Article

Sustainable Modularity Approach to Facilities Development Based on Geothermal Energy Potential

Nataša Ćuković Ignjatović [1],* , **Ana Vranješ [2],*** , **Dušan Ignjatović [1]** , **Dejan Milenić [2]** and **Olivera Krunić [2]**

[1] University of Belgrade - Faculty of Architecture, 11000 Belgrade, Serbia; ignjatovic.dusan@arh.bg.ac.rs
[2] University of Belgrade - Faculty of Mining and Geology, 11000 Belgrade, Serbia; dejan.milenic@rgf.bg.ac.rs (D.M.); olivera.krunic@rgf.bg.ac.rs (O.K.)
* Correspondence: natasa@arh.bg.ac.rs (N.Ć.I.); ana.vranjes@rgf.bg.ac.rs (A.V.)

Abstract: The study presented in this paper assessed the multidisciplinary approach of geothermal potential in the area of the most southeastern part of the Pannonian basin, focused on resources utilization. This study aims to present a method for the cascade use of geothermal energy as a source of thermal energy for space heating and cooling and as a resource for balneological purposes. Two particular sites were selected—one in a natural environment; the other within a small settlement. Geothermal resources come from different types of reservoirs having different temperatures and chemical compositions. At the first site, a geothermal spring with a temperature of 20.5 °C is considered for heat pump utilization, while at the second site, a geothermal well with a temperature of 54 °C is suitable for direct use. The calculated thermal power, which can be obtained from geothermal energy is in the range of 300 to 950 kW. The development concept was proposed with an architectural design to enable sustainable energy efficient development of wellness and spa/medical facilities that can be supported by local authorities. The resulting energy heating needs for different scenarios were 16–105 kW, which can be met in full by the use of geothermal energy.

Keywords: geothermal energy; Pannonian basin; geothermal cascade use; energy efficiency; wellness and spa facilities; balneology; bioclimatic architecture; passive design strategies; modular building

1. Introduction

Geothermal energy is recognized as a valuable resource having a variety of uses: from electricity generation (through geothermal power plants or through cogeneration systems) [1] and space heating and cooling (using the heat pumps) to direct use in a wide range of applications in areas such as balneotherapy [2,3], agriculture, industry, swimming pool heating, and in individual and district heating systems [4,5]. While harnessing geothermal energy for electricity production is mainly related to specific tectonic regions, its direct use is more common. Coupling the energy potential with the healing properties of water's temperature and chemical composition, is recognized as a versatile and efficient way of exploiting this geothermal resources [6–9].

Hot water springs have been used for healing and medical recovery since ancient times. Today, however, balneology is undergoing a transition both concerning its place in formal medical science and as an asset for the development of tourism, local and state economies and general popular well-being. Contemporary definitions of medical tourism encompass medical travel, recreational travel and traveling for other purposes [10]. All of the stated aspects are highly relevant for balneotherapy, which, by its nature, can successfully meet a variety of their needs if provided with adequate infrastructure. Serbia is particularly rich in mineral, thermal and thermo-mineral waters with sites that have been in use ever since the Roman Empire [11]. The same hydrogeological resources show great potential as a convenient source of hydrogeothermal energy [12] that could be used to achieve high levels of energy efficiency in wellness and spa facilities. The Serbian province of Vojvodina, despite its abundance of various resources, is undergoing constant depopulation and even

impoverishment in certain agricultural areas. Although current national and regional planning documents barely consider geothermal energy to be a strategic resource [13,14], its great potential should be used as a tool for sustainable development, especially in areas where the abundance of this resource may help address the economic challenges and a decades-long trend of depopulation.

In recent times, comprehensive research has been carried out in northern Serbia—Vojvodina province—with the aim of considering and estimating the geothermal potential. The defined potential of geothermal resources represents a strategic foundation for planning sustainable economic development, since geothermal energy is an abundant source of renewable energy that requires low-carbon and non-intermediary technology [15,16]. A multidisciplinary research concept was applied, which tended to display, in a single place, the potential for geothermal resources to provide sustainable models for development supported by local municipalities. The areas for the application of geothermal energy were analyzed through an integrated approach of economic-commercial factors based on the main assumption of cascade use [17]. In that respect, among other things, an analysis of increasing the share of geothermal energy within the field of balneology was performed. Geothermal resources were observed both as a healing factor due to temperature and chemical composition and also as an energy source for heating and cooling facilities where geothermal waters are already used for medical and wellness purposes.

The studied terrain represents a typical basin structure genetically correlated to southeastern parts of the Pannonian basin, which extends over the territory that includes present-day Hungary, Croatia, Slovenia, Romania and Serbia, where it occupies terrain to the north of the Sava and Danube rivers (Figure 1) [18]. Generally speaking, the Pannonian basin represents an area that has an expressed geothermal anomaly and extraordinary geothermal potential [19,20]. The basin's highest heat flow values, above 100 mW/m^2, have been registered in the northeastern part and in the central part with distribution towards the southern peripheral parts, that is, towards the Serbian basins and the Vardar zone [21,22]. The values of geothermal gradients in the area of Vojvodina province range from 4.0 to 7.5 °C/100 m [23,24]. The dominant way of geothermal exploitation is via wells. The average geothermal outlet temperature ranges from 25 to 75 °C. In Vojvodina province, 50 new balneological facilities were proposed for development [25–27]. When defining prospective locations for them, wellness and spa, sports and recreation, and medical programs were all taken into account as was the urban-development potential for these facilities. These were also analyzed from the point of view of energy efficiency, different building material, energy independence, energy self-sustainability, and carbon footprint minimization.

