

New accommodation capacities for visitors were desperately needed. Therefore, the restoration project for the Haybarn Complex was launched. The restoration was realized in 2005 and 2006 [11]. The restoration was performed in accordance with conservation requirements and all the construction methods and materials used for the restoration were in compliance with these requirements – the authentic look was preserved (stone façade walls, roof structures and covering)*.

Weather data

The data used for model calculations is design climate data for the city of Kavala/Chrisoupolis, tab. 1, and typical meteorological year (TMY) for dynamic simula-

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* The main and preliminary design for the restoration of the Haybarn Complex were made under the supervision of Prof. M. Kovacević, Ph. D., Prof. N. Šekularac, Ph. D., S. Tripković, Arch., D. Krivokuća, Arch., 2004 and 2005. Prof. N. Šekularac, Ph. D., Member of Expert Council for the Reconstruction of Holy Monastery Hilandar, construction manager and structural engineer.

tions (buildings dynamic behavior study), being the region that best presents the climate conditions of the location included in this case study. The analyzed buildings are located on Mt. Athos, Greece, figs. 2 and 3 are displaying the annual external air temperature profiles. The building is in unsheltered position, and all of the façades are exposed to wind.

Table 1. Weather properties – heating and cooling design data used in calculations [7]

Weather data: Kavala/Chrisoupolis, Greece		
Heating and cooling design load weather data (MN6 WMO#166240)		
Latitude	40° 58' N	
Longitude	24° 36' E	
Heght	5 m asi	
Climate design data:	2013 ASHRAE Handbook	
Design data	Cooling	Heating
Design dry bulb temperature	32.8 °C	–2.8 °C
Mean coincident wind speed:	3.7 m/s	1.8 m/s

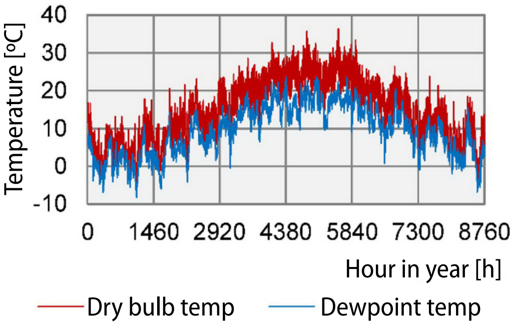

Figure 2. Annual air temperature-hour oscillation profiles [7] (*for color image see journal web site*)

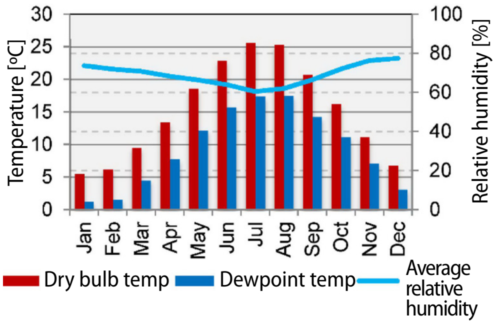

Figure 3. Annual air temperature and humidity oscillation profiles [7] (*for color image see journal web site*)

Application of renewable energy sources in the case study of Hilandar Monastery

Currently, there are two heat distribution systems – radiators and water-based underfloor heating. Wood-fired boilers are used for heating. Since Hilandar Monastery owns large forested areas, all needed quantities of wood are obtained by thinning and pruning their own forests. At the moment, Diesel aggregates are used for electricity supply.

The performed investigation determined that comfort improvements for the Haybarn Complex require: energy for heating, energy for cooling, electric energy supply (for lighting, electrical appliances, sanitary hot water).

This case study analyses the possibility to apply RES: geothermal resources, biomass, solar power. Undertaken geological exploration of this site confirmed the existence of geothermal water, $t = 21$ °C, at 100 m depth [12]. The conducted analyses and performed measurements showed that the found water is hard, due to dissolved calcium salts, which means that it can not be used as a RES for having desired temperature in the building. Consequently, geothermal energy was considered inadequate and biomass was chosen as a primary source of energy for heating. Not only is it included in this study, but it will also be used in further research. Wood chip boilers are going to be used in the coming period. Type of a heating system and wood as the source of energy meet the requirements of environmental protection and reduction of CO_2 emission. When wood is obtained by pruning your own trees, it contributes to cost reduction and easier transport of energy sources, since this is an isolated site and boats are the only means

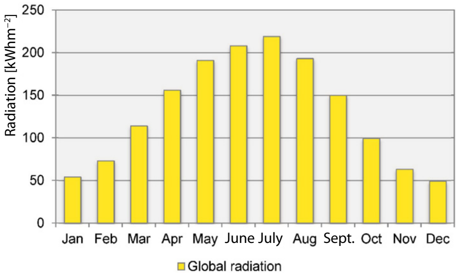

Figure 4. Annual solar radiation profile, Kavala/Chrisoupolis [7]

of transport. The value of 3.5 kWh/t net calorific values of wood chips [13] was used for the conversion of annual energy consumption for heating to required biomass amount. The annual biomass amount was calculated for each building, depending on the model, in order to meet the heating energy demands, figs. 8, 11, and 14.

The main objective of photovoltaic (PV) module technology was to obtain maximum solar radiation, fig. 4, which is a significant part of the energy for heating space and prepare sanitary hot water for Haybarn Complex. It was planned to set PV modules at appropriate distance from the monastery complex, in a secluded area, without negatively impacting visual and aesthetic characteristics of the site, thus preserving the authentic look of the entire site. All PV modules face south at a pitch angle of 20°, as the best orientation and position.

Energy analyses and energy efficiency optimization of the Haybarn Complex

This study analyzes all three buildings of the Haybarn Complex (Stable, Mulekeepers' House and Haybarn, fig. 5, concerning energy refurbishment of the existing buildings that underwent a restoration in 2006 (model MO1), as well as a few different simulation models of the entire complex (M02-M05). As for energy refurbishment, each of the analyzed buildings was improved in a specific way.

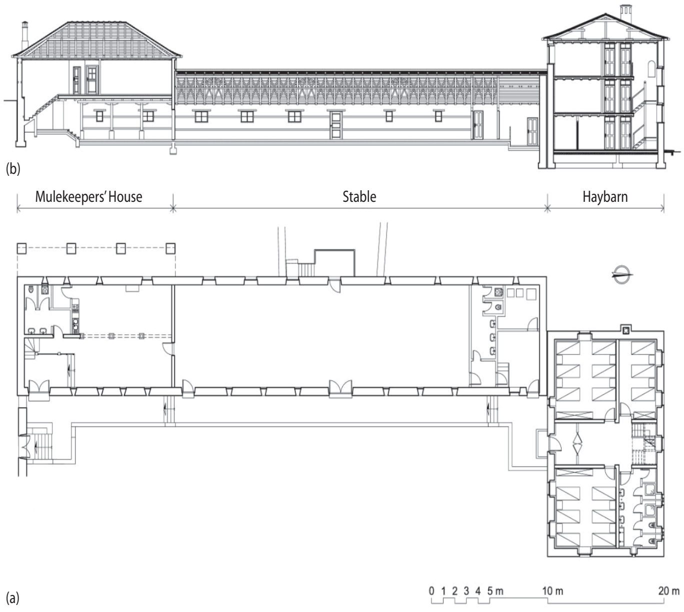

Figure 5. The Haybarn Complex (after the restoration): (a) ground floor plan, (b) cross-section [11]

For each model of the buildings that belong to the Haybarn Complex the energy demands for heating, cooling, lighting, household appliances (electrical appliances) and hot water supply are calculated. Energy efficiency optimization has been widely studied in many contexts: reducing energy use, reducing energy consumption in order to meet lower energy demands, and challenges of implementing RES.

Definitions of scenarios (models) for complex energy improvement used for BPS using Bentley AECOsim Energy simulator software for the TMY of Kavala. The BPS were done for the following models of buildings of the Haybarn Complex – existing building model based on the restoration model (MO1) and a group of four models (MO2-MO5). Technical advances in BPS offer their effective energy efficiency optimization and RES integration.

The study identifies total energy demands (heating, cooling, lighting, electrical appliances and hot water supply) estimated by modeling and simulation. The presented results are obtained using a steady-state simulation in AECOSim Energy simulator [7]. Modeling was carried out by applying a mathematical model developed by Bentley for AECOSim Energy simulator software [7].

Bentley AECOsim Energy simulator [7] with academic license was used as the analysis software. It supports dynamical simulation and analysis of building mechanical systems, environmental conditions, and energy performance and it is integrated with EnergyPlus energy simulation software [14]. The software also supports 3-D object elements geometry input, fig. 6, which is accompanied by additional modeling capabilities such as material characteristics input and design, climate data assignment, heating and cooling temperatures setting and schedules, the choice of heating and cooling, building occupancy schedules and other processes such as lighting design and schedules, household appliances design and schedules, and other functions.

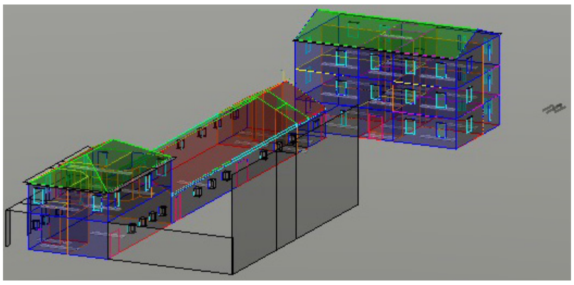

Figure 6. The Haybarn Complex: Mulekeepers' house, Stable, Haybarn (from left to right) – 3-D model
(*for color image see journal web site*)

Parameter values and schedules needed for calculation and description of systems' behavior (heating and cooling), occupancy, lighting, electrical appliances and hot water systems (HWS) were adopted in compliance with the real users' needs determined by *in situ* based measures. All the buildings are ventilated naturally. The air change rate (ACR) value is set to 1 h^{-1} for all five models (MO1-MO5) to approximate the ACR in well refurbished old structure with good air tightness, which has low value of air infiltration into the object.

The PV modules used in calculations are SAMSUNG LPC250SM [15], with an active area of 1.60 m^2 per module. Nominal power of PV module is 0.25 kW per module and his energy efficiency is 0.156 kW/m^2. The total power output of PV panels and the required number of PV panels were calculated for each building of the Haybarn Complex, in accordance with individual models and energy requirements for lighting, air-conditioning, electrical appliances and HWS.

The existing restored buildings (model MO1) are not provided with cooling. However, this study presents the calculated energy demand in case that cooling is to be added in the coming period (MO3-MO5). Takin into account protection and isolation of the site as well as the purpose of visits, *i. e.* staying at Hilandar Monastery and spending nights in the buildings of the Haybarn Complex, the conducted research and performed measurements provided the calculation of total energy demands, total power output of PV models and needed number of PV panels for each building included in the Haybarn Complex, for models MO3-MO5, tabs. 5, 9, and 13. Energy saving is achieved by establishing energy management on this isolated site and by carrying out all the plans concerning energy efficiency improvements.

Restoration of the Stable

The Stable is a single-store building with the stone façade across the perimeter walls. It was connected to the ground floor of the Mulekeepers' House. After the 2006 restoration (tab. 2, model MO1), the façade walls remained unchanged – both exterior and interior walls of the façade are covered with visible stone, fig. 1(b). Reconstruction of the floor was carried out on the ground and thermal insulation was added. Thermal transmittance, also known as U-value [$Wm^{-2}K^{-1}$], is the rate of transfer of heat through a structure, divided ba the difference

Table 2. Comparative review of the improved elements of building envelope, in terms of thermal protection and total annual energy demands, tested through the simulation models – the Stable

<table>
<tr><th colspan="2">MODEL</th><th>MO1</th><th>MO2</th><th>MO3</th><th>MO4</th><th>MO5</th></tr>
<tr><td colspan="2">Façade wall
$U_{max} = 0.40\ W/m^2K$</td><td colspan="2">1. stone wall 60.0 cm</td><td>1. stone wall 60.0 cm
2. thermal insulation polystyrene 5.0 cm
3. brick 6.5 cm
4. mortar coating 1.5 cm
5. heated space</td><td>1. stone wall 60.0 cm
2. thermal insulation polystyrene 20.0 cm
3. gypsum board 2.5 cm
4. heated space</td><td>1. stone wall 60.0 cm
2. thermal insulation polystyrene 30.0 cm
3. gypsum board 2.5 cm
4. heated space</td></tr>
<tr><td colspan="2">$U\ [Wm^{-2}K^{-1}]$</td><td colspan="2">2.950</td><td>0.512</td><td>0.161</td><td>0.110</td></tr>
<tr><td colspan="2">Roof
$U_{max} = 0.20\ W/m^2K$</td><td>1. ridge tiles
2. air layer
3. waterproofing
4. wood decking 2.2 cm
5. air layer 5.0 cm
6. thermal insulation polystyrene 15.0 cm
7. wood ceiling 2.2 cm
8. rafter - timber construction</td><td colspan="3">1. ridge tiles
2. air layer
3. waterproofing
4. wood decking 2.2 cm
5. thermal insulation polystyrene 20.0 cm
6. wood ceiling 2.2 cm
7. rafter - timber construction</td><td>1. ridge tiles
2. air layer
3. waterproofing
4. wood decking 2.2 cm
5. thermal insulation polystyrene 30.0 cm
6. wood ceiling 2.2 cm
7. rafter - timber construction</td></tr>
<tr><td colspan="2">$U\ [Wm^{-2}K^{-1}]$</td><td>0.285</td><td colspan="3">0.156</td><td>0.108</td></tr>
<tr><td colspan="2">Ground floor
$U_{max} = 0.40\ W/m^2K$</td><td colspan="3">1. brick 4.0 cm
2. mortar 4.0 cm
3. concrete 4.0 cm
4. thermal insulation polystyrene 5.0 cm
5. waterproofing
6. concrete 12.0 cm
7. gravel 6.0 cm
8. ground</td><td>1. brick 4.0 cm
2. mortar 4.0 cm
3. concrete 4.0 cm
4. thermal insulation polystyrene 15.0 cm
5. waterproofing
6. concrete 12.0 cm
7. gravel 6.0 cm
8. ground</td><td>1. brick 4.0 cm
2. mortar 4.0 cm
3. concrete 4.0 cm
4. thermal insulation polystyrene 20.0 cm
5. waterproofing
6. concrete 12.0 cm
7. gravel 6.0 cm
8. ground</td></tr>
<tr><td colspan="2">$U\ [Wm^{-2}K^{-1}]$</td><td colspan="3">0.505</td><td>0.207</td><td>0.160</td></tr>
<tr><td rowspan="6">Energy demands [kWh/year]</td><td>Heating</td><td>33616.42</td><td>32682.75</td><td>21813.11</td><td>19147.88</td><td>18179.84</td></tr>
<tr><td>Cooling</td><td>0.00</td><td>0.00</td><td>4331.83</td><td>5148.43</td><td>5173.84</td></tr>
<tr><td>Lighting</td><td>1484.10</td><td>1484.10</td><td>1484.10</td><td>1484.10</td><td>1484.10</td></tr>
<tr><td>El. Appliances</td><td>17246.25</td><td>17246.25</td><td>17246.25</td><td>17246.25</td><td>17246.25</td></tr>
<tr><td>HWS</td><td>4560.19</td><td>4560.19</td><td>4560.19</td><td>4560.19</td><td>4560.19</td></tr>
<tr><td>Total</td><td>56906.96</td><td>55973.29</td><td>49435.48</td><td>47586.85</td><td>46644.22</td></tr>
</table>

in temperature across that structure. New rafters were placed over the existing timber roof structure to strengthen the roof structure. Thermal insulation was added between the rafters. Ridge tiles were used as authentic roof covering. Fenestration remained the same (small windows arrangement), considering the previous purpose of the building, protection from excessive sunlight and preventive healthcare for animals. Roof dormers were placed where they used to be, thus preserving the authentic design of the building. The windows were replaced with new wooden frames, 9 cm thick, and double-glazed, low-emissivity glass (low-E glass) (4 + + 12Kr + 4 mm) filled with krypton gas. The entrance door was replaced with a new, solid wood door. The only change was the new purpose of the building. The restored Stable consists of a spacious bedroom for visitors, sanitary rooms and a laundry with washing machines and dryers. Also, the underfloor heating was installed.

Recommendations for energy-efficient refurbishment of the Stable were defined in accordance with maximum benefits of restoration (model MO2), without major interventions and construction works. It is planned to add thermal insulation to the existing roof structure (tab. 2, model MO2), and to replace the existing wooden windows with new wooden frames, 11 cm thick, and triple-glazed, low-E glass (4 + 8Xe + 4 + 8Xe + 4 mm) filled with xenon gas, in order to improve energy efficiency and overall comfort and indoor quality of the entire place (models MO2, MO3, MO4, MO5). Further interventions include (tab. 2, model MO3) adding thermal insulation to peripheral walls, interior stone walls and brick walls. Recommendations for further interventions (model MO4, MO5) include major works – adding thermal insulation to peripheral elements, wherever it is possible: floor, between the layers of roof, peripheral walls. Also, thermal insulation is to be added to interior stone peripheral walls, in a way that each of the following models is provided with a thicker layer of insulation, as presented in tab. 2 (models MO4, MO5).

All the rooms are heated. The existing building is not provided with cooling but the needed energy demands have already been calculated in case the cooling is to be installed. The energy demands are calculated for models (MO3-MO5). If the cooling is to be installed, it will be applied to all rooms but sanitary rooms and a laundry. Comparative review of all five analyzed models of the Stable (MO1-MO5) shows how much restoration and recommended energy refurbishment measures could reduce specific annual heating energy, tab. 2.

Annual energy demands – the Stable

Annual heating and cooling energy demands in relation to total energy demands for the building (heating, cooling, lighting, electrical appliances and hot water supply) is presented in fig. 7. Annual heating and cooling energy demands per square meter of the air-conditioned space – the Stable, tab. 3. Annual biomass demands for heating The Stable is presented in fig. 8. The relation between electricity demands and possibilities to realize these demands based on total power output – calculated using the PV panels, is presented in tabs. 4 and 5, and fig. 9.

Total power output, tab. 5, meets the requirements of total annual electricity demands. However, the analyses of different models MO3-MO5 and monthly consumption needs, showed that it is not possible to obtain all the required energy for the Stable during certain months, fig. 9. In four winter months, November, December, January, and February, it is not possible to obtain the needed electricity. Thus, it is important to include some additional sources of energy supply. There is a lack of 50.1% of electricity in December, tab. 4, if the only source of energy implies the application of PV panels, total power output equals 24 kW, tab. 5.

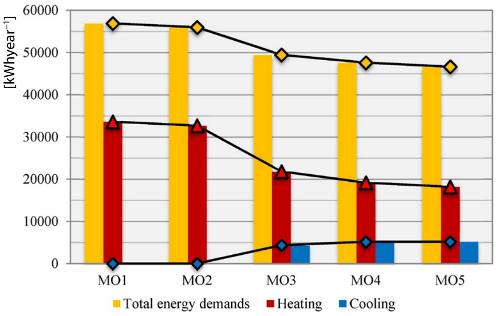

Figure 7. Annual energy demands – the Stable
(*for color image see journal web site*)

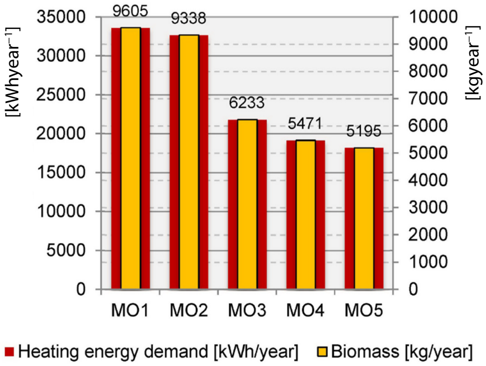

Figure 8. Annual biomass needs for heating – the Stable (*for color image see journal web site*)

Table 3. Annual energy demands – the Stable

Conditioned area					
$A_{HEATING}$	238.91 m^2		$A_{COOLING}$	214.00 m^2	
Energy demands [kWhm^{-2}year^{-1}]					
Model	MO1	MO2	MO3	MO4	MO5
Heating	140.71	136.80	91.30	80.15	76.09
Cooling	0.00	0.00	20.24	24.06	24.18

Table 4. Electricity demands and PV electricity production – the Stable

Cooling, heating, electrical appliances and HWS						
Model	MO3	MO4	MO5	MO3	MO4	MO5
	Energy demand [kWh year^{-1}]			The PV panels energy production [%]		
Jan.	2246.95	2246.95	2246.95	56.5	56.5	56.5
Feb.	2062.07	2062.07	2062.07	83.2	83.2	83.2
Mar.	2318.84	2318.84	2318.84	105.3	105.3	105.3
Apr.	1923.61	1923.61	1923.61	167.1	167.1	167.1
May	1659.40	1700.41	1722.92	216.7	211.4	208.7
June	2410.48	2624.34	2640.24	160.0	147.0	146.1
July	3495.88	3741.35	3728.28	107.9	100.8	101.1
Aug.	3168.16	3420.17	3420.03	111.0	102.9	102.9
Sept.	1884.17	1948.42	1948.63	143.5	138.8	138.7
Oct.	1994.83	1994.83	1994.83	105.3	105.3	105.3
Nov.	2210.80	2210.80	2210.80	62.1	62.1	62.1
Dec.	2247.18	2247.18	2247.18	49.9	49.9	49.9
Anual	27622.37	28438.97	28464.38	111.1	107.9	107.8
Sufficient production of electric power provided by PV panels						■
Insufficient production of electric power provided by PV panels						□

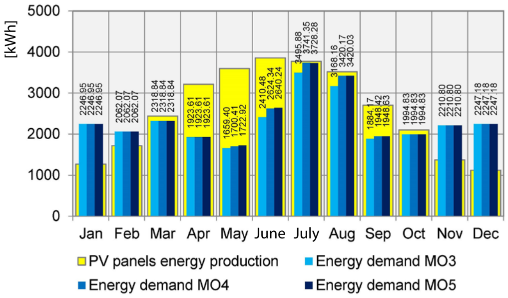

Figure 9. Electricity demands and PV electricity production – the Stable (*for color image see journal web site*)

Table 5. Annual electricity demands and PV electricity production – the Stable

The PV panels power production			
Model	MO3	MO4	MO5
Number of modules	96	96	96
Total power output [kW]	24.00	24.00	24.00
Total panels area [m^2]	153.66	153.66	153.66
The PV panels annual energy demands and production [kWh year^{-1}]			
Demands	27622.37	28438.97	28464.38
Production	30681.39	30681.39	30681.39

Restoration of the Mulekeepers' house

This building consists of a ground floor and first floor. The ground floor used to be connected to the Stable. It was a space where their animals had been kept. The first floor was occupied by mulekeepers. The exterior walls are made of roughly dressed stone and rubble [10]. Interior area of the peripheral walls of the ground floor was covered with visible stone. All the upstairs interior walls were plastered. The original windows were single, wooden and single-glazed. During the 2006 restoration of the Mulekeepers' House (tab. 6, model MO1) the authentic look of the façade walls was preserved – both exterior and interior ground floor walls were covered with stone, fig. 1(b). Since the upstairs façade stone walls were plastered, thermal insulation was added to the existing façade wall from the inside and the wall was lined with bricks. As for the ground floor, the floor was restored and thermal insulation was added. In accordance with the restoration design, the joists as structural components between the stores remained. However, new fillings were applied as well as the authentic cladding. Above the first floor, toward the attic area, thermal insulation coating was applied. Roofing with stone plates, as the authentic roof covering, was carried out in accordance with the latest requirements of ventilated roofing. This modern technology design of ventilated roofing and stone as a final cover was applied for the first time in entire conservation practice during the restoration of Hilandar Monastery [16]. The windows were replaced with new, wooden framed windows, 9 cm thick, and double-glazed low-e glass (4 + 12Kr + 4 mm) filled with krypton gas. The front door was also replaced with a new, solid wood door. Today, after the restoration, the ground floor of the Mulekeepers' House consists of a sitting room, a kitchenette and a sanitary block. The space upstairs consists of a smaller sitting room, three bedrooms and a sanitary block. Underfloor heating was installed on the ground floor and low-temperature radiators were added upstairs.

The recommendations for thermal improvements were developed in accordance with maximum benefits of the restoration (model MO2), without major interventions. In order to improve energy efficiency and overall comfort conditions the following construction methods are proposed: adding thermal insulation to attic area, over the existing ceiling layers (tab. 6, MO2) and replacing the original wooden windows with new, wooden framed windows, 11 cm thick, with triple-glazed low-e glass (4 + 8Xe + 4 + 8Xe + 4 mm) filled with xenon gas (models MO2-MO5). Further interventions aimed at improving energy efficiency (tab. 6, MO3) included thermal insulation on peripheral walls of the ground floors, from the inside of the stone walls lined with bricks. In this way, the interior of the building would change its original look but the entire exterior design is preserved in accordance with the conservation requirements. Further recommendations for improving energy efficiency (model MO4, MO5) include major interventions, such as adding thermal insulation to the peripheral elements wherever it is possible: the floor, between the layers of the roof, on the peripheral walls. Also, thermal insulation is to be added to interior stone peripheral walls, in a way that each of the following models is provided with a thicker layer of insulation, as presented in tab. 6 (model MO4, MO5).

Table 6. Comparative view of the improved elements of cladding in terms of thermal protection and annual energy demands, tested through simulation models – The Mulekeepers' House

MODEL		MO1	MO2	MO3	MO4	MO5
Façade wall - Ground floor $U_{max} = 0.40\,W/m^2K$		1. stone wall 60.0 cm		1. stone wall 60.0 cm 2. thermal insulation polystyrene 5.0 cm 3. brick 6.5 cm 4. mortar coating 1.5 cm 5. heated space	1. stone wall 60.0 cm 2. thermal insulation polystyrene 20.0 cm 3. gypsum board 2.5 cm 4. heated space	1. stone wall 60.0 cm 2. thermal insulation polystyrene 30.0 cm 3. gypsum board 2.5 cm 4. heated space
U [Wm^{-2}K^{-1}]		2.950		0.512	0.161	0.110
Façade wall - First floor $U_{max} = 0.40\,W/m^2K$		1. stone wall 40.0 cm 2. thermal insulation polystyrene 5.0 cm 3. brick 6.5 cm 4. mortar coating 1.5 cm 5. heated space			1. stone wall 40.0 cm 2. thermal insulation polystyrene 20.0 cm 3. gypsum board 2.5 cm 4. heated space	1. stone wall 40.0 cm 2. thermal insulation polystyrene 30.0 cm 3. gypsum board 2.5 cm 4. heated space
U [Wm^{-2}K^{-1}]		0.529			0.163	0.111
Floor Attic $U_{max} = 0.40\,W/m^2K$		1. attic area 2. wood decking 2.5 cm 3. air layer 5.0 cm timber construction 4. thermal insulation polystyrene 10.0 cm 5. gypsum boards 2.5 cm 6. timber construction 7. heated space	1. attic area 2.5 cm 2. wood decking 2.5 cm 3. thermal insulation polystyrene 15.0 cm 4. wood decking 2.5 cm 5. thermal insulation polystyrene (5+10) 15.0 cm 6. gypsum boards 2x1.25 cm 2.5 cm 7. timber construction 8. heated space			
U [Wm^{-2}K^{-1}]		0.285	0.108			
Ground floor $U_{max} = 0.40\,W/m^2K$		1. brick 4.0 cm 2. mortar 4.0 cm 3. concrete 4.0 cm 4. thermal insulation polystyrene 5.0 cm 5. waterproofing 6. concrete 12.0 cm 7. gravel 6.0 cm 8. ground			1. brick 4.0 cm 2. mortar 4.0 cm 3. concrete 4.0 cm 4. thermal insulation polystyrene 15.0 cm 5. waterproofing 6. concrete 12.0 cm 7. gravel 6.0 cm 8. ground	1. brick 4.0 cm 2. mortar 4.0 cm 3. concrete 4.0 cm 4. thermal insulation polystyrene 20.0 cm 5. waterproofing 6. concrete 12.0 cm 7. gravel 6.0 cm 8. ground
U [Wm^{-2}K^{-1}]		0.505			0.207	0.160
Energy demands [kWh/year]	Heating	23801.23	22853.90	16643.61	13906.37	13487.84
	Cooling	0.00	0.00	3028.23	2877.19	2892.37
	Lighting	1331.60	1331.60	1331.60	1331.60	1331.60
	El. Appliances	1058.50	1058.50	1058.50	1058.50	1058.50
	HWS	285.01	285.01	285.01	285.01	285.01
	Total	26476.34	25529.01	22346.95	19458.67	19055.32

Annual energy demands – The Mulekeepers' house

Annual cooling and heating energy demands in relation to total energy demands for the building (heating, cooling, lighting, electrical appliances, and hot water supply) is presented in fig. 10. Annual heating and cooling energy demands per square meter of the air-conditioned area in the Mulekeepers' House, tab. 7. Annual biomass demands for heating of the Mulekeepers' House, presented in fig. 11. The relation between electricity demands and possibilities to realize these demands based on total power output – calculated using the PV panels, is presented in tabs. 8 and 9, and fig. 12.

Total power output, tab. 9, meets the requirements of total annual electricity demands. However, the analyses of different models MO3-MO5 and monthly consumption needs, showed that it is not possible to obtain all the required energy for the Mulekeepers' House during certain months, fig. 12. In two summer months, July and August, it was necessary to include additional sources of energy supply. There is a lack of 46.0% of electricity in July, and 42.9% in August, tab. 8, if the only available source of energy implies PV panels, total power output of 5 kW, tab. 9.

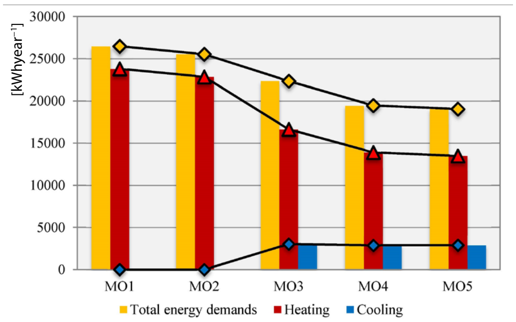

Figure 10. Annual energy demands – the Mulekeeper's House (*for color image see journal web site*)

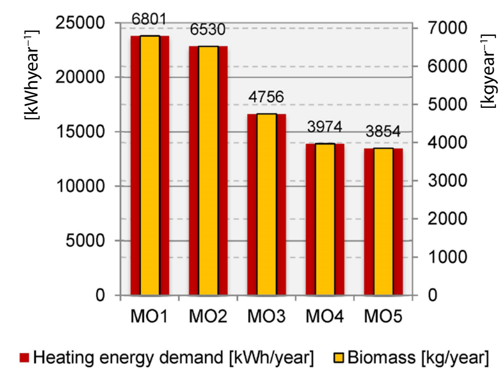

Figure 11. Annual Biomass needs for heating – the Mulekeeper's House (*for color image see journal web site*)

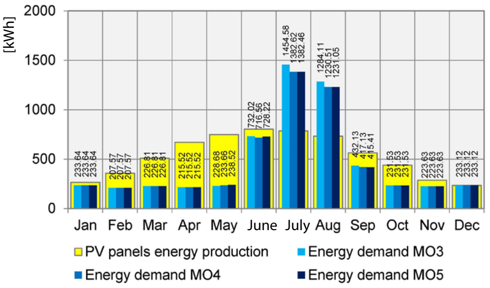

Figure 12. Electricity demands and PV electricity production – the Mulekeeper's house (*for color image see journal web site*)

Table 7. Annual energy demands – the Mulekeeper's House

Conditioned area					
A_{HEATING}	194.33 m^2		A_{COOLING}	178.66 m^2	
Energy demands [kWhm^{-2}year^{-1}]					
Model	MO1	MO2	MO3	MO4	MO5
Heating	122.48	117.60	85.65	71.56	69.41
Cooling	0.00	0.00	16.95	16.10	16.19

Table 8. Electricity demands and PV electricity production – the Mulekeeper's house

Cooling, heating, electrical appliances and HWS						
Model	MO3	MO4	MO5	MO3	MO4	MO5
	Energy demand [kWhyear^{-1}]			The PV panels energy production [%]		
Jan.	233.64	233.64	233.64	113.2	113.2	113.2
Feb.	207.57	207.57	207.57	172.1	172.1	172.1
Mar.	226.81	226.81	226.81	224.3	224.3	224.3
Apr.	215.52	215.52	215.52	310.7	310.7	310.7
May	228.68	233.66	238,52	327.5	320.5	314.0
June	732.02	716.56	728.22	109.8	112.1	110.3
July	1454.58	1382.62	1382.46	54.0	56.8	56.8
Aug.	1284.11	1230.51	1231.05	57.1	59.6	59.5
Sept.	432.13	417.13	415.41	130.3	135.0	135.6
Oct.	231.53	231.53	231.53	189.1	189.1	189.1
Nov.	223.63	223.63	223.63	127.9	127.9	127.9
Dec.	233.12	233.12	233.12	100.3	100.3	100.3
Anual	5703.34	5552.30	5567.48	112.1	115.1	114.8

Sufficient production of electric power provided by PV panels	▨
Insufficient production of electric power provided by PV panels	□

Table 9. Annual electricity demands and PV electricity production – the Mulekeeper's house

The PV panels power production			
Model	MO3	MO4	MO5
Number of modules	20	20	20
Total power output [kW]	5.00	5.00	5.00
Total panels area [m^2]	32.01	32.01	32.01
The PV panels annual energy demands and production [kWhyear^{-1}]			
Demands	5703.34	5552.30	5567.48
Production	6391.96	6391.96	6391.96

Restoration of the Haybarn

The Haybarn used to be a tall building for hay storage. Its perimeter walls were extremely high and made of roughly dressed stone and rubble. Visible stone covered the façade and stone plates of the roof cover, fig. 1(a). After the 2006 restoration (model MO1), the original homogeneous space was horizontally divided into three levels by placing wooden joists and creating two mezzanine ceilings. All the façade walls were thermally insulated from the inside and lined with bricks. As for the ground floor, the floor was reconstructed and thermal insulation was applied. Above the top level, toward the attic area, thermal insulation was placed between the joists. New windows were installed – wooden framed windows, 9 cm thick, with double-glazing and low-E glass (4 + 12Kr + 4 mm) filled with krypton gas. The front door of solid wood is completely new. The roof structure is made of wood and roof cover consists of plastered stone plates, in accordance with all modern requirements of ventilated roofing, just as it was carried out in case of the Mulekeepers' House. The authentic look of the Haybarn was preserved by keeping all the façade stone walls with wooden frames as well the roof cover, considering its height, structure and shape, fig. 1(b). Traditional radiator heating was installed and the entire building is heated. This three-level restored building consists of bedrooms and sanitary rooms.

The recommendations for improvements of the Haybarn were developed in accordance with maximum benefits of the restoration (model MO2), without major interventions and construction works. Thermal insulation is planned for the attic area, over the existing ceiling layers (tab. 10, MO2). The existing windows are to be replaced with new, wooden framed windows, 11 cm thick, with triple-glazed and low-E glass (4 + 8Xe + 4 + 8Xe + + 4 mm) filled with xenon gas, in order to improve the overall comfort of the entire space (models MO2-MO5). Further recommendations for energy efficiency improvement (models MO3, MO4, and MO5) include major interventions, such as adding thermal insulation to peripheral elements, wherever it is possible: the floor and the peripheral walls. Also, thermal insulation is to be added to interior stone peripheral walls, in a way that each of the following models is provided with a thicker layer of insulation and brick lining, as presented in tab. 10 (model MO3-MO5). In this way, thermal protection of the building is improved.

All the rooms are heated except for the attic area. The existing building is not provided with cooling but the needed energy demands have already been calculated in case the cooling is

Table 10. Comparative view of the improved elements of building envelope in terms of thermal protection and annual energy demands, tested through simulation models – The Haybarn

MODEL		MO1	MO2	MO3	MO4	MO5
Façade wall $U_{max} = 0.40$ W/m^{2}K		1. stone wall 60.0 cm 2. thermal insulation polystyrene 5.0 cm 3. brick 6.5 cm 4. mortar coating 1.5 cm 5. heated space		1. stone wall 60.0 cm 2. thermal insulation polystyrene 10.0 cm 3. brick 6.5 cm 4. mortar coating 1.5 cm 5. heated space	1. stone wall 60.0 cm 2. thermal insulation polystyrene 20.0 cm 3. gypsum board 2.5 cm 4. heated space	1. stone wall 60.0 cm 2. thermal insulation polystyrene 30.0 cm 3. gypsum board 2.5 cm 4. heated space
U [Wm^{-2}K^{-1}]		0.512		0.296	0.161	0.110
Floor Attic $U_{max} = 0.40$ W/m^{2}K		1. attic area 2. wood decking 2.5 cm 3. air layer 5.0 cm timber construction 4. thermal insulation polystyrene 10.0 cm 5. gypsum boards 2.5 cm 6. timber construction 7. heated space	1. attic area 2.5 cm 2. wood decking 2.5 cm 3. thermal insulation polystyrene 15.0 cm 4. wood decking 2.5 cm 5. thermal insulation polystyrene (5+10) 15.0 cm 6. gypsum boards 2x1.25 cm 2.5 cm 7. timber construction 8. heated space			
U [Wm^{-2}K^{-1}]		0.285	0.108			
Ground floor $U_{max} = 0.40$ W/m^{2}K		1. decking 2.2 cm 2. plywood 2.2 cm 3. thermal insulation polystyrene 5.0 cm 4. waterproofing 5. concrete 12.0 cm 6. gravel 6.0 cm 7. ground		1. decking 2.2 cm 2. plywood 2.2 cm 3. thermal insulation polystyrene 10.0 cm 4. waterproofing 5. concrete 12.0 cm 6. gravel 6.0 cm 7. ground	1. decking 2.2 cm 2. plywood 2.2 cm 3. thermal insulation polystyrene 15.0 cm 4. waterproofing 5. concrete 12.0 cm 6. gravel 6.0 cm 7. ground	1. decking 2.2 cm 2. plywood 2.2 cm 3. thermal insulation polystyrene 20.0 cm 4. waterproofing 5. concrete 12.0 cm 6. gravel 6.0 cm 7. ground
U [Wm^{-2}K^{-1}]		0.464		0.279	0.200	0.155
Energy demands [kWh/year]	Heating	27542.35	25658.98	22624.11	20692.04	19896.28
	Cooling	0.00	0.00	6431.20	6243.51	6196.21
	Lighting	2249.33	2249.33	2249.33	2249.33	2249.33
	El. Appliances	0.00	0.00	0.00	0.00	0.00
	HWS	6982.79	6982.79	6982.79	6982.79	6982.79
	Total	36774.47	34891.10	38287.43	36167.67	35324.61

to be installed. The energy demands are calculated for each model (MO3-MO5). If the cooling is to be installed, it will be applied to all rooms but attic area and sanitary rooms on the ground floor and all other floors. Comparative review of all five analyzed cases of the Haybarn (models MO1-MO5) determines how much the restoration and recommended measures for improving energy efficiency could reduce specific annual heating energy, tab. 10.

Annual energy demands – the Haybarn

Annual heating and cooling energy demands in relation to total energy demands for the building (heating, cooling, lighting, electrical appliances and hot water supply) is presented in fig. 13. Annual heating and cooling energy demands per square meter of the air-conditioned area in the Haybarn, as shown in tab. 11. Annual biomass demands for heating the Haybarn is shown using simulation models MO1-MO5, fig. 14.

The relation between electricity demands and possibilities to realize these demands based on total power output - calculated using the PV panels, is presented in tabs. 12 and 13, and fig. 15 – the Haybarn.

The calculated total power output, tab. 13, meets the requirements of total annual electricity demands. However, the analyses of different models MO3-MO5 and monthly consumption needs, showed that it is not possible to obtain all the required energy for The Haybarn

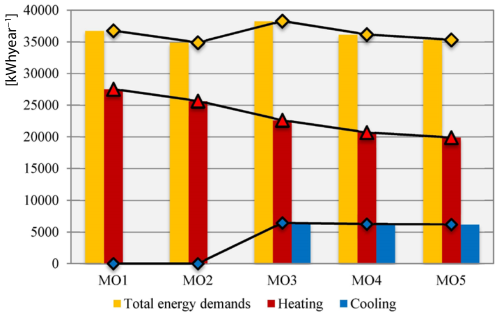

Figure 13. Annual energy demands – the Haybarn [17] (*for color image see journal web site*)

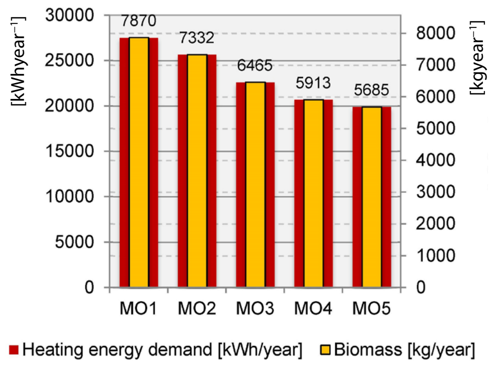

Figure 14. Annual biomass needs for heating – the Haybarn [17] (*for color image see journal web site*)

Table 11. Annual energy demands – the Haybarn [17]

Conditioned area					
$A_{HEATING}$	408.01 m^2		$A_{COOLING}$	346.77 m^2	
Energy demands [$kWhm^{-2}year^{-1}$]					
Model	MO1	MO2	MO3	MO4	MO5
Heating	67.50	62.89	55.45	50.71	48.76
Cooling	0.00	0.00	18.55	18.00	17.87

Table 12. Electricity demands and PV electricity production – the Haybarn [18]

Cooling, heating, electrical appliances and HWS						
Model	MO3	MO4	MO5	MO3	MO4	MO5
	Energy demand [$kWh\,year^{-1}$]			The PV panels energy production [%]		
Jan.	615.35	615.35	615.35	115.4	115.4	115.4
Feb.	607.09	607.09	607.09	157.8	157.8	157.8
Mar.	727.25	727.25	727.25	186.6	186.6	186.6
Apr.	755.63	755.63	755.63	235.2	235.2	235.2
May	875.12	887.61	890.54	227.5	224.3	223.6
June	2006.50	1992.84	1990.56	106.3	107.0	107.1
July	3468.47	3382.14	3357.97	60.3	61.9	62.3
Aug.	3208.18	3131.01	3111.46	60.8	62.3	62.7
Sept.	1342.30	1318.55	1314.12	111.8	113.8	114.2
Oct.	789.13	789.86	790.06	148.6	148.4	148.4
Nov.	652.36	652.36	652.36	117.8	117.8	117.8
Dec.	615.94	615.94	615.94	102.1	102.1	102.1
Anual	15663.32	15475.63	15428.33	108.8	110.1	110.4

Sufficient production of electric power provided by PV panels	▨
Insufficient production of electric power provided by PV panels	□

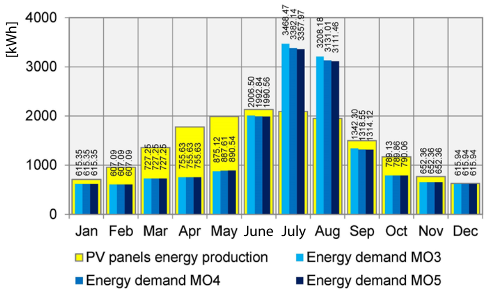

Figure 15. Electricity demands and PV electricity production – the Haybarn [17] (*for color image see journal web site*)

Table 13. Annual electricity demands and PV electricity production – the Haybarn [17]

The PV panels power production			
Model	MO3	MO4	MO5
Number of modules	54	54	54
Total power output [kW]	13.50	13.50	13.50
Total panels area [m^2]	86.44	86.44	86.44
The PV panels annual energy demands and production [kWhyear^{-1}]			
Demands	15663.32	15475.63	15428.33
Production	17040.03	17040.03	17040.03

during certain months, fig. 15. In two summer months, July and August, it was necessary to include additional sources of energy supply. There is a lack of 39.7% of electricity in July, and 39.2% in August, tab. 12, if the only available source of energy implies PV panels, total power output of 13.5 kW, tab. 13.

The Haybarn Complex – the overall results of energy refurbishment

The analysis and evaluation of all three buildings included in the Haybarn Complex (Stable, Mulekeepers' house, and Haybarn), along with the realized restoration models (MO1) and recommended measures for energy refurbishment, simulation, and analysis of new models (MO2-MO5) via BPS method, led to the findings about energy saving achieved by thermal protection, using RES in accordance with all conservation requirements, environmental protection and site protection principles, tab. 14. Annual heating and cooling energy demand in relation to total energy demands for the entire Haybarn Complex building (heating, cooling, lighting, electrical appliances, and hot water supply) is presented in fig. 16. Annual heating and cooling energy demands per square meter of the air-conditioned area in all the buildings of the Haybarn Complex, as shown in tab. 15. Annual biomass heating demands for the Haybarn Complex are presented in fig. 17. The relation between electricity demands and possibilities to realize these demands based on total power output – calculated using the PV panels, is presented in tabs. 16 and 17, and fig. 18.

The calculated total power output, tab. 17, meets the requirements of total annual electricity demands. However, the analyses of different models MO3-MO5 and monthly consumption needs, showed that it is not possible to obtain all the required energy for the Haybarn Complex during certain months, fig. 18.

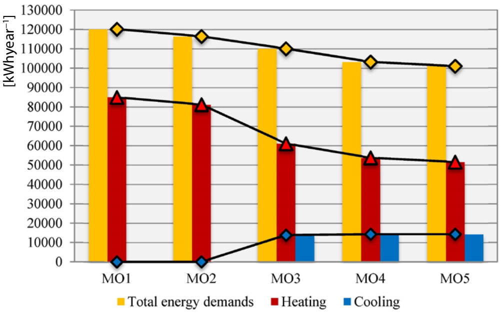

Figure 16. Annual energy demands – the Haybarn complex (*for color image see journal web site*)

Table 14. Comparative view of annual energy demands through simulation models of the buildings that belong to the Haybarn Complex (MO1 – MO5)

Energy demands [kWhm^{-2}year^{-1}]					
Model	MO1	MO2	MO3	MO4	MO5
Heating	84960.00	81195.63	61080.83	53746.29	51563.96
Cooling	0.00	0.00	13791.26	14269.13	14262.42
Lighting	5065.03	5065.03	5065.03	5065.03	5065.03
Elect. apliances	18304.75	18304.75	18304.75	18304.75	18304.75
HWS	11828.00	11828.00	11828.00	11828.00	11828.00
Total	120157.78	116393.41	110069.87	103213.20	101024.16

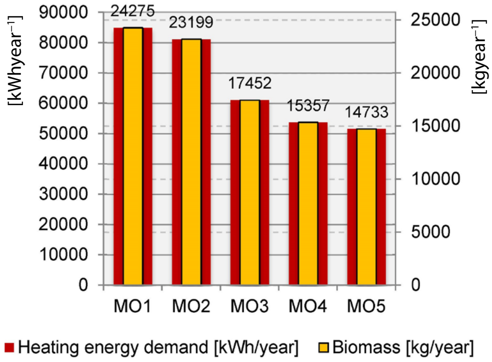

Figure 17. Annual biomass heating needs – the Haybarn Complex (*for color image see journal web site*)

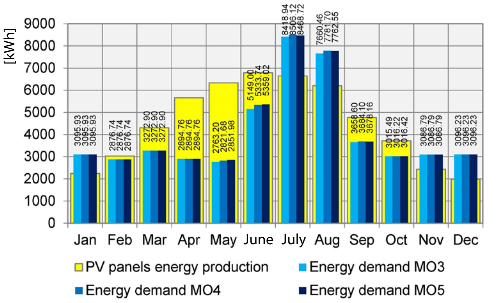

Figure 18. Electricity demands and PV electricity production – the Haybarn Complex (*for color image see journal web site*)

Table 17. Annual electricity demands and PV electricity production – the Haybarn Complex

The PV panels power production			
Model	MO3	MO4	MO5
Number of modules	170	170	170
Total power output [kW]	42.5	42.50	42.50
Total panels area [m^2]	272.11	272.11	272.11
The PV panels annual energy demands and production [kWhyear^{-1}]			
Demands	48989.04	49466.91	49460.20
Production	54113.38	54113.38	54113.38

Table 15. Annual energy demands – the Haybarn Complex

Conditioned area					
$A_{HEATING}$	841.25 m^2		$A_{COOLING}$	739.43 m^2	
Energy demands [kWhm^{-2}year^{-1}]					
Model	MO1	MO2	MO3	MO4	MO5
Heating	100.99	96.52	72.61	63.89	61.29
Cooling	0.00	0.00	18.65	19.30	19.29

Table 16. Electricity demands and PV electricity production – the Haybarn Complex

Cooling, heating, electrical appliances and HWS						
Model	MO3	MO4	MO5	MO3	MO4	MO5
	Energy demand [kWh year^{-1}]			The PV panels energy production [%]		
Jan.	3095.93	3095.93	3095.93	72.5	72.5	72.5
Feb.	2876.74	2876.74	2876.74	105.3	105.3	105.3
Mar.	3272.90	3272.90	3272.90	131.6	131.6	131.6
Apr.	2894.76	2894.76	2894.76	195.6	195.6	195.6
May	2763.20	2821.68	2851.98	229.3	224.5	222.1
June	5149.00	5333.74	5359.02	131.9	127.4	126.8
July	8418.94	8506.12	8468.72	79.0	78.2	78.5
Aug.	7660.70	7781.70	7762.55	81.0	79.7	79.9
Sept.	3658.60	3684.10	3678.16	130.3	129.4	129.6
Oct.	3015.49	3016.22	3016.42	123.1	123.0	123.0
Nov.	3086.79	3086.79	3086.79	78.6	78.6	78.6
Dec.	3096.23	3096.23	3096.23	64.1	64.1	64.1
Anual	48989.04	49466.91	49460.20	110.5	109.4	109.4

Sufficient production of electric power provided by PV panels	▨
Insufficient production of electric power provided by PV panels	□

The lack of electricity during winter months: November, December and January, due to increased energy consumption for certain electrical appliances. During warmest summer months, July and August, air-conditioning requires increased energy consumption, fig. 18. As for winter months, the biggest issue is December, since there is the lack of 35.9%. Similar situation is with July, when the calculated lack of electricity equals to 21.8%, tab. 16, if the only available source of energy implies the usage of PV panels, total power output of 42.5 kW, tab. 17.

Discussion

Taking into account the conducted analysis and evaluation of these historic buildings, the performed restoration models (MO1), the recommended measures for increasing their energy efficiency, the simulation and analysis of new models (MO2-MO5) and sustainable energy refurbishment via BPS method, carried out in compliance with current needs and conservation requirements, the authors drew the conclusions that have never before been evaluated in scientific literature in this way.

The analysis of the simulated models and recommended measures for energy efficiency improvements concerning the buildings of the Haybarn Complex provided the results regarding total energy savings for this complex of buildings. The values obtained by assessments and analyses of five models of the Haybarn Complex, carried out via BPS method, show that the most effective energy saving measures for models MO2 and MO3 occur when MO2 models are provided with thermal insulation, figs. 7, 10, 13, and 16. Application of additional thermal protection measures for models MO3, MO4, and MO5 brings a considerably less difference in energy saving for models MO3 and MO5.

Improvements in energy efficiency of the Stable and upgrading MO2 model to MO3 model, imply the application of 5 cm thick thermal insulation that is lined with 6.5 cm thick bricks, on façade walls, which reduces heating energy consumption by 33.26%, cooling energy consumption by 39.54% and total energy consumption by 21.70%. Upgrading MO3 model to MO5 model includes the application of 15 cm thick thermal insulation on the floor and 25 cm thick thermal insulation on the façade walls, which reduces heating energy consumption by 16.65% and increases cooling energy consumption by 19.44%. In this case, total energy saving is 5.65%, (tab. 2, fig. 7).

Improvements in energy efficiency of the Mulekeepers' House and upgrading of the model MO2 to model MO3 require the application of 5 cm thick thermal insulation lined with 6.5 cm thick bricks, on the façade walls of the ground floor, which reduces heating energy consumption by 27.17%, cooling energy consumption by 28.10% and total energy consumption by 24.86%. Upgrading of the model MO3 to model MO5 includes the application of 15 cm thick thermal insulation on the floor and 25 cm thick thermal insulation on the façade walls, which reduces heating energy consumption by 18.96%, cooling energy consumption by 4.49% and total energy consumption by 14.73% (tab. 6, fig. 10).

Improvements in energy efficiency of the Haybarn and upgrading of the model MO2 to model MO3 require the application of 5 cm thick thermal insulation on the floor and 5 cm thick thermal insulation lined with 6.5 cm thick bricks on the façade walls, which reduces heating energy consumption by 11.82%, cooling energy consumption by 2.94% and total energy consumption by 7.78%. Upgrading of the model MO3 to model MO5 implies the application of 10 cm thick thermal insulation on the floor and 20 cm thick thermal insulation on the façade walls, which reduces heating energy consumption by 12.06%, cooling energy consumption by 3.65% and total energy consumption by 7.74% (tab. 10, fig. 13).

Upgrading of the model MO2 to model MO3 ensures the reductions in total energy consumption for all the buildings of the Haybarn Complex by 18.10%: heating energy consumption is reduced by 24.77% and cooling energy consumption by 23.39%. Upgrading of the model MO3 to MO5 reduces total energy consumption by 8.22% and heating energy consumption by 15.58%, but increases cooling energy consumption by 3.42%. Based on the conducted research, total thickness of thermal insulation is not to exceed 20 cm on the floor and 30 cm on the façade walls, in case of the model MO5, in all the buildings of the Haybarn Complex, fig. 16. Concerning energy efficiency, the upgrading of the model MO3 to models MO5 requires the application of thermal insulation on the floor, 10 to 15 cm thick, as well as on the façade walls, 20 cm to 25 cm thick. The presented measures reduce energy consumption. The obtained results lead to the conclusion that it is possible to reduce energy consumption by adding thermal insulation and increasing thermal insulation thickness in the restored buildings, that is – in the models MO1. From the architectural point of view, this is the only permitted method of adding thermal insulation to interior façade walls, in accordance with the conservation requirements. However, if the applied thermal insulation is excessively thick, it will reduce the usable area of the buildings.

The first hypothesis was tested on-site, along with the evaluation of each building included in the Haybarn Complex, using all models (MO1-MO5), and energy efficiency testing via BPS method. The obtained findings confirmed the hypothesis in terms of potential energy saving and energy efficiency improvement during the restoration of historic buildings, while applying specific construction methods, in accordance with conservation requirements and authenticity preservation. All the measures aim to refurbish historic buildings, without negatively impacting harmony with the protected site of Mount Athos.

The second hypothesis concerning the use of renewable sources was also tested and confirmed. The application of wood chips (biomass) as RES is an appropriate choice of energy supply for this isolated site. Knowing that significant amounts of wood are obtained by thinning and pruning the trees owned by Hilandar Monastery, the biomass demands for heating are satisfied. Solar radiation (potential solar power) can be used to produce energy for lighting, cooling, electrical appliances and hot water supply via PV panels. The analysis confirmed that total power output, obtained by PV panels, meets the annual energy demands for the entire Haybarn Complex. However, the analysis of various models MO3-MO5 and monthly energy consumption, showed that it is not possible to obtain all the needed electricity throughout the year. Hence the conclusion that it is inevitable to apply additional sources of energy during critical months. Since the location of the Holy Mountain of Athos is the very essence of isolation, it means that the surplus electricity from PV panels, in certain seasons, can not be transferred into another electric power system. For the time being, it can only be stored in accumulators.

The research also confirms the conclusion made by Murgul [6] – not only does protection of historic buildings imply the protection of visual historic environment, but also the historic construction system itself, being a unique, environmentally optimal system, considering its century-long endurance and durability. The research again points out the significance of detailed observation and analyses of all elements that could negatively impact the restoration of historic buildings, since the only way to have a successfully increased energy efficiency of historic building is the absence of negative effects on historic character and integrity, which confirms the findings presented by Hensley and Aguilar [2].

This paper presents the same conclusions as the ones drawn by Bionaz [3], in relation to the restoration of historic buildings made of massive stone walls: interventions such as replacing windows and installation of curtains are not sufficient to satisfy the standards of modern living and thermal comfort and increase energy efficiency, unless adequate thermal insulation is installed on all peripheral stone walls from the inside. What makes this paper innovative in comparison to research papers provided by other authors is its unique model of the restoration of auxiliary buildings (Stable, Haybarn, and Mulekeepers' house), for the purpose of their refurbishment and re-use, which means that the performed restoration transformed the buildings into accommodations for visitors of the monastery. This research tested the principles and measures of energy efficiency in order to improve energy performance of the listed buildings. This was the first time to apply such restoration method on Mount Athos, thus proving the professional value and justification of the conducted research, in relation to scientific and practical use as well as potential further application on other historical sites and architectural heritage having similar structural systems and materialization.

Further research in this field implies finding the best solution to compensate for the lack of needed energy, as presented by analyzed simulation models of the Haybarn Complex.

The future research could deal with analyzing economic viability of installing more PV panels in comparison to recommended number, in order to increase total power output via PV panels, thus compensating for the lack of needed electricity during the mentioned critical periods.

Conclusions

The need for additional accommodation for a growing number of visitors shaped the restoration and adaptive re-use of demolished buildings within the Haybarn Complex, transforming them into lodgings. The newly restored Haybarn Complex is a link between cultural heritage and modern demands.

In order to re-use historic buildings and increase their energy performance, the following procedures are to be carried out during the restoration works.

- Determine the level and type of restoration and refurbishment, considering the analysis of current condition of historic buildings.
- Choose appropriate construction measures for energy refurbishment and re-use, in accordance with conservation requirements.
- Implement the principles of energy management in order to use RES and find the best solution to annual energy demands and energy saving in this isolated site, in accordance with energy efficiency and environmental protection requirements.

Restoration and re-use of protected historic buildings require a specific individual approach to each historic building and application of energy efficiency measures. Energy saving implies the following construction measures, in accordance with conservation requirements: the installation of thermally insulated cladding, replacement and installation of adequate windows and doors. The application of these construction measures as well as RES significantly increase energy efficiency of historic buildings. The main contribution of this paper is practical testing and evaluation of achieved results in energy refurbishment, using the energy efficient principles of restored historic buildings. This evaluation was carried out using various restoration models, via BPS method, in accordance with conservation requirements and authentic preservation principles applied to the Haybarn Complex.

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