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Sustainable Vernacular Architecture: The Renovation of a Traditional House on Stara Planina Mountain in Serbia

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Abstract: In the last few years, Stara planina (the Balkan Mountains) and its surroundings have been improving their tourist offer. The area is protected by law, as a nature park, and the construction of new buildings requires a complex administrative procedure. Renovation of country houses is part of the usual construction procedures and is easier to carry out. Typical renovation solutions involve application of industrial materials with significant impact on the environment from the process of their production and further on. The traditional houses found in many mountains across Serbia and the Balkans are constructed using natural materials. Hence, this paper tackles the problem of renovating such dwellings by application of natural materials to improve their usability and reduce their energy and carbon footprint. An analysis is performed on a case study model of a typical house from Stara planina. The advantages of using natural materials in the process of renovating a traditional house are analysed. By using TRNSYS software, the total amount of energy demands of the house during a typical meteorological year with four scenarios (current state, walls isolated with sheep and hemp wool panels and EPS) was simulated. These materials were further analysed for their environmental impact by means of Life Cycle Analysis (LCA). In the synthesis of the research, the best results were brought into connection with the sustainable development of the architectural heritage. The results prove that natural products provide the necessary thermal comfort and have a significantly more positive impact on the environment than artificial materials. Based on this study, recommendations were created for the sustainable renovation of vernacular architecture in Serbia. The goal of the paper is to create scientific and professional evidence that local and natural materials must be used to reduce the impact of climate change and that such sustainable renovation is in accordance with modern architectural design and thermal comfort. The goal is also to fill the gap in renovation methods in Serbia, according to the principles of sustainable design.

Keywords: vernacular architecture; hemp wool isolation; sheep wool isolation; sustainable house renovation

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1. Introduction

Due to the negative consequences of the digital era, pandemics, economic instability and climate change, nature conservation is becoming increasingly important. During times of crisis, people in Serbia are increasingly relying on domestic tourism offerings. In the last few years, Stara planina (Old Mountain or Balkan) and its surroundings have been improving their capacities and tourist offer. It offers a large number of winter and summer activities that are dedicated to preserving the tradition of this region. The area is protected by the law, as a nature park, and the construction of new buildings requires a complex architectural and administrative procedure. This leads to the expansion of rural tourism, as opposed to the development of hotel accommodations. Adaptations of country houses belong to the usual construction procedures and are easier to carry out. A common problem is the use of cheap and artificial materials, as well as the violation of the architectural language of country houses. If tourism continues to develop in Stara planina, there will be a justified desire to transform old houses into tourist apartments. On the other hand, it is presumed that the method of that transformation does not correspond to the guidelines of sustainable and architectural development [1]. Within the spatial plan of the nature park area and the Stara planina tourist region (Official Gazette of the Republic of Serbia, no. 115/2008), environmental protection and the growth of sustainable development of this area are supported [2]. However, the rules for the construction of new buildings and the reconstruction of old ones do not specify the method of realisation in the context of the preservation of the ethno-architecture of Stara planina motifs. Not even specific materials were proposed.

The topic of sustainability is extensively covered in the literature. The development of the economy in the world significantly increases living standards. In such an industrialised environment, the consumption of energy resources is also increasing. The construction industry has a significant share in this problem [3]. It is responsible for as much as 40% of total energy consumption and CO_2 emissions. It follows from this that it is really important to find a method to reduce the high need for energy in the construction business [4] so that construction would have a less negative impact on the environment [5]. In this regard, a significant number of scientific studies are dedicated to the topics of reducing the ecological and economic footprint [6–11], bioclimatic strategy in architecture [12] and sustainable development of the traditional house [3,13–22].

Bearing this in mind, this research deals with the harmonisation of the architectural and technological condition of the renovation of the vernacular house in accordance with the modern interpretation of traditional architecture and sustainable development. Traditional architecture is accepted worldwide as a part of the national heritage that describes the identity of a certain nation. It is used as a primary attraction in tourism and further in the economic development of a country. Because of this, many countries (the Netherlands, France, England, Germany, Spain, Italy, etc.) have made significant efforts to preserve areas with traditional architecture [12,23,24]. The implemented measures in these countries elaborate the manner of restoration of old architecture in accordance with local customs and according to the promotion of traditional concepts in architecture and culture [25]. This implies the use of a certain type of construction material that is allowed within a certain area. Moreover, training courses are promoted for people who will present heritage and who will raise the awareness of the local population about the importance of ethnocultural heritage [26–28].

As far as the authors know, the sustainable development of traditional architecture in Serbia has not been discussed in the literature. That actually constitutes the innovation of this article, created in order to fill the gaps in international science. The initial hypothesis of this work is that by applying natural materials, better thermal comfort of houses can be achieved, with minimal impact on the natural environment, and that such application is more expensive than solutions that use modern materials. The goal of this paper is to:

- Create a study that scientifically proves the justification of using domestic and natural materials in accordance with modern architectural theory;
- Fill the gap in the methods of reconstruction of rural architecture on Stara planina in Serbia, according to the principles of sustainable construction;
- Create recommendations that can be applied in the process of renovating traditional houses according to the principles of sustainability.

This paper is structured using standard scientific format (introduction, materials and methods, results, discussion and conclusions) with one addition. After the introduction, a chapter was added in which the architectural problem of the traditional house on Stara planina was described. The paper first establishes the concept of the renovation on the example of the Stara planina house. Then it discusses the various advantages of natural materials used to insulate the heated space of the house. Insulations made of hemp wool, sheep's wool and expanded polystyrene (EPS) were analysed according to the total energy required for one year, using the TRNSYS software [29]. Their impact on the environment (life cycle assessment) was also checked using Solid Works Sustainability software [30] and GaBi database [31]. Finally, this paper shows which of the materials have the highest average success rate.

2. The Case of a Traditional House on Stara Planina

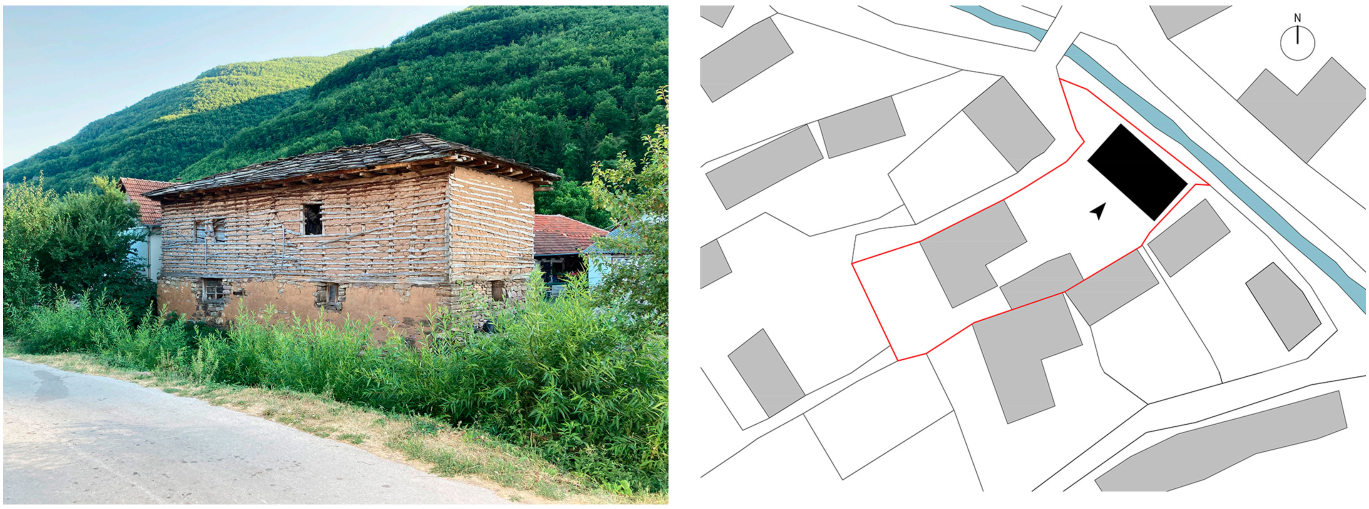
The climatic characteristics of the traditional houses in the village of Dojkinci are related to the characteristics of Stara planina. Stara planina is located in south-eastern Serbia and Bulgaria. The western part of this mountain range is located in Serbia and extends over the territories of the towns of Zajecar, Knjazevac, Pirot and Dimitrovgrad. In the mountain massif near Pirot, the village of Dojkinci (Figure 1) is located in the Visok morphological unit. The barn in this village is undergoing renovation. In this example, the possibility of applying ecological materials was explored in order to achieve sustainable thermal comfort. The climate in this area is continental. Summers are hot and dry; winters are cold with strong winds and lots of snow. Transitional seasons (spring and autumn) are less pronounced. That is why this mountain has favourable climatic conditions for the development of tourism, in summer and winter. The warmest month with the highest maximum average temperature is August, 26.7 °C. In January, the lowest average maximum temperature is 1.4 °C. The highest average minimum temperature is 12.3 °C in August. The lowest average minimum temperature is −5.4 °C in January [32].

Figure 1. Dojkinci village on Stara planina in Pirot district. Photo: M. Stanimirovic, 2022.

Rural architecture is one of the main elements for attracting tourism in this area. Directing the sustainable reconstruction of rural houses is in the competence of the local government and the competent ministry. Despite the success in the conservation of important cultural monuments (such as churches), Stara planina is losing its architectural tradition under the influence of inappropriate renovation of houses.

According to the literature [33–35] related to this topic, traditional houses on Stara planina in Serbia were built by the peasants and craftsmen themselves. Settlers built their first habitat which had a temporary character. Country houses, which are small marks of more developed architecture, were built by local builders—craftsmen by profession. Groups of peasants who went to other regions to work influenced the development of village architecture. Thus, construction conditions were transmitted in both directions. Builders from Pirot received influences from Macedonia and central Serbia, but also from neighbouring Romania and Bulgaria. On the other hand, they spread their influence over the rest of the Balkans, which was organised into a state called Yugoslavia. That is why, in the literature, the architecture in Serbia is associated with the common architecture of the same era on the Balkan Peninsula. It is recorded that primitive shelters in Serbia during the time of the Turks were built by the settlers who used local materials, wood, earth and wicker. Later, shelters were replaced by more developed types of smaller houses. At the end of the 19th century, after the liberation from the Turks, the layout of the rural houses changed. Houses got two or three rooms. The external expression of the house and the method of construction were also changed. The timber-framed system replaced the wooden hut (cottage), in the form of a skeleton made of wooden posts and beams, with infill walls made of mud, straw and reeds. The walls were covered with mud. A stone foundation appears as a constructive improvement. By raising the walls on the foundations, there was a need for a diagonal brace in the wall structure, which carried the roof trusses, on which the roof structure was supported. The roofs always consist of four slopes (hip roof). Houses were simple; they had one room with a fireplace, and a porch facing the courtyard. They had white flat walls and a low roof covered with stone slabs. The overhangs of the roofs are deep, in order to protect the mud-covered walls. All those houses were very similar. The dimensions were almost identical; the structural systems were the same. Differences existed only as a consequence of field conditions. Below the rooms, a basement was built on the foundations, and the ground floor was accessed via external stone steps. From the beginning of the 20th century, under the influence of the city, the timber-framed house lost its established architectural features. Decorative forms of false character appear, such as semi-circular arcades on the porch, which have nothing to do with the applied construction system [33–35].

According to the project assignment, the investor intended to reconstruct the barn (Figure 2) and to keep the characteristics of the rural architecture of the village of Dojkinci. Tourism was meant to be a new function of the barn. A barn should be designed as an apartment with two bedrooms and a living room. The barn is a timber-framed (bundwerk or bondruk or post and pan) system on a stone basement, with a hip roof, with stone slabs. Due to time, the porch in the yard was dismantled. It was oriented towards the south.



(**a**) (**b**)

Figure 2. Dojkinci: (**a**) Country barn (photo: M. Stanimirovic, 2023), (**b**) Situation plan.

The usual procedure of renovating rural houses in this area involved several operations, which were mostly justified by the amount of financial investment. First, the roof covering is changed. Tiles are installed instead of stone slabs, because they are lighter, cheaper and more available. Moreover, wooden windows are removed and PVC windows are installed instead. Finally, the walls are insulated with EPS, from the outside. The white colour is often avoided, in order to cancel the earlier appearance, which is, according to the peasants, a symbol of poverty. The problem described in the literature concerns the internal organisation of village reconstructions, which is usually not done by architects [36–40]. These include errors in the required minimum dimensions of certain contents, as well as the poor connection of new and found functionalities. The toilet did not exist in old houses and in the case of its incorporation into a new organisation, it is often placed on the south side of the house.

3. Materials and Methods

Houses in protected rural areas most often represent a mirror of green wisdom in the framework of architectural design and construction technology using natural materials [23]. In rural areas, people built houses from available materials, which they could find in their surroundings. Earlier, artificial materials did not exist, so rural houses did not have a problem with the current toxic influence of plastic and chemistry. Nowadays, the preservation of cultural heritage dictates the use of local and traditional materials in the process of renovating old country houses.

Materials that can be applied in the process of renovating a country house according to the principles of sustainable development and reducing energy consumption are related to this research. Thus, sheep's wool can be a material with suitable use [41–47], as well as hemp [48–56]. The popularity of hemp as a construction material is growing in the world, including in Serbia. Replacing mineral aggregates with plant aggregates in building materials can significantly affect energy consumption in this sector [48–56]. In this context, energy efficiency, eco-materials, and eco-design are presented in order to indicate the importance of searching for environmentally friendly and natural materials and technologies that enable the reduction of material and energy consumption in buildings.

3.1. Materials: Hemp Wool

Industrial hemp grown for construction purposes is *Cannabis sativa*. It contains 0.3% THC and this distinguishes it from marijuana whose percentage ranges from 6–20%. By processing industrial hemp and combining it with other materials, various products are made for the construction and thermal insulation of existing and new buildings. Some of them are hempcrete, hempcrete blocks, hemp-based insulation wool ("hemp wool"), plywood/chipboard, hemp-based mortar and bricks. The thermal conductivity of hemp-based materials ranges from 0.035 to 0.043 W/mK [57], which makes them acceptable thermal insulation materials [48–56].

Today, several methods are used to process and treat industrial hemp for its use in the production of thermal insulation materials. Depending on the method of processing and production, three basic types of thermal insulation products are distinguished from industrial hemp. It is mainly produced in the form of rolls or panels [58], but it can also be in the form of rigid or semi-rigid boards The price of the 10 cm panel used in the research is €13.9/m^2 (λ = 0.036) [59].

3.2. Materials: Sheep's Wool

The production of sheep's wool requires only 14% [60] of the energy used for the production of glass wool. Sheep wool is one of the few construction products that have the highest European certificate for the quality of natural properties. After shearing, the wool is washed and treated with chemicals harmless to humans, to further increase its resistance to moths, insects and fire. By pressing the wool into sheets or bales, a dense material is obtained that can be cut and tailored, and then installed with the same method as mineral wool. It is most often sold in the form of plates with a thickness of 50, 75 and 100 millimetres, while the price of one square meter with a thickness of 50 millimetres on the Western market is from €6 and up. It has excellent thermal insulation characteristics. The thermal conductivity coefficient of sheep's wool ranges between 0.035 and 0.04 W/mK, depending on the insulation density, which can be 18–30 kg/m^3 of wool [41–47].

Thermal insulation materials are made from sheep's wool fibres that are mechanically processed in a special way in order to obtain the final product. In the market, thermal insulation materials made of sheep's wool can be found in three forms: as rolls, as panels [61] or as puffy, non-compact thermal insulation material that is installed by blowing. Rolls and panels are easier to install, but they can settle over time, while the puffy non-compact type of thermal insulation is more difficult to install but maintains its volume over time. Some manufacturers offer thermal insulation materials that are made from 100% sheep wool, while others combine 75% sheep wool with 25% recycled polyester. Moreover, thermal insulation rolls and panels made of sheep's wool come in standard dimensions, as well as conventional types of thermal insulation, and can be easily cut and cut into the intended construction. The price of the 10 cm panel used in the research is €18/m^2 (λ = 0.036) [62].

3.3. Materials: EPS

One of the most commonly used insulators in Serbia is expanded polystyrene (EPS). Its thickness varies (there are plates with a thickness of 5 to 15 cm), but for the purposes of this research, EPS with a thickness of 10 cm is used. Expanded polystyrene is most often obtained by the process of suspended polymerisation, whereby products are obtained from a raw material that looks like a grain of sugar and is steamed at about 100 °C. Each grain expands to about 30–50 times its original volume, and its density decreases from 600 kg/m^3 to 10–30 kg/m^3. The pre-expanded granules mature in the air in ventilation silos, after which they are installed in metal moulds and sealed into the final shape. After removal from the mould, ripening is required to remove residual water and pentane from the material. Suspended polymerisation is a batch process that enables the conversion of styrene monomer into expansive polystyrene beads through the polymerisation process. After that, the suspension is cooled and the expanded polystyrene beads are separated via centrifugation, washed and dried. Finally, the beads are sieved, coated and packed for further transport [63].

Expanded polystyrene is the first association when mentioning the isolation of the object in Serbia. Compared to stone wool, it is much cheaper. EPS is most often used in thermal insulation of facades, as one of the layers of a sandwich wall or when insulating buildings from the inside [64]. EPS is an expanded polystyrene available in various densities for insulation, construction and craft applications. It is more cost effective then XPS (extruded polystyrene foam) [65]. The price of the 10 cm panel used in the research is €5/m^2 (λ = 0.035) [66].

3.4. Methods

The research results were obtained within three phases: Architectural design, Energy simulation and LCA. In the first phase of the research, a BIM of a renovated house in the village of Dojkinci on Stara planina was built using the modelling method, for the needs of LCA [67] and energy analysis. Four scenarios were created according to the materials of the exterior walls. Timber-framed (bundwerk) walls made of wooden construction with mud and straw filling, with insulation made of EPS, sheep's wool and hemp wool were used. The 3D model was transferred from Archicad [68] to Sketchup [69], which has the TRNSYS3D plugin [70]. In that model, surfaces are defined by assigning them the value of the appropriate insulating material.

In the second phase, the simulations were checked according to thermal comfort for one year. The obtained data were classified using the statistical method and presented in the form of an overview graph. Building simulation is widely accepted in the field of the study of the thermal performance of buildings [23]. The four scenarios were entered into the Transient System Simulation Tool (TRNSYS) software, resulting in four simulation models.

In order to determine the energy performance of the building and the retrofit of its thermal envelope, a TRNSYS simulation [71] for a typical meteorological year was performed using Meteonorm data [72]. The model assumes that a local wood fired furnace is used for heating of the three rooms, each of which is modelled as a separate thermal zone. The simulation timestep used was 1h. The thermal envelope, considered for the renovation scenarios, consists of exterior walls, adjacent ceilings and windows and glazing surfaces. The simulation included four scenarios: (1) current building condition, (2) renovation thermal envelope insulated with sheep wool, (3) renovation thermal envelope insulated with hemp wool and (4) renovation thermal envelope insulated with EPS. The window glazing system used for the current state for the simulation was single glazed, wood windows with a heat transfer coefficient of 5.8 W/m^{2}K, whereas all of the three renovation scenarios assumed 4/16/4 double glazing, wood windows with a heat transfer coefficient of 1.4 W/m^{2}K. The simulation was performed using a TrnBuild heating system model with a constant radiative heat transfer ration of 0.1, and periods without heating of 10 h per day. Furthermore, the set point indoor temperature in the living room was assumed to be 23 °C, as a mean temperature value during the heated period of the local furnace heating, and a mean temperature of 20 °C for the bedrooms. Such conditions are considered typical for this type of dwelling, equipped typically with local wood fired furnace heaters. It is assumed that the infiltration of outside air reduced the ventilation heating loss of the building significantly after the retrofit, decreasing the air change rate in the building zones from 1.2 to 0.6 for the renovation scenarios. The goal of the simulation was to determine the typical annual energy consumption of the building, before and after the retrofit, as well as to estimate the annual wood consumption. The fire wood consumption was estimated for the average firewood heating value of 14,000 kJ/kg, whereas the density of log wood for storage was 650 kg/m^3.

In the third phase, the LCA and the prices of the materials used in the walls were compared. SolidWorks/Sustainability Software was used for the purposes of LCA analysis. It determines the environmental impact throughout the entire product life cycle and complies with the ISO 14040 [73] quality standard. SolidWorks/Sustainability calculates the environmental impact in four key areas: carbon dioxide emissions (kg CO_{2e}), energy consumption (MJ), acidification (kg SO_{2e}) and eutrophication (kg PO_{4e}). Life cycle assessment (LCA) is a common tool for assessing the environmental impact of products [74].

In the following, after obtaining the results, the obtained data were considered through a comparative analysis. In the synthesis of the research, the best results were highlighted, which were further, in the discussion, brought into connection with the preservation of the sustainable development of the architectural heritage. Based on the conclusions, recommendations were created for the sustainable renovation of vernacular architecture on Stara planina in Serbia.

4. Results

4.1. Architectural Design

The architectural problems described in the second chapter were overcome within the new organisation of the space according to the given program (Figures 3 and 4). The conceptual solution was made according to the principles of sustainable construction and rural architecture. Towards the south, an entrance porch is added to the raised part of the house in which a tourist apartment is created. The timber-framed walls are expanded in the part of the necessary openings according to the internal organisation of the apartment. The windows are mostly facing south, in order to use the energy of the sun in the winter. The roof is extended in the part of the porch, so that its shade reduces the heat of the interior in the summer.

Two new scenarios were designed as a novelty in the process of reconstruction of rural houses on Stara planina in Serbia. In the first, the walls are lined with sheep wool panels, in the second with hemp wool panels. Reeds are placed over that layer, with mud over it. Finally, this cover is protected with white natural lime (Figure 5). Considering the fact that the basement is used as storage, and the attic space is not used at all, hemp or sheep's wool is installed as floor and ceiling insulation. On the inside of the walls, plasterboard panels were placed over a minimal wooden structure. The reason for their use is the touristic need for flat interior surfaces and space for new electrical installations.

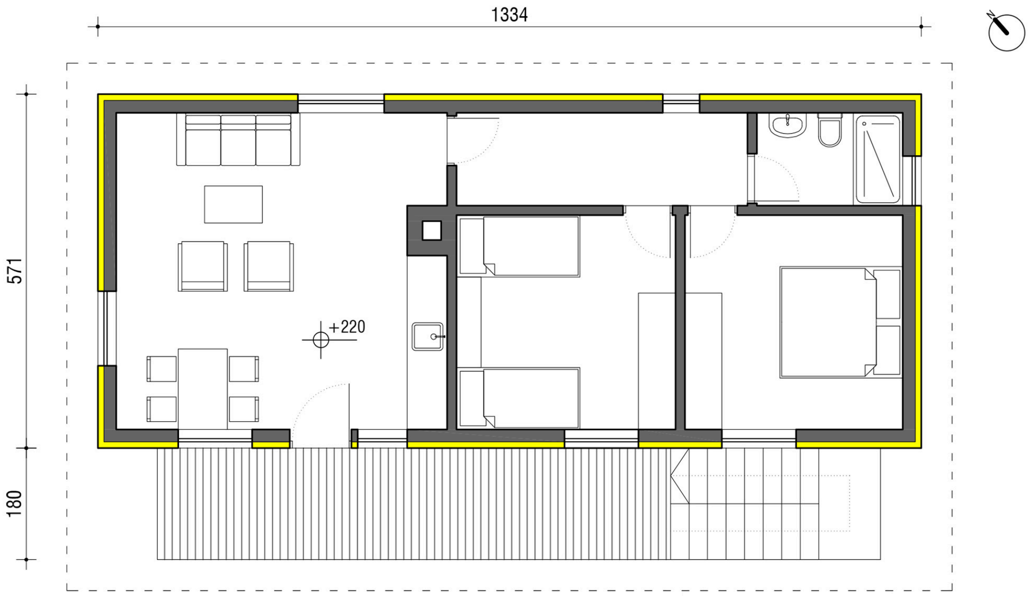


Figure 3. Renovation: Floor plan.

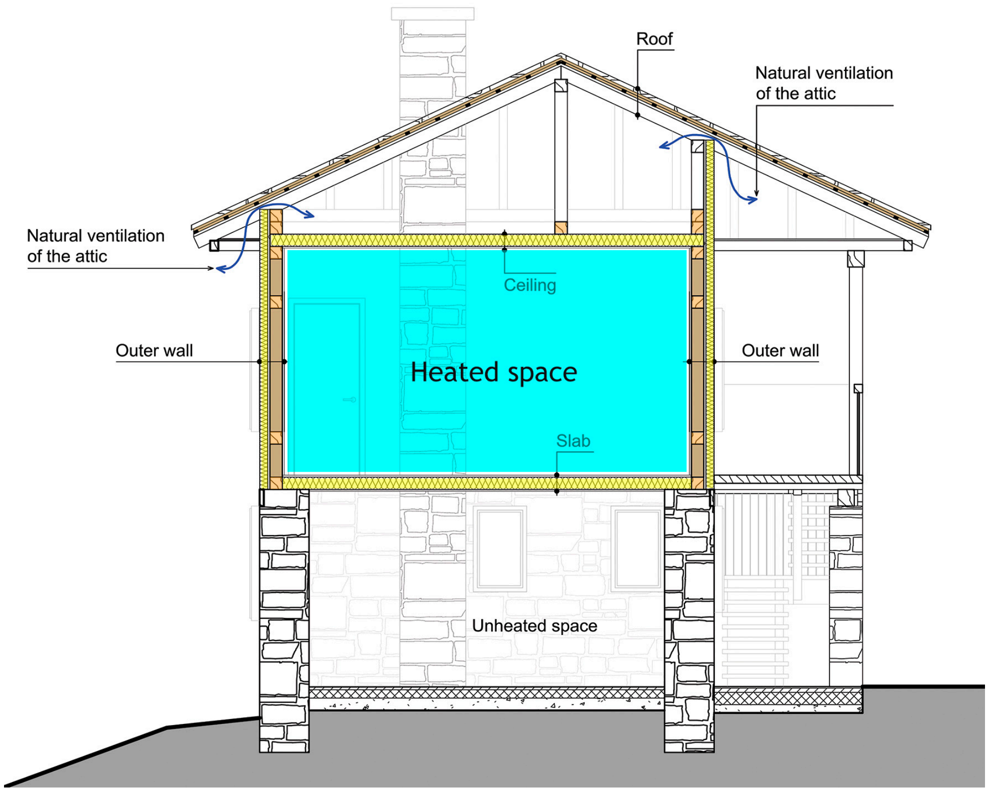


Figure 4. Renovation: Section plan.

The layers of the walls of this reconstruction can be presented in a table within four scenarios (Table 1). In the next step, the model prepared in this way was observed through the simulated energy consumption for one year. The amount of insulation material, 10 cm thick, was calculated from the Archicad model: P = 267 m^2 in 188 panels.

(**a**)

(**b**)

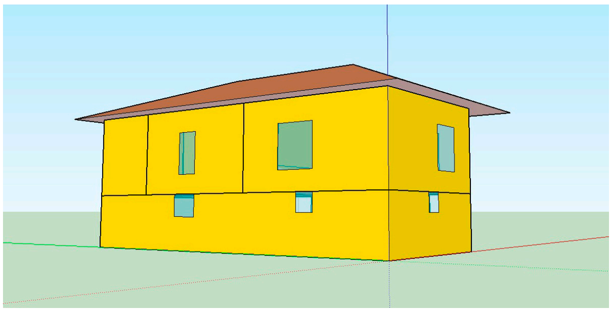
Figure 5. Three-dimensional rendering (renovation): (**a**) street view and (**b**) courtyard view.

Table 1. Outer wall layers.

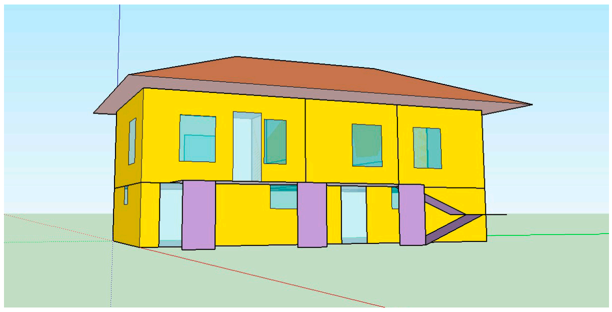
Scenario 1 (Current State)	Scenario 2 (Sheep's Wool)	Scenario 3 (Hemp Wool)	Scenario 4 (EPS)
	Finish lime coat	Finish lime coat	Finish coat
	Mud mortar 2 cm	Mud mortar 2 cm	Base coat
	Reed board 1cm	Reed board 1 cm	Reinforcing mesh
	Sheep wool insulation panel 10 cm	Hemp wool insulation panel 10 cm	Adhesive and EPS board 10 cm
Wooden board 2.5 cm	Wooden board 2.5 cm	Wooden board 2.5 cm	Wooden board 2.5 cm
Wooden construction with filling of mud and straw 15 cm	Wooden construction with filling of mud and straw 15 cm	Wooden construction with filling of mud and straw 15 cm	Wooden construction with filling of mud and straw 15 cm
Wooden board 2.5 cm	Wooden board 2.5 cm	Wooden board 2.5 cm	Wooden board 2.5 cm
	Vapor barrier	Vapor barrier	Vapor barrier
	Plasterboard sheets 2.5 cm	Plasterboard sheets 2.5 cm	Plasterboard sheets 2.5 cm
	Base coat	Base coat	Base coat
	Finish lime coat	Finish lime coat	Finish lime coat
20 cm	36 cm	36 cm	36 cm

4.2. Energy Simulations

For the purpose of this research, the model of the house (Figure 6) was used to simulate the energy consumption for a year according to the influence of the external temperature. Based on the performed annual building performance simulation, it can be concluded that the energy consumption significantly decreases after the retrofit, reducing the annual heat demands approximately to one half in each of the renovation scenarios. The estimated fire wood consumption follows this trend. The differences between the renovation options in terms of their energy performance are negligible, which is a result of the similar heat conductivity values of the analysed insulation materials. The applied simplified heating model assumed limited heating power availability for each of the heated zones, i.e., 5 kW for the living room and 3 kW for each of the bedrooms. Equivalent or better thermal comfort conditions were met in each of the heated zones after the retrofit, as presented in the graph(s) showing the change in the simulated indoor zone temperatures during a typical meteorological year. Although the simulation was done for the abovementioned location in Serbia, the conclusions acquired through the simulations can apply for other locations as well. The simulations contain energy consumption per month (Figures 6–9).

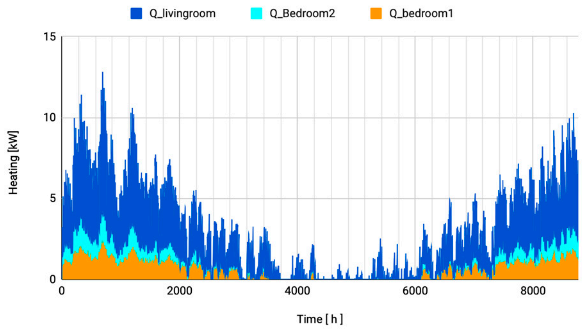


(**a**)



(**b**)

Figure 6. SketchUp model for the energy performance simulation: (**a**) street view, (**b**) courtyard view.



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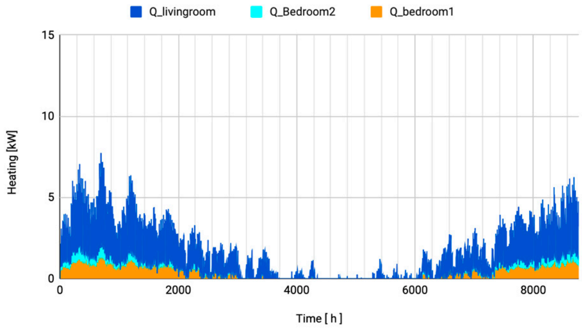

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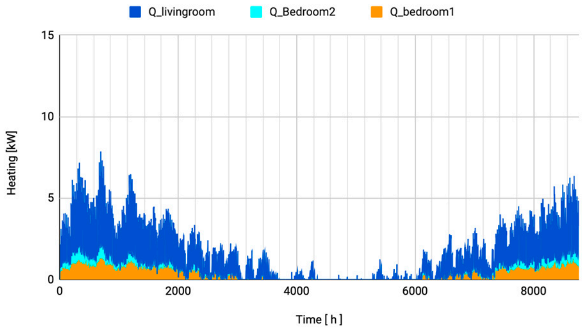
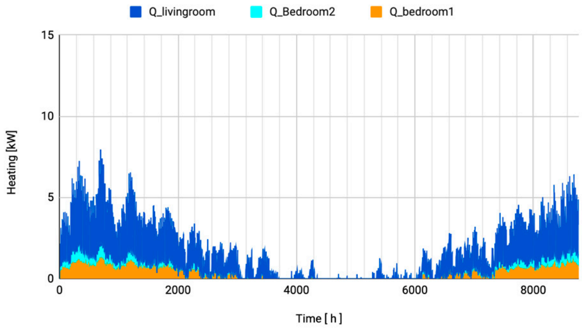
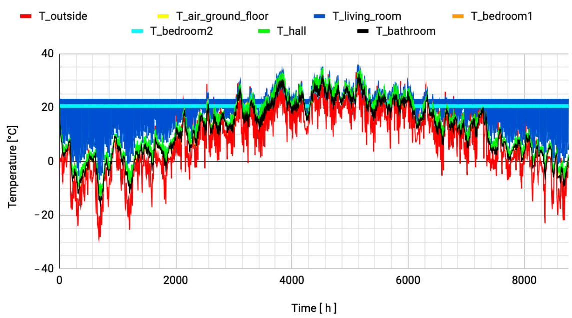


(**c**)



(**d**)

Figure 7. Energy performance simulation (Heating consumption in kWh): (**a**) current state, (**b**) with sheep's wool, (**c**) with hemp wool, (**d**) with EPS. The simulation is valid for 8760 h of a typical meteorological year.



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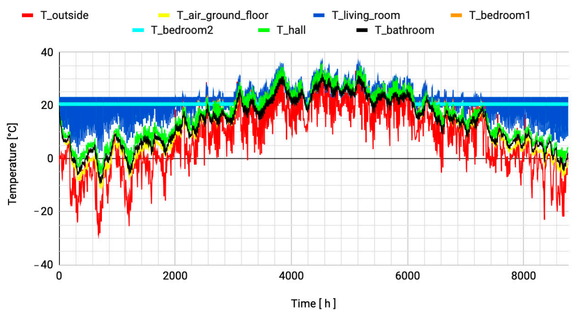
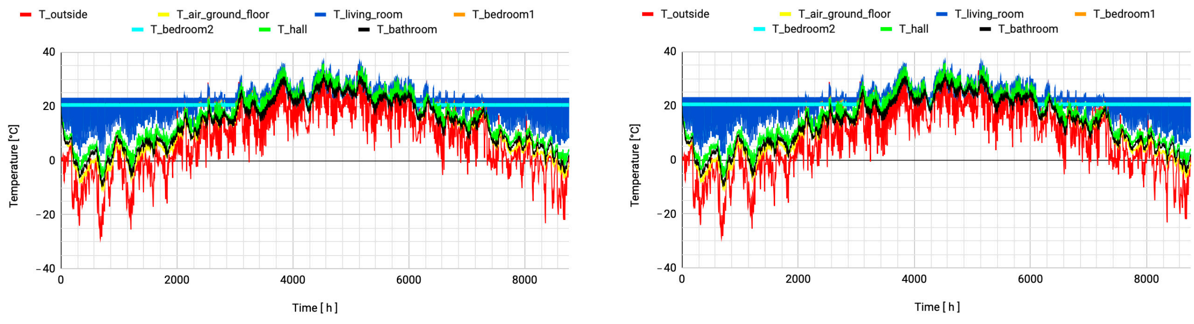


(**b**)

Figure 8. *Cont*.



(c) (d)

Figure 8. TRNSYS simulation of temperature change: (**a**) current state, (**b**) with sheep's wool, (**c**) with hemp wool, (**d**) with EPS. The simulation is valid for 8760 h of a typical meteorological year.

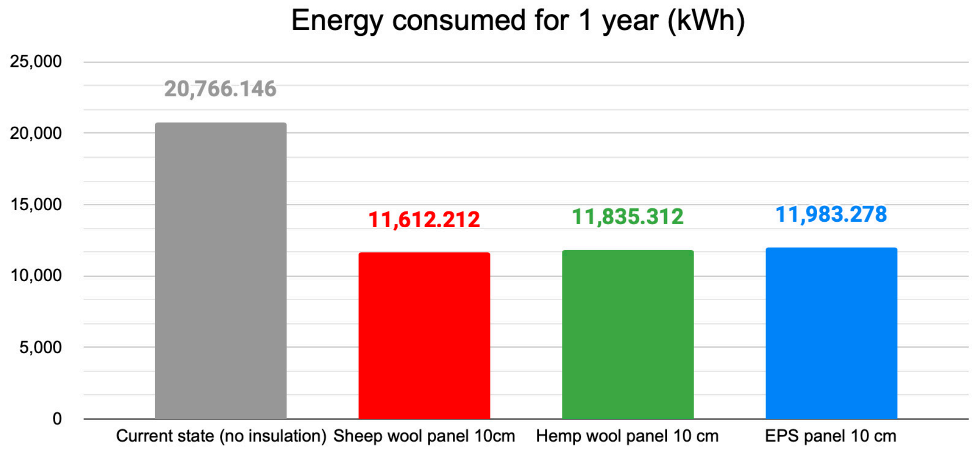


Figure 9. Energy consumed for one year (based on simulation).

4.3. LCA Simulation

Life cycle analysis (LCA, Figure 10) evaluates the various impacts of the life cycle of materials or products on the environment from five main points of view, namely: extraction—obtaining raw materials; processing to the final product; product application; and finally withdrawal of the product from use, at the end of its life cycle [75].

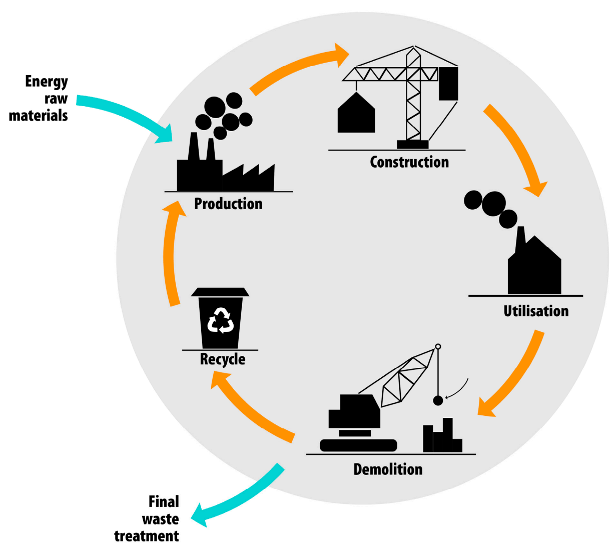


Figure 10. LCA cycle.

The LCA analysis performed for the purposes of this paper is in cradle-to-grave form. It represents an assessment of the impact of the production and installation of three types of materials for the insulation of buildings on the environment. LCA is a multi-criteria and multi-phase environmental assessment, standardised according to ISO 14040 [73] and ISO 14044 [76]. The analysis applied in this research included selected insulation materials (10 cm thick), natural (sheep's wool and hemp wool) and artificial (EPS), providing the opportunity for a clear understanding of the environmental consequences of the production system during its lifetime.

Table 2 shows the thermal characteristics of the materials used in this research based on the data from the literature [45,74,77,78]. Inventory flows and environmental burden related to the collection, transport and processing of sheep's wool, as well as activities (tumbling and scouring) have been quantified [44,53]. The inputs and outputs as well as the flows (i.e., energy and additives) related to the process of mixing washed wool and hemp were studied in order to assess potential environmental impacts. All data on the inventory for the production of wool and hemp was collected directly from the partners [79,80] involved in the production of this type of insulation and then processed using an international database [31].

Table 2. Thermal characteristics of sheep wool, hemp wool and expanded polystyrene.

Thermal Characteristics	Sheep's Wool	Hemp Wool	EPS
Thermal conductivity λ (W/mK)	0.035–0.045	0.035–0.043	0.034–0.038
Flammability class	B 2 normally combustible material	B 2 normally combustible material	B 1 heavy combustible material
Water vapor resistance factor μ	1	7.4–11	30–70
Density (kg/m^3)	22	20–68	16–28
R thermal resistance of the material (m^2 K/W)	285.7–222.2	263.2–232.56	294.12–263.12

Tables 3–5 show the level of carbon dioxide emissions (kg CO_{2e}), energy consumption (MJ), acidification (kg SO_{2e}) and eutrophication (kg PO_{4e}), during material extraction, production, transportation and lifetime of 10 cm thick EPS, required for the isolation of the entire analysed object. The values shown in the table refer to the suspension polymerisation manufacturing method, which is the most common method in use, and were obtained using the SolidWorks Sustainability software package. According to information from ArchiCAD, a total of 267 m^2 of insulation is required for the renovation of the house. Below are the records for 188 panels. The values obtained for insulation with sheep and hemp wool were taken from the literature [79,80] because it is not possible to adopt it as such in the software package that was used. For the purposes of this analysis, it was adopted that the expected working life of all the mentioned insulation materials is 50 years.

Table 3. Presentation of emissions obtained via LCA analysis for the analysed object for EPS with a thickness of 10 cm.

	Material	Manufacturing	Transportation	End of Life	Total
Carbon Footprint (kg CO_{2e})	6392.0	1579.2	10.716	1240.8	9598.716
Total Energy Consumed (MJ)	148,520	30,080	157.732	902.4	179,660.13
Air Acidification (kg SO_{2e})	28.388	10.34	0.04888	0.6392	39.41608
Water Eutrophication (kg PO_{4e})	4.888	0.376	0.01128	1.5416	6.815

Table 4. Presentation of emissions obtained via LCA analysis for the analysed object for hemp wool with a thickness of 10 cm.

	Material	**Manufacturing**	**Transportation**	**End of Life**	**Total**
Carbon Footprint (kg CO_{2e})	14.140244	38.066286	33.899128	31.3894688	117.495127
Total Energy Consumed (MJ)	29.872436	48.0581008	68.453764	3.3992772	149.783578
Air Acidification (kg SO_{2e})	0.163877	0.078642231	0.16013124	0.00804402	0.41069449
Water Eutrophication (kg PO_{4e})	1.966524	0.11377746	0.01919702	0.49818608	2.59768456

Table 5. Presentation of emissions obtained via LCA analysis for the analysed object for sheep wool with a thickness of 10 cm.

	Material and Manufacturing	**Transportation**	**End of Life**	**Total**
Carbon Footprint (kg CO_{2e})	541.824184	74.5780816	8.59090056	624.9931662
Total Energy Consumed (MJ)	636.591912	150.5982808	6.71614768	793.9063405
Air Acidification (kg SO_{2e})	2.82243016	0.352288728	0.377010744	3.551729632
Water Eutrophication (kg PO_{4e})	0.574786872	0.042233444	0.016728564	0.63374888

In cases of presented renovation, during the production of the expanded polystyrene with a thickness of 10 cm, 9598.72 kg of CO_{2e} was emitted. For the transport to the desired location, 10.716 kg of CO_{2e} is emitted. The fact that the factory for the production of expanded polystyrene is located at a distance of 150 km from the location of the installed facility was adopted. The truck was used for the transport. At the end of the life cycle, 80% of the used expanded polystyrene with a thickness of 10 cm was adequately deposited, while 20% was burned, emitting 1240.8 kg of CO_{2e}. For the case of wool insulation, the same transport value was adopted (truck and distance of 150 km). EPS panel is produced in Surdulica (Serbia), and hemp insulation in Sofia (Bulgaria). If the wool is produced in the surroundings of Stara planina, there would certainly be less impact on the environment, considering that the area where the house is being renovated was known for growing sheep and hemp in the past.

The total energy consumption for the production of the required amount of expanded polystyrene with a thickness of 10 cm is 179,660 MJ, of which the most energy used for the extraction of the material is 148,520 MJ. Acidification is expressed in kg of SO_{2e}, and for the construction of the insulation of the object in question, the total amounts to 28.388 kg of SO_{2e}, and the most is emitted during the extraction of materials. For the case of the eutrophication, the total amount reduced to kg PO_{4e} is 6.815.

Table 6 shows the overall impact on the environment through the analysed four basic segments, carbon footprint, total energy used, acidification and eutrophication, for all three insulators. It can be concluded that the smallest impact on the environment is realised via the installation of hemp wool insulation, while the greatest impact is the installation of expanded polystyrene insulation.

Table 6. Total Carbon Footprint, Total Energy Consumed, Air Acidification and Water Eutrophication for production (extraction and manufacturing), transport, end of life for expanded polystyrene, sheep's wool and hemp wool, with a thickness of 10 cm.

	Sheep's Wool	**Hemp Wool**	**EPS**
Carbon Footprint (kg CO_{2e})	624.9931662	117.4951268	9598.716
Total Energy Consumed (MJ)	793.9063405	149.783578	179,660.1
Air Acidification (kg SO_{2e})	3.551729632	0.410694491	39.41608
Water Eutrophication (kg PO_{4e})	0.63374888	2.59768456	6.815

5. Discussion

The concept of reconstruction of a traditional house on Stara planina in the previous chapter was observed through three units: architectural design, energy analysis and LCA analysis. The research results are expected and they show the connection between architecture, technology and sustainable development.

5.1. Architectural Design

The internal organisation and external design take into account the following: improvement of existing thermal comfort, minimal impact on the environment, preservation of heritage. The traditional architecture in Serbia was realised in accordance with those tasks [33,34,39]. However, what is missing is the modern adaptation of rural houses according to the new functions of the house, such as indoor toilets and electrical and mechanical installations. In a similar study [23] the orientation of a renovated traditional house was proposed in a similar way, according to the task of creating thermal comfort. The southern orientation of that house and the low height of the interior space were chosen in accordance with the principles of passive design. However, modern housing functions (toilet, living room) that are the result of a modern way of life were not introduced in that research. Earlier, people worked in the fields, and used the houses for sleeping and resting. Today, it is necessary to fulfil the function of a living room, which, in addition to thermal characteristics, also has aesthetic requirements. There are examples [1] where special attention is paid to the preservation of rural authenticity and the ambience of traditional houses, in accordance with sustainable development and the development of tourism. In addition, to conserve tradition, future research was proposed to competent institutions concerning a concrete way to preserve heritage. In this regard, the proposed architectural concept for renovating the house on Stara planina does not radically change the shape of the house, nor the size of the windows. The claim on the use of natural materials, the shape of the roof and the orientation of the new contents was also in accordance with this research. Recommendations for the renovation of traditional houses on Stara planina can also be created. The obtained result is in accordance with the conclusions of another similar study [81] in which solutions for the revitalisation of a typical traditional house were proposed. In this study, a model was created that refers to the creative processing of the inherited building principle, which is very important for architecture. The principles of bioclimatic architecture and the modern housing context were also taken into account. In other words, the old architecture was harmonised in accordance with the new functions, which is in line with the goal of this research. The presented modern interpretation of the traditional house is very similar to the concept of renovation of the house on Stara planina. Nevertheless, the result of this research went a step further in the process of processing traditional architecture, which is reflected in the application of panels made of sheep and hemp wool.

In this paper, the position is supported that traditional architecture is recognised as an expression of bioclimatic principles and national principles of authentic construction. [82]. "Vernacular architecture, above all, means appreciating the characteristics of the location of its creation, the application of available materials, and harmonisation with the needs of space users without disturbing the harmony between the natural and created environment" [81]. It has already been shown that under the influence of modern globalisation, examples of traditional architecture are disappearing. Their preservation concerns the culture of a certain nation, but also the natural environment. That is why the combination of sustainable materials and architecture is necessary. However, a successful reconstruction of an old house in a village will not be achieved only by applying natural materials. The world is constantly changing, as well as people's needs. Living the way people lived 100 years ago is almost impossible due to the changes in the ideas of life. Therefore, preserving traditional heritage is a very difficult task. This research advocates that a successfully reconstructed country house cannot be achieved if the inherited models are not reworked, in the architectural sense, according to the principles of bioclimatic construction. Tradition means more than literal copying and memory. The architectural design of a country house in the stage of reconstruction according to the changed organisation of space is one of the most difficult tasks of contemporary architecture. It is possible to live without architecture, but with it, the memory of life is more pleasant [83].

5.2. Energy Simulations

According to TRNSYS energy simulation the use of insulation reduces the total required energy by almost 50% compared to a house without insulation. From the summation of the data obtained from this simulation, the sheep wool panel is the most thermally efficient. It is followed by hemp wool panels and finally the EPS panel. It is clear from the results that by applying natural materials, better thermal comfort of houses can be achieved. This statement is in line with the hypothesis.

The results of the energy analysis are in line with previous studies that have investigated the benefits of using natural materials in building (sheep [84] and hemp [85] wool) insulation. For example, a study by Bisegna et al. [86] analysed the energy and environmental performance of different insulation materials in a typical Italian residential building. The study found that natural materials, such as sheep wool, cork, and cellulose, provided better thermal insulation and had lower environmental impacts compared to synthetic materials.

Similarly, a study by Zach et al. [85] evaluated the energy and environmental performance of different insulation materials. Authors found that natural materials, such as sheep wool, had lower environmental impacts and provided better thermal insulation compared to synthetic materials. Within this research, the test results show that the thermal insulation from sheep wool has comparable characteristics with mineral/rock wool, and in some applications even performs better. Additionally, in comparison to mineral wool, sheep wool is more ecological and has fewer damaging health aspects.

The research of Braulio-Gonzalo et al. [87] revealed that sheep wool and recycled cotton, jointly with traditionally used mineral and glass wool, should be promoted in the construction industry as they offer the highest eco-efficient performance among the analysed insulation materials. In the same study, it was recommended that an additional effort be made to optimise the thickness of the insulation, for the sake of balance between energy and economic characteristics.

The results of the energy analysis are also in line with the statements exposed in Firfiris et al.'s study: the passive techniques and systems can reduce heat gains, the shading plays a major role on the cooling, the initial architecture design leads to energy conservation for cooling and the natural ventilation decreases the temperature levels in a building [88]. Similarly, a study by Fedorik et al. analysed the thermal characteristics of bio-based materials [89]. Properties of bio-based thermal insulations are comparable with conventional materials. Moreover, bio-based materials provide high thermal resistance and water vapor permeability. In a similar study, Korjenic et al. [85] used the evaluation of energy efficiency in buildings to show that the use of natural materials is completely comparable with convectional material development. Savic et al. concluded that natural thermal insulation displays substantial thermomechanical properties [90].

The results of these studies support the findings of the energy analysis presented in the paper on the renovation of a traditional house on Stara planina Mountain in Serbia, which concluded that natural materials, such as sheep wool and hemp wool, provide better thermal comfort and have a significantly more positive impact on the environment than synthetic materials, such as EPS.

Overall, these studies highlight the importance of using natural and locally sourced materials in building insulation to reduce the environmental impact of construction and improve energy efficiency. However, as these simulations were conducted using software, future research should be managed in situ, through real measurements.

5.3. LCA Simulations

The results of the LCA analysis provide important insights into the environmental impact of natural materials used in the renovation of traditional houses. The study compared three insulation materials, namely sheep's wool, hemp wool and EPS, in terms of their carbon footprint, total energy consumed, air acidification and water eutrophication. The results clearly show that natural materials, such as sheep and hemp wool, have a significantly lower environmental impact than artificial materials, such as EPS. The carbon footprint of sheep wool insulation was found to be 624.99 kg CO_{2e}, which is over 15 times lower than the carbon footprint of EPS insulation (9598.72 kg CO_{2e}). However, the insulation made of hemp wool has the smallest impact on the environment (117.49 kg CO_{2e}).

The findings of this study are consistent with previous research in the field of energy-efficient buildings made of ecologically acceptable materials. For example, Maodus et al. also found that natural materials have a lower environmental impact than artificial materials [8]. The study also suggests that future research should focus on collecting real data within the long-term monitoring of the consumption and energy performance of the analysed wall types. Their study also uses the LCA method for material analysis, with a focus on reducing the environmental impact of building construction. Furthermore, the paper mentions the need for collecting real data through long-term monitoring of energy consumption and efficiency in insulated buildings. This is consistent with the recommendations of Stazi [91], who proposed long-term monitoring and measurement of energy efficiency and environmental impact in sustainable building.

In addition, the paper emphasises the importance of using local and natural materials in sustainable building. This is in line with previous research that has analysed the ecological aspects of building, such as Cao et al. who analysed the use of natural materials in building as a way to reduce environmental impact [92].

Based on the results of this LCA analysis, the authors of this paper recommend the use of natural materials in the sustainable renovation of vernacular architecture in Serbia. By doing so, they argue, it is possible to reduce the impact of climate change and ensure that sustainable renovation is in accordance with modern architectural design and thermal comfort. Overall, this study provides important insights into the potential of natural materials in reducing the environmental impact of building renovation and highlights the importance of sustainable design principles in construction.

As hemp and sheep wool insulation have slightly weaker thermal properties (according to their thermal conductivity λ in W/mK), the same material thickness results in different thermal values (thermal transmittance U in W/m^{2}K). For the purposes of equalising the heat transfer coefficient, a different amount of material is needed (different insulation thickness), which is reflected in the LCA analysis for the use stage. As this research is set within the evaluation of the same amount of material, overcoming the limitations of this study is suggested for future research.

Based on this research, it can be said that sustainable reconstructions should use sustainable methods and materials in the processes of construction. Their realisation and subsequent use should have a neutral impact on the environment. Reconstruction which uses materials from the environment causes less environmental impact than materials transported from long distances. Using local products, such as wool from sheep and hemp, is an opportunity to connect ecology and the sustainability of the local economy. Currently, this type of insulation is not produced in Serbia, unlike the surrounding countries (Bosnia and Herzegovina, Bulgaria and Romania). The justification for starting such production is the fact that the area of Stara planina is suitable for livestock breeding, cheese production and sheep farming. On the other hand, hemp was widely used in the past, but under the influence of the use of modern artificial materials, its benefits were forgotten.

It was confirmed by the LCA approach that energy reduction is necessary for the reconstruction. Another condition is that the reconstructed building uses energy efficiently. The end of the building's life cycle and its demolition represents the final stage. The materials used should be easy to recycle, with minimal impact on the environment. It is familiar that hemp and sheep's wool can be used as fertiliser, from which it follows that there is reason to use the proposed materials in the process of sustainable reconstruction.

It can be concluded that the negative impact on the environment, while using hemp and sheep wool, is minimised.

Based on the presented data, the insulation panels made of EPS, hemp and sheep wool can be compared in the context of the reconstruction of rural architecture, taking into account the CO_2 footprint, environmental impact and prices. EPS panels are generally the most cost-effective insulation. Sheep wool panels are more expensive if they are not produced from the shearing sheep waste, grown in households as part of the family business. Hemp wool panels are in the middle price range. However, it is important to consider the long-term savings that can be associated with the use of sustainable and more durable materials.

Sheep wool panels are generally more expensive compared to hemp panels. This is because sheep's wool is a premium material that requires more processing and labour. In contrast, hemp is a more affordable material, as it is easier to grow and process. Production of sheep wool panels has a smaller carbon footprint compared to hemp panels. This is because sheep's wool is a natural material that requires less energy and resources to process and transport. In addition, sheep's wool is biodegradable and can decompose naturally, while hemp panels can release carbon dioxide during decomposition.

Hemp and sheep wool panels are sustainable materials with a low environmental impact. Hemp is a renewable and fast-growing crop that requires less water and pesticides compared to traditional crops. Sheep wool panels are made of a natural material that is biodegradable and recyclable. This makes them a more sustainable alternative to synthetic insulation materials. Sheep's wool is a local material that can be sourced from nearby farms, supporting the local economy and reducing transport emissions. EPS panels, on the other hand, are often produced in centralised factories and transported over long distances. Ultimately, the choice between these materials will depend on the specific needs of the rural architecture reconstruction project, including factors such as availability and cost.

In the end, the summary of the results proves that natural products, such as panels made of sheep and hemp wool, provide the necessary thermal comfort and have a significantly more positive impact on the environment than artificial materials. If the duration of renovating a traditional house is observed over a longer period of time, the cost of hemp and sheep wool panels becomes justified. With this conclusion, we have positively answered the initial hypothesis. Additionally, the use of these materials does not compromise the principles of architectural design within the theme of renovating a traditional house in Serbia, or the creative reworking of inherited building principles. The synthesis of the results (Figure 11) shows that the hemp wool panel is slightly superior to the sheep wool panel.

Based on this research, the principles for the renovation of rural houses on Stara planina are proposed with the following:

1. Use of local stone slabs in part of the roof covering (2.5 cm planks are first placed on the wooden structure, then 5 cm laths and 3 cm mud over them).
2. Timber-framed walls (2.5 cm boards, 15 cm wooden construction with mud filling, 2.5 cm boards) insulated from the outside using hemp or sheep's wool 10 cm.
3. Protect the insulation from the outside with reeds 1 cm, mud 2 cm and lime.
4. Treat the walls from the inside with mud or cover them with plasterboard.
5. Use the roof space for ventilation, not for living.
6. Keep the traditional geometry of the hip roof.

A future study could be related to the issue of building new tourist facilities that are connected to the redesign of the inherited architectural concept of rural houses and the use of green forms of energy.

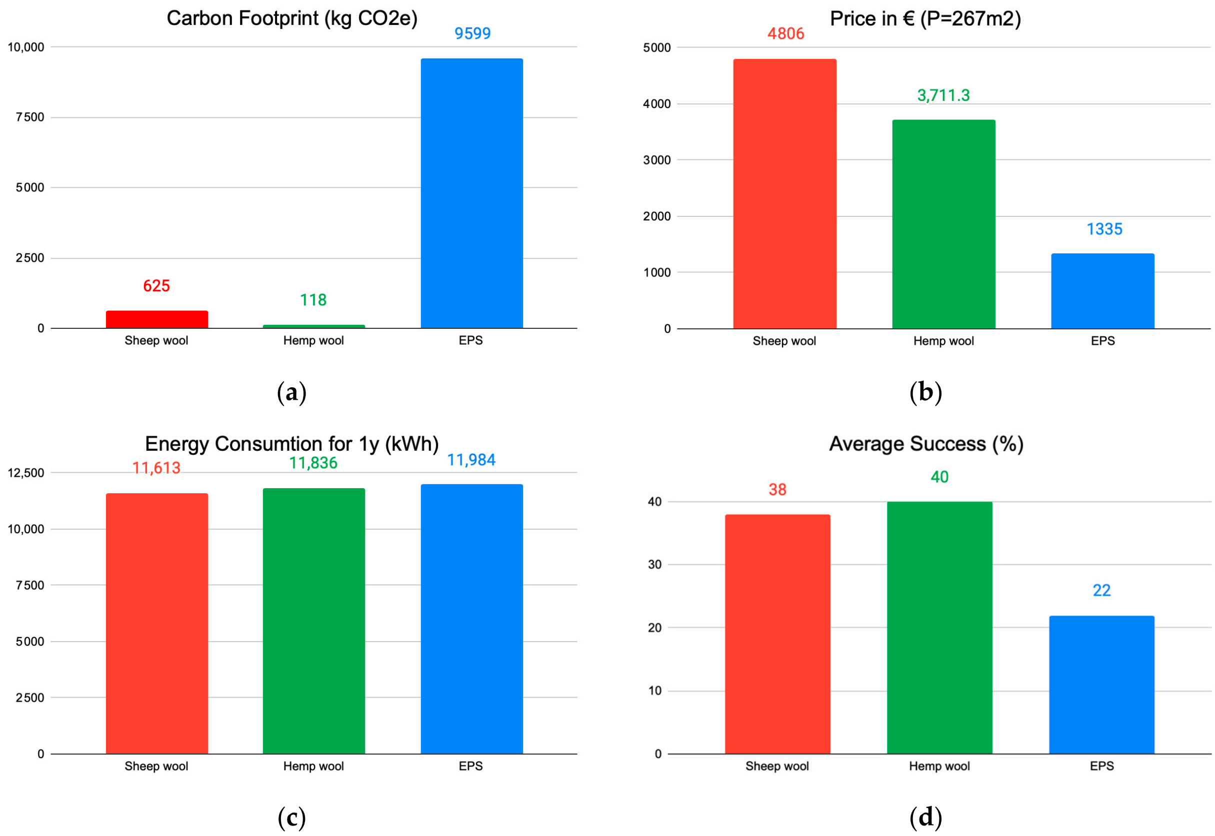


Figure 11. Synthesis of results: (**a**) Carbon Footprint, (**b**) Price, (**c**) Energy Consumption, (**d**) Average Success.

6. Conclusions

This paper analyses renovation of a typical mountain house in Stara planina (the Balkan Mountains) by means of the using three insulation materials (EPS, hemp and sheep's wool), according to sustainable construction. The aspiration towards the development of sustainable tourism in this area carries the risk that the villages on Stara planina in Serbia will completely lose their traditional architecture if the rules of reconstruction are not defined. At a time when living standards are increasing and there is a need for increased energy use, providing an adequate renovation model is a priority of the Government of the Republic of Serbia and the Ministry of Construction, Transport and Infrastructure. Ensuring quality and sustainable tourism in reconstructed facilities in the Stara planina Park in Serbia requires the cooperation between owners and designers, as well as the analysis of possible innovations and improvements.

The results of this research show that insulation made of hemp and sheep's wool is a slightly better choice than EPS. Although the difference in renovation scenarios in energy demands is not significant, better results are achieved using sheep wool as insulation, from an energy consumption perspective. This material's good environmental properties make it suitable for insulation in rural mountain areas where sheep are grown, promoting sustainable resource use. For countries such as Serbia, with a significant decline in livestock numbers in the last 20 years, production of sheep wool thermal insulation could help the livestock sector as well. In the end, hemp wool insulation represents the best choice, according to the average success realised by summarising the results of LCA analysis, energy analysis and price.

This evidence, derived through LCA and energy analysis, presents a compelling case in support of the affirmation of the circular economy concept. The use of natural materials is aligned with achieving sustainable development at a global level, without any compromise in the quality of life for people or a decrease in the profits of producers.

Consistent with innovative thinking in all production processes, the use of hemp and sheep's wool corresponds to prolonging the lifespan of products and their subsequent recycling. Although it was expected that natural materials would be suitable for the transition to a resource-efficient circular economy model, this has been demonstrated with concrete numbers through the research.

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