The architectural programs, derived from the multidisciplinary research and conceived as illustrative proposals for potential developments on the site, range from modest drinking fountains to complex resorts with variety of facilities (Figure 2). Since 20 out of 50 proposals refer to wellness and spa facilities, they have remained in the spotlight of further investigations. Throughout the process, a series of model units was developed and tailored to match medical and therapeutical requirements bearing in mind the imperatives of environmental consciousness, sustainability and architectural resilience suited to the local municipalities' needs and resources. The two sites, Ljuba and Banatsko Veliko Selo, were chosen to further explore the proposed model in two different settings regarding the built-up environment and geothermal capacities. The study presented in the paper aims to point out the general design guidelines for development of wellness and spa/medical facilities that can be supported by local municipalities. The resulting proposals should help them gradually develop facilities for public or commercial use by relying primarily on their own resources rather than waiting for developers to exploit the balneological potential.
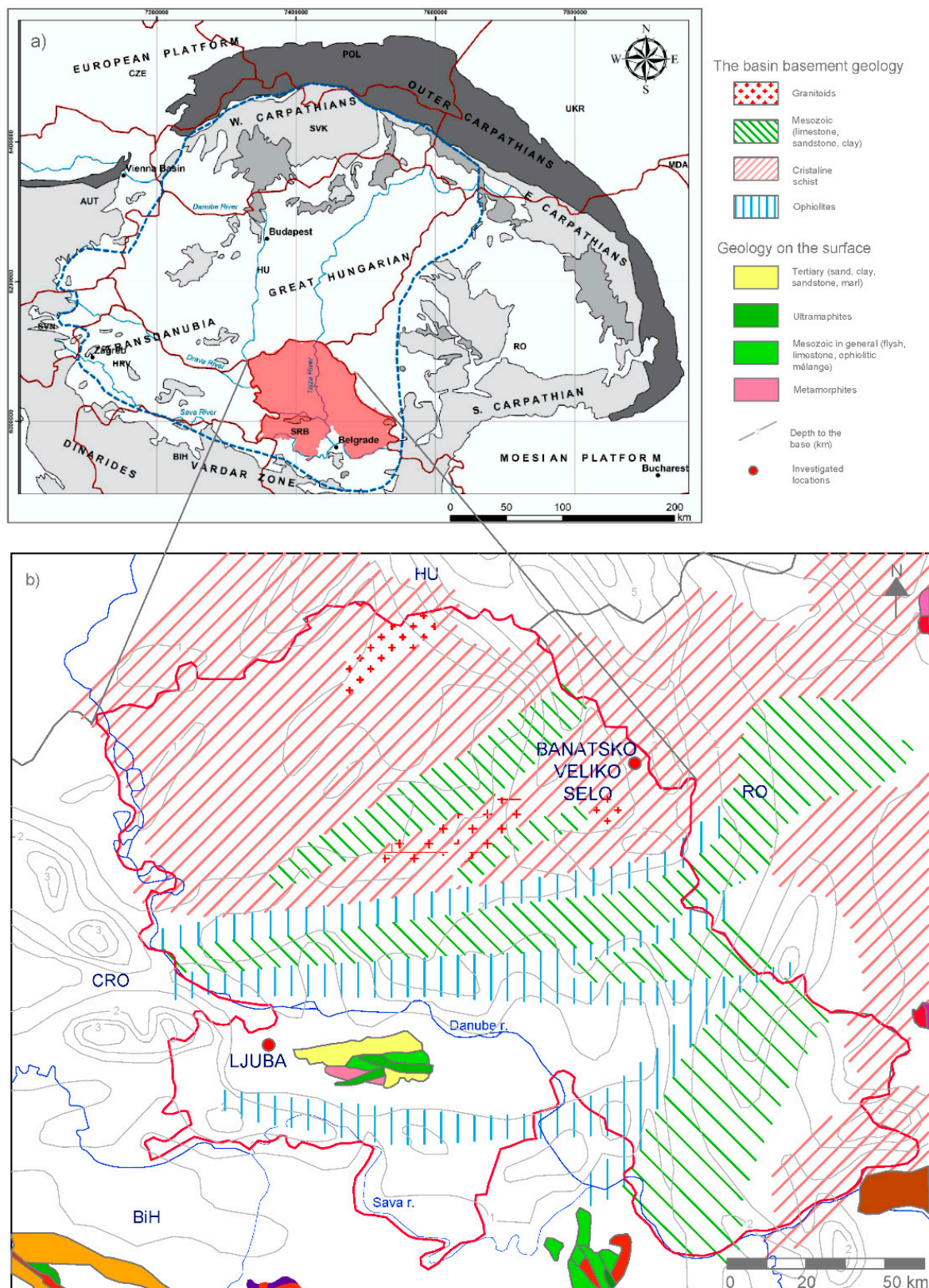
Figure 1. (**a**) Main tectonic units of the Alpine Fold Belt and Alpine–Carpathian–Dinaric Mountains (modified after [28]); (**b**) Geological map of the Vojvodina part of the Pannonian basin basement (modified after [29]).
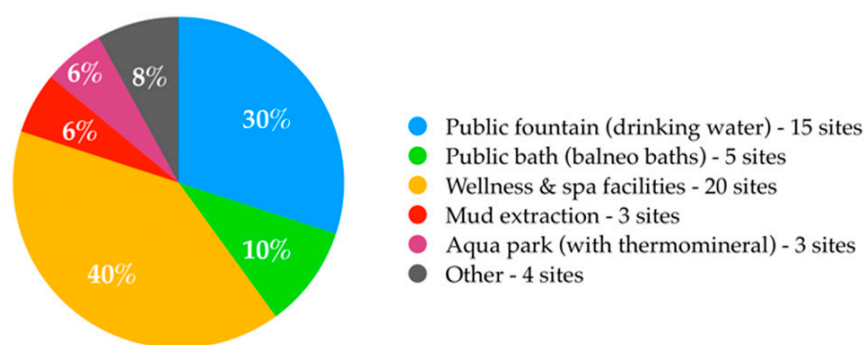
Figure 2. Proposed programs for new balneological sites in Vojvodina.

Since the design proposals referred to on-site use of the balneological resource, the character of the sites also varied greatly, from facilities placed within urban or rural settlements to sometimes rather remote places with poor or no infrastructure.

2. Materials and Methods

This paper shows two sites where geothermal resources were formed within different types of reservoirs, as well as with different temperatures and diverse chemical compositions. According to the features of these resources and spatial-urban conditions of the terrain, the manner of exploiting the resources and an architectural concept was suggested. The first site, Ljuba, is characterized by low-temperature geothermal water (<30 °C), which requires a geothermal heat pump (GHP) for heat production. The geothermal source is in the form of a spring, which is very rare for the basins. The reservoir is formed within Triassic limestone, and the water belongs to the HCO_3–Ca type as expected with this kind of reservoir. The uniqueness of this geothermal water may be seen from the chemical-specific composition of its microelements. From a water sample, a high concentration of arsenic was detected. The second location presented typical geothermal resources formed in basin sediments. The reservoir was formed within the sandy layers of the Pliocene epoch, with temperatures that ensure direct use (54 °C). The geothermal waters, produced by the geothermal well, belong to the HCO_3–Na type, and the main balneological factor is temperature. The available thermal power from the geothermal resource was calculated for both sites, along with setting the cascade system concept. Simultaneously, the architectural concept was developed, matching energy availability according to the concept of modularity.

2.1. Architectural Model—Design Premises

Design premises were in line with UN sustainability goals [30], where sustainable and resilient architecture for healthcare and spa facilities was conceived as the driver for a circular economy and improved well-being of the local population. The design approach was tailored with regard to the urban environment, the facility's current development status, need for (and availability of) accommodation, and seasonal sensitivity. The study of such a size was also seen as an opportunity to explore options for "branding" the wellness and spa/medical facilities of Vojvodina through recognizable design features.

The urban context was classified as "town" for sites within small urban settlements, "village" for those within rural settlements, and "remote" for those the farthest away from existing settlements (Figure 3). The fact that remote sites have no infrastructure and the ones in the villages are often poorly equipped stressed the necessity of providing a high level of infrastructure independence.

Figure 3. Number of proposed wellness and spa/medical facilities regarding urban/rural context.

The majority of proposed facilities (13 out of 20, Figure 4) were supposed to be completely new developments, while 7 cases were supposed to offer additional content mainly to partly developed outdoor facilities (usually pools, baths or ponds). In almost all cases, small scale structures were more suitable than conventional buildings that had all utilities in a single volume (Figure 5).

Figure 4. Number of proposed new developments and complementary contents that are adjacent to already existing wellness and spa or leisure facilities.

Figure 5. (**a**) Ljuba—currently an undeveloped site although used in Roman era; (**b**), Banatsko Veliko Selo—paths to outdoor pools (**c**,**d**) Banatsko Veliko Selo—outdoor swimming pool (existing facility).

The need to provide accommodation directly associated with the exploitation of balneological resource varied (Figure 6a). In 7 cases there was already accommodation in the vicinity (usually within walking distance); in 7 cases accommodation was not necessary due to the location and the nature of the balneological resource; and in 6 cases some accommodation had to be provided within the new development. This led the team to

explore flexible design concepts where accommodation would be an optional feature rather than placing all functions within a single volume. While allowing gradual development in pace with the local municipality's strategies and investment capability, this approach also provided more options for public use, which is of great importance to the community, giving the locals easier access to the wellness and spa/medical facilities.
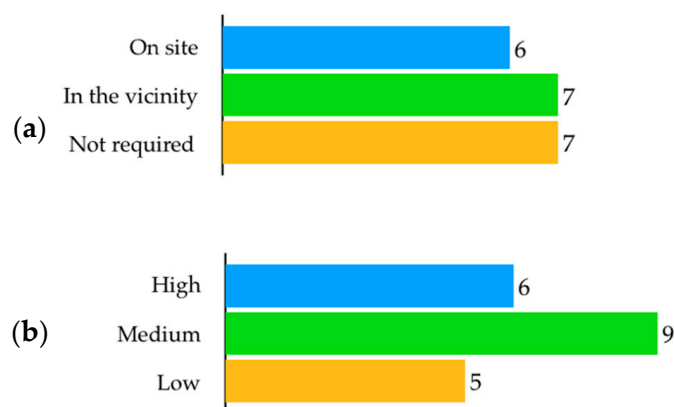

Figure 6. Number of proposed wellness and spa/medical facilities regarding (**a**) the need for and availability of accommodation, and (**b**) seasonal sensitivity.

The nature of the resource along with the site and the expected modes of use reflect the facility's "seasonal sensitivity" (Figure 6b). Most developments show medium seasonal sensitivity, which means that they can operate year-round in but with greater variation in capacity, while the ones with low seasonal sensitivity show less oscillation in seasonal use. In both cases, more demand on weekends than on weekdays can be expected. The modular approach presented in this paper addresses the issues of flexibility in the use of certain features and mitigation of operating costs for periods of lower demand. High seasonal sensitivity implies that the facility may operate only during the summer, so providing thermal comfort and natural ventilation on warmer days while staying in direct contact with the environment was dominant.

Climate in Vojvodina is classified as warm temperate, predominantly Cfa with areas of Cfb according to the Köppen–Geiger system. Month-to-month weather data for Vojvodina (Table 1) indicates that for 6 to 7 months some additional heating is needed while cooling might be needed for certain periods during the summer.

Table 1. Weather data for Vojvodina [31].

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	0.8	2.5	7.4	13.2	18	21.9	23.9	23.9	18.6	13.2	7.9	2.2
Min. Temperature (°C)	−2.3	−1.4	2.5	7.9	12.6	16.5	18.5	18.5	14	9	4.6	−0.6
Max. Temperature (°C)	4.3	6.7	12.4	18.2	23	26.7	28.7	28.9	23.4	17.9	11.8	5.4
Precipitation/Rainfall (mm)	43	43	46	60	67	75	64	56	55	49	50	53
Humidity (%)	80	76	69	63	63	61	58	57	64	71	77	81
Rainy days (d)	6	6	6	8	8	9	7	6	6	6	6	7

The issues of sustainability and resilience were addressed on several levels:

- program—defined to be sensitive to local needs and capacities, conceived for gradual development (reflected on various design aspects);
- adaptive capacities—aimed at enabling year-round functioning bearing in mind seasonal changes as well as prospective changes (anticipated and unexpected) throughout the facility's lifespan;
- infrastructure independence—aimed at off-grid functionality, especially for the remote sites;
- carbon footprint—aimed at carbon-neutral developments;

- local production—supported by the choice of proposed building technology and materials.

While resource efficiency in material use with reference to the 3R (reduce, reuse, recycle) concept remained as a general design goal, specific design strategies were proposed for energy efficiency, stressing the impact of architectural design on minimizing demand, thereby enabling coverage from on-site (renewable) energy sources. Program-specific energy efficiency design strategies focused on a wide range of passive design measures that integrated the technology related to necessary active systems from the conceptual design phase.

Water management in these facilities is very dependent on water composition, flow and temperature yet needs to be treated with extreme delicacy case be case to preserve the unique hydrogeological characteristics. All proposals were designed with extreme care to maximize porous surfaces, minimize potential contamination of surface water, and to make recommendations for rainwater collection and use where appropriate.

Design goals were addressed through a variety of design strategies, which were applied to 20 sites with wellness and spa facilities that ranged in size from small mobile units for balneotherapy to complex multifunctional developments. The main design strategies, developed mainly based on bioclimatic architecture, [32] included

- modularity,
- sizing and positioning of open-air and indoor features,
- passive design, and
- use of on-site renewable energy sources.

The general concept was developed with south-facing wellness and spa/medical units and corresponding utility spaces in the centre with optional additions of hospitality and medical facilities (Figure 7). However, adjacent medical and hospitality facilities might be planned with program-specific design strategies, so they were not further discussed in detail at this stage of the research.
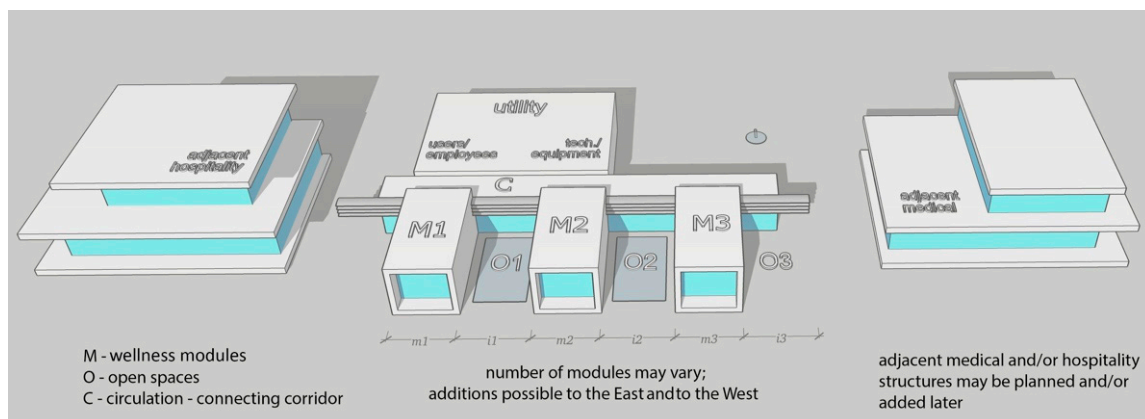

Figure 7. Model for modular wellness facilities with optional hospitality and medical facilities.

2.2. Architectural Model—Boundary Conditions and Calculation Methodology

Following the principles of modular design, modules of the same footprint (5.5 × 10 m) were used for both wellness and spa/medical facilities and utility spaces (heated and unheated). To enhance functionality and energy efficiency of the study model, balneotherapy units were grouped in pairs with a small joint space to access interior and exterior facilities. Heated auxiliary spaces were designed as combinations of 2–4 modules, while unheated modules may be placed along the northern side of the connecting corridor in a manner that enables efficient service and easy access. Figure 8 presents three development stages.
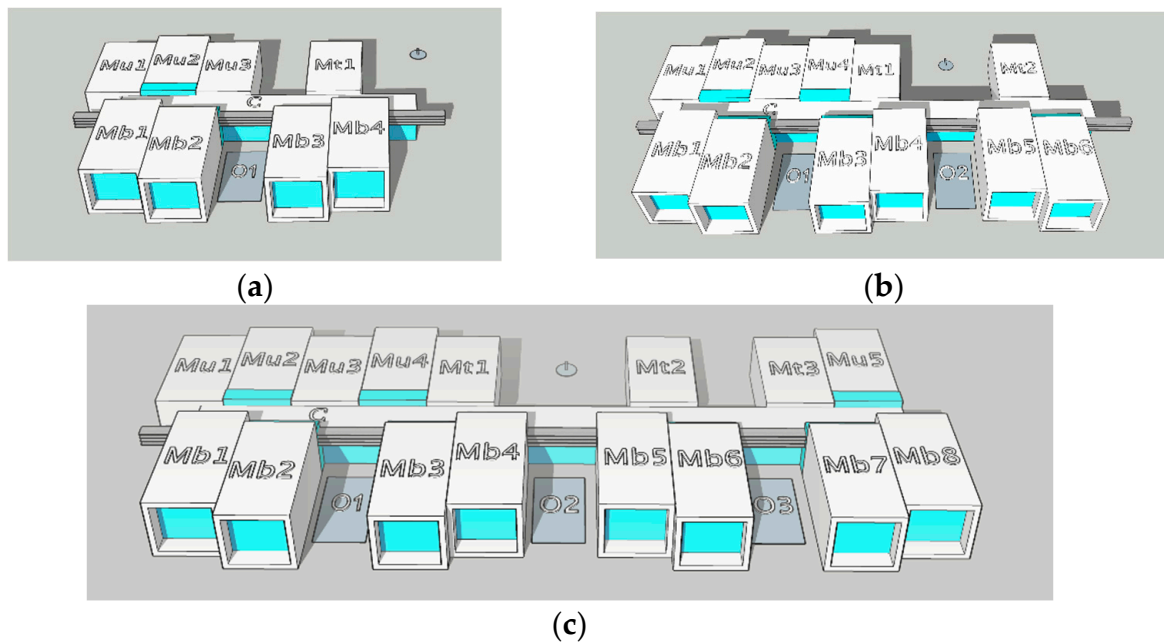
Figure 8. Three development stages for balneotherapy facility: (**a**) Stage 1 with 4 balneotherapy units, (**b**) Stage 2 with 6 balneotherapy units, and (**c**) Stage 3 with 8 balneotherapy units.

(1)   an initial stage, with a small number of units and basic utility spaces (475 m^2, 2 × 2 units for balneotherapy);

(2)   an intermediate stage, conceived as an extension of the initial stage (737 m^2, 3 × 2 units for balneotherapy), and

(3)   high-capacity stage, (988 m^2, 4 × 2 units for balneotherapy).

Stage 1 (Figure 8a) comprises of 4 balneotherapy units *Mb1–Mb4* with 3 additional utility modules *Mu1–Mu3* for reception, changing rooms, office, examination room and café, and an unheated module *Mt1* as the mechanical room. Stage 2 (Figure 8b) is conceived as an expansion of Stage 1 with 2 added balneotherapy units *Mb5–Mb6*, an additional utility module *Mu4* and an additional technical module *Mt2*. The third stage (Figure 8c) presents a further extension with balneotherapy modules *Mb7–Mb8*, additional utility module *Mu5* and technical module *Mt3*. An overview of the basic data for all three stages is given in Table 2.
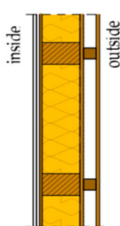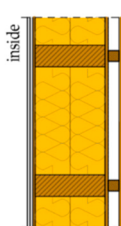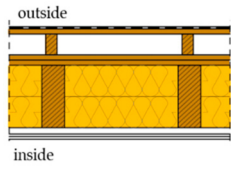
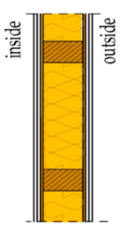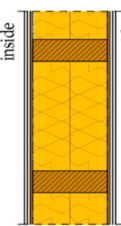**Table 2.** Development stages—an overview of basic data.
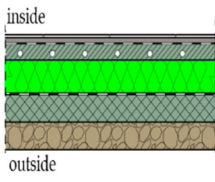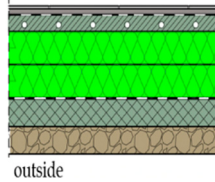
Development Stage	Balneo Units (Heated)		Utility Units (Heated)		Utility Units (Unheated)		Intermediate (Heated)		Corridor (Heated)	Net Heated Area	Total Useful Area
	pcs.	(m^2)	pcs.	(m^2)	pcs.	(m^2)	pcs.	(m^2)	(m^2)	(m^2)	(m^2)
1. Initial phase	4	220	3	165	1	55	2	17	18	420	475
2. Extended	6	330	4	220	2	110	4	34	43	627	737
3. High capacity	8	440	5	275	3	165	7	59	49	823	988

In terms of energy performance, two different approaches to building the thermal envelope were explored:

(a)   base case, designed to comply with national regulations—EPC class C structure, with all envelope components meeting the mandatory *U*-values (thermal transmittance coefficient) thresholds; and

(b)   enhanced performance case, with *U*-values of thermal envelope components designed in accordance with Passive House standards.

The thermal envelope components and their *U*-values are presented in Table 3.

Table 3. Thermal envelope components.

Component	U_{max} [W/(m² × K)] National [1]	EnerPHit [2]	Base Case	Enhanced Case
External wall	0.3	0.15	$U = 0.294$ W/(m² × K) gypsum board 1.25 cm; gypsum board 1.25 cm; wood particle board 1 cm; vapor barrier –; insulation/wood 50/10cm 15 cm; wood particle board 1 cm; rainscreen –; air 5 cm; wood cladding 1.8 cm	$U = 0.148$ W/(m² × K) gypsum board 1.25 cm; gypsum board 1.25 cm; wood particle board 1 cm; vapor barrier –; insulation/wood 50/10cm 32 cm; wood particle board 1 cm; rainscreen –; air 5 cm; wood cladding 1.8 cm
Flat roof above heated space	0.15	0.15	$U = 0.148$ W/(m² × K) hydroinsulation (membrane) 1.25 cm; wood particle board 2.5 cm; air layer / wood 10 cm; wood particle board 2.5 cm; wood particle board 2.5 cm; insulation / wood 50/10cm 30 cmn; vapor barrier –; air layer / wood 3 cm; gypsum board 1.25 cm; gypsum board 1.25 cm	
Windows, balcony doors to heated areas	1.5	0.85	$U = 1.5$ W/(m² × K) Aluminium frame with enhanced thermal break, Low-e double glazing with krypton gas filling *Fx* = 1 solar factor *g* = 0.4 frame factor *ff* = 0.25	$U = 0.85$ W/(m² × K) Aluminium frame with enhanced thermal break, Low-e triple glazing with krypton gas filling *Fx* = 1 solar factor *g* = 0.35 frame factor *ff* = 0.25
Glass roofs	1.5	1.1	$U = 1.50$ W/(m² × K) Aluminium frame with enhanced thermal break, Low-e double glazing with krypton gas filling *Fx* = 1 solar factor *g* = 0.4 frame factor *ff* = 0.25	$U = 1.1$ W/(m² × K) Aluminium frame with enhanced thermal break, Low-e triple glazing with krypton gas filling *Fx* = 1 solar factor *g* = 0.35 frame factor *ff* = 0.25
Wall to unheated space	0.4	0.35	$U = 0.278$ W/(m² × K) gypsum board 1.25 cm; gypsum board 1.25 cm; wood particle board 1 cm; vapor barrier –; insulation/wood 50/10cm 15 cm; wood particle board 1 cm; gypsum board 1.25 cm; gypsum board 1.25 cm	$U = 0.144$ W/(m² × K) gypsum board 1.25 cm; gypsum board 1.25 cm; wood particle board 1 cm; vapor barrier –; insulation/wood 50/10cm 32 cm; wood particle board 1 cm; gypsum board 1.25 cm; gypsum board 1.25 cm
Floor on the ground	0.35		$U = 0.280$ W/(m² × K) ceramic tiles 1 cm; adhesive 1 cm; membrane 0.2 cm; screed / floor heating 6 cm; insulation XPS 12 cm; hydroinsulation 1 cm; concrete 10 cm; gravel 10 cm	$U = 0.149$ W/(m² × K) ceramic tiles 1 cm; adhesive 1 cm; hydroinsulation 0.2 cm; screed / floor heating 6 cm; insulation XPS 24 cm; hydroinsulation 1 cm; concrete 10 cm; gravel 10 cm

[1] Values defined for new construction in national Rulebook on energy efficiency of buildings [33]. [2] Values defined for cool-temperate climate in Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard [34].

For all six scenarios, energy needs were calculated in accordance with national legislation [33,35], which is based on the methodology defined by EN-ISO13790. All calculations regarding the annual energy needed for heating were done using the software *KnaufTerm2s v.27.20* [36] using the following calculation parameters:

- Linear thermal bridges $\sum A \times 0.1$ W/(m^{2}K)
- Air exchange rate—infiltration 0.5 n
- Indoor temperature—winter 22 °C
- Indoor temperature—summer 26 °C
- Occupancy—surface per person (all regimes) 30 m^2/pers
- Metabolic heat emission per person 80 W/pers
- Metabolic heat emission per m2 2.7 W/m^2
- Dissipated heat from appliances 30 W/m^2
- Fresh air flow per surface area 1 (m^3/h)/m^2
- Fresh air flow per person 30 (m^3/h)/pers
- Heat gain utilization factor for the heating period $\eta_{H,gn} = 0.9$ (value for lightweight construction)

Maximum values for annual energy needs for heating for relevant building categories are shown in Table 4.

Table 4. Maximum values for annual energy needs for heating for mandatory EPC class C [35].

Building Category	$Q_{H,an}$ [kWh/m^2]
Healthcare and social welfare	100
Tourism and hospitality	90
Sport and recreation	80

Energy demands were compared to the resource capacity for two sites in Vojvodina: Ljuba, a remote location with no available infrastructure, and Banatsko Veliko Selo, a settlement with a population of 2525 [37]. Here, the proposed structure should be placed adjacent to an existing outdoor swimming pool.

Complementary structures for hospitality and healthcare services were not considered in the study since the focus was on investigating innovative design approaches for wellness and spa/medical facilities, such as wellness and spa and public baths. In regard to estimating overall potential use of geothermal energy for heating, an approximation was made using current national regulations (estimated energy needs according to the EPC mandatory class C).

2.3. Geothermal Potential—Geological and Geothermal Conditions

Generally speaking, in the lithological structure of the Pannonian basin, one can clearly observe two massive lithological complexes: (1) The basin's Palaeozoic–Mesozoic bedrock and (2) the Neogene–Quaternary complex and the related two main types of geothermal reservoirs: fractured and karstified basement reservoirs, and sand/sandy-clay basin-fill reservoirs. The bedrock of the basin in a wider study area is represented by all types of rock: metamorphic, igneous and sedimentary, whereas the Neogene-Quaternary complex is represented by conglomerates, sandstones, clay stones, marl, alevrolites, clay sediments, sands and pebbles (Figure 1). The rocks of the basin bedrock were discovered on the surface of the terrain in the zone of the Fruska Gora horst.

The site of Ljuba is located in the southwestern part of Vojvodina province on the southern slopes of the Fruska Gora horst. The horst structure, extending east–west on its southern and northern sides, is controlled by gravity faults, along which blocks were downthrown in the Neogene period [38]. On Fruska Gora three outcropping domains can be distinguished: (1) a metamorphic core from the Palaeozoic era, (2) a clastic–carbonate sequence with intercalated ophiolites, ophiolitic mélange, and volcanics of the Upper

Permian–Paleogene period, and (3) Miocene–Quaternary sediments [39]. Palaeozoic metamorphites are in tectonic contact with low- and middle-Triassic rock [40].

In terms of its geothermal features, this part of the terrain is characterized by high geothermal gradients, particularly on the edges of Fruska Gora. These values range from 6 to 7.5 °C/100 m. Geothermal basement reservoir discharge is carried out in two ways: predominantly via deep geothermal wells or in a natural way over the springs. The natural discharge is connected only to the terrain of Fruska Gora, where it takes place along fault-line structures and at the contact point of water-permeable and water-resistant rocks. The outlet temperatures of geothermal waters formed within this type of reservoir in the vicinity of Fruska Gora vary from 15 to 60 °C. At the study site, geothermal resources were formed within the dolomite and partially silicified Triassic limestone.

The site of Banatsko Veliko Selo is located in the northeastern part of Vojvodina province and is known for largest depths to the basin bedrock, which has the largest thickness of Neogene sediments. The terrain belongs to the area of intensive sinking (Great Hungarian Depression) from the Neogene period. This area is characterized by block structure and gravitational faults. In this part of the terrain, there is a dominant exploitation of geothermal waters formed within the basin-fill reservoirs. The Geothermal reservoir is represented by sands and sandstones of the Pliocene and Upper Pontian age and this kind of reservoir can be followed continuously over the whole area.

In this part of the terrain, relatively low of geothermal gradients were registered. The reason is the presence of very thick Neogene sediment (up to 3.5 km), overlaying magmatite and metamorphic rock. The correlation between low geothermal gradients and geological settings of this area can also be found in the existence of marly and silty layers at depths greater than 1000 m. Geothermal gradients measured in Pliocene sediment displayed very low values from 2.5 °C/100 m to 3 °C/100 m. Basin-fill reservoir discharge is performed exclusively via geothermal wells, whereas outlet temperatures do not exceed 60 °C. Geothermal waters, from the Pliocene and Upper Pontian belong to the HCO_3–Na–Cl water type, respectively to HCO_3–Na type and are characterized by relatively low mineralization (up to ≈8 g/L). As for gases, the dominant one is methane with 84–88 mol%, followed by nitrogen and CO_2.

2.4. Geothermal Potential—Calculation Methodology

Available thermal power from the geothermal resource is calculated based on geothermal conditions at the sites along with the cascade method of usage. The geothermal resource is considered as a source of energy for providing heat for facilities and balenological purposes. This principle led to the three limiting parameters for the system:

- temperature stability,
- available resource quantity,
- and chemical composition

The possibility of geothermal energy application depends on fluid temperature. The two selected locations covering the whole range of geothermal heating purposes. The Ljuba site comes with hydrogeothermal resources accumulated in the groundwater of a temperature scope to 30 °C which is conditioned by the application of geothermal heat pumps [41], while Veliko Banatsko Selo comes with hydrogeothermal resources accumulated in the groundwater of temperature above 30 °C, which means direct use is possible. Therefore, the heating operating system on the Ljuba site is considered to be an open loop GHP system contrary to the passive geothermal system with heat exchanger at the Banatsko Veliko Selo site.

The thermal power availability for the both geothermal sites can be calculated as in Equation (1)

$$E = H \times Q \times \Delta T \tag{1}$$

where E is the nominal available power quantity (kW); H the specific heat of water (constant, 4.2 kJ/kg/°C); Q the yield of the source (kg/s, for water the same as l/s); and ΔT denotes the temperature difference between the entering water and the leaving water.

Geothermal systems on the both sites perform heating operations and must be able to cover the maximum thermal load demands. The physical and chemical characteristics have been analyzed simultaneously to define the method for balneological use (drinking, swimming, inhalation). Furthermore, the concept of the geothermal heating system is conditioned by the method of balneological application. For example, drinking does not consider temperature, but swimming does, which means a projected geothermal system must satisfy these conditions.

In order to provide relevant data for calculations, a geological/hydrogeological reconnaissance was carried out, followed by groundwater parameters regime monitoring (temperature, chemical composition, flow capacity). For the purpose of geothermal water and reservoir characterization, the D'Amore method and diagram was applied [42]. The method is based on the determination of six main genetic parameters, mainly based on cation–anion ratios. Calculated genetic parameters are in line with geothermal reservoir geology and are applied for both sites, Ljuba and Banatsko Veliko Selo. Geothermal investigations and monitoring last for 12 months.

3. Results and Discussion

The concept of a multidisciplinary approach to geothermal energy utilization has been justified by building modular wellness facilities. The calculated thermal power that can be obtained from geothermal energy is in the range of 300 kW (GHP) to 950 kW (direct use). The size of wellness facilities can be predicted by matching developed scenarios based on different standards for envelope U values and outside temperature in modular facilities with available geothermal energy. The results of the investigation on geothermal waters showed that resources can be used as a balneological resource as well. Two factors determine multipurpose usage: chemical composition, in the case of the first site, and increased temperature, in the case of the second location. The direct benefit is increased efficiency of the geothermal cascade systems.

### 3.1. Available Thermal Power and Potential Balneological Utilization

3.1.1. The Site of Ljuba

The yield of geothermal waters at the discharge site is changeable, and its average value equals Q = 4.5 L/s. Geothermal resources at the site of Ljuba can be classified as sub-geothermal [43] since the temperature is 20.5 °C. According to their chemical composition, groundwater belongs to the HCO_3–Ca water type with low mineralization.

Table 5 shows basic physical–chemical values of the analyzed geothermal phenomenon. Taking into account the complex geological composition of the terrain and its active tectonics, what was carried out is the classification of geothermal water using the method of D'Amore's genetic parameters. According to the calculations of genetic parameters, geothermal water on the Ljuba site belong to the carbonated type, and this confirmed that the primary geothermal reservoir was formed in the Triassic rocks of the basin bedrock (Figure 9).

Table 5. Physical-chemical features of geothermal waters on the site of Ljuba.

T	Conductivity	pH	Na	K	Ca	Mg	HCO$_3$	SO$_4$
(°C)	(μS/cm)		mg/L	mg/L	mg/l	mg/L	mg/L	mg/L
20.5	850	7.2	20.5	2.7	102.9	39.9	495.8	26.5
Cl	**Fe**	**Mn**	**F**	**Al**	**As**	**Cu**	**Zn**	**Cr**
mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	mg/L	mg/L	mg/L
14.4	<0.1	<0.02	0.276	<0.05	47.6	<0.05	<0.03	<0.01
Cd	**Ni**	**Pb**	**Se**	**Si**	**Hg**	**Sr**	**Li**	**H$_2$SiO$_3$**
mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	mg/L	mg/L	mg/L
<0.002	<0.02	<0.01	<0.002	5.6	<0.5	0.77	<0.04	15.6
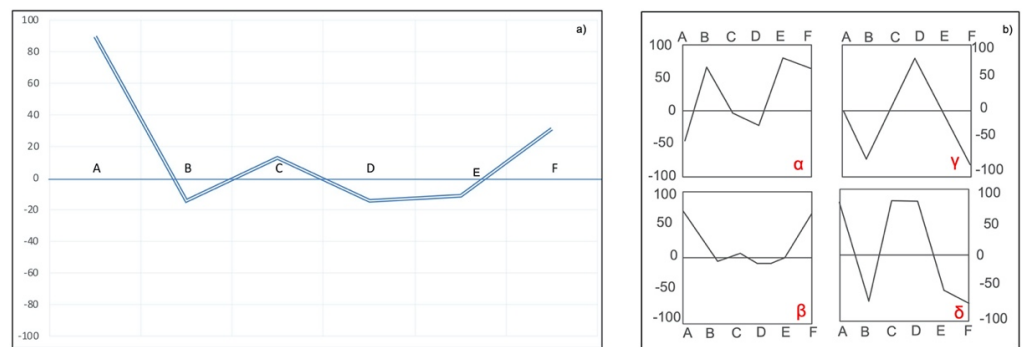
Legend for Figure 9a: A—indicates that geothermal waters had circulated through a calcareous terrains rather than an evaporative one; B—indicates that the geothermal water is enriched by sodium and may come from sedimentary terrains; C—is low, which excludes water deriving from a flysch, volcanite or schistose basement; D—indicates water circulation through dolomite; E—indicates that geothermal water had circulated in a carbonated reservoir rather than in a sulfated one; F—no indication in growth of potassium content, which excludes possible circulation in granitic field.

Figure 9. (**a**) D'Amore parameters diagram of chemical analyses; (**b**) α: evaporative terrains; β circulation in limestone; γ: circulation through a crystalline basement; δ: circulation in argillaceous rocks.

Available thermal power from the geothermal resource at the Ljuba site is calculated for the following scenario:

- open-loop geothermal heat pump system
- covering peak-load demands
- first cascade stage (temperature reduction for heating)
- second cascade stage (balneological purposes but not bathing)
- temperature reduction, ΔT = 16 °C. This temperature reduction, which we obtained from the resource temperature of 20.5 °C, was taken to calculate the total available thermal power on the site. In that case, the leaving water temperature was near 4 °C, reaching the highest liquid density.

In accordance with Equation (1) the available thermal power was:

$$E = 4.2 \text{ kJ/kg/°C} 4.5 \text{ l/s} \times 16°C$$

which generates around 300 kW of thermal power available for use.

Geothermal waters on the Ljuba site, apart from their energy significance, also possess a healing importance, so they can be used for balneological purposes as well. On the basis of their physical–chemical characteristics, these are characterized as natural, hypothermal, arsenic oligomineral waters, which can be used for health purposes under medical surveillance.

3.1.2. The Site of Banatsko Veliko Selo

At the site of Banatsko Veliko Selo, two geothermal wells were drilled: VS-1/H (925 m) and VS-2/H (895 m). The maximum measured outlet temperature was 43 °C at VS-1/H and 54 °C at VS-2/H. The yield of the VS-1/H well equaled 10 l/s, whereas the VS-2/H well had a somewhat higher yield of 12 L/s. According to the temperature values, geothermal resources at Banatsko Veliko Selo could be categorized as geothermal resources with low enthalpy, and according to their chemical composition belong to the HCO_3–Na water type. Table 6 shows the basic physical–chemical values of geothermal waters sampled from the borehole VS-2/H. Applying the method of D'Amore's genetic parameters, geothermal waters at Banatsko Veliko Selo belong to the clastic water type, and this confirmed that the primary geothermal reservoir was formed within the sands of Pliocene epoch (Figure 10).

Table 6. Physical-chemical features of geothermal waters VS-2/H.

T	TDS	pH	Na	K	Ca	Mg	HCO$_3$	SO$_4$	Cl
(°C)	(mg/L)		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
54	219	7.6	478.5	4.0	12.0	11.0	1415.2	14.0	12.0
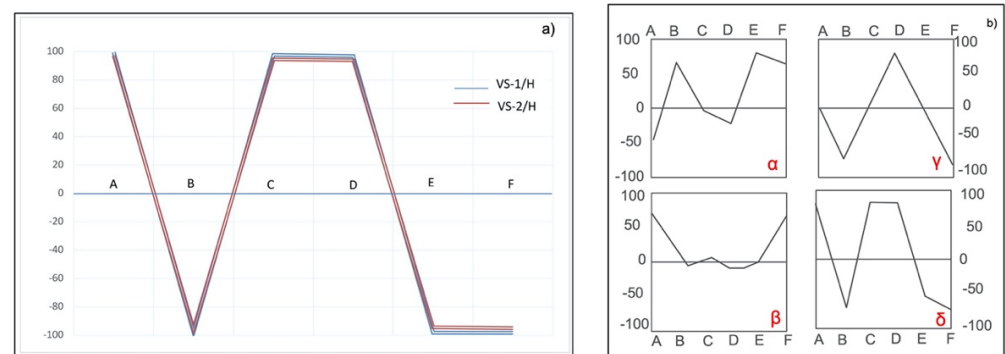
Legend for Figure 10a: A—indicates that geothermal waters had circulated through calcareous terrain rather than an evaporative one; B—indicates that this geothermal water, highly rich in sodium, may have come from sedimentary terrain; C—indicates that the geothermal water may have circulated through flysch sediments; D—excludes water circulations through dolomite; E—indicates the geothermal water had circulated in a sulfated reservoir rather than a carbonated reservoir; F—indicates no in growth of potassium content, which excludes possible circulation in a granitic field

Figure 10. (**a**) D'Amore parameters diagram of chemical analyses from Table 3; (**b**) α: evaporative terrains; β circulation in limestone; γ: circulation through a crystalline basement; δ: circulation in argillaceous rocks.

Available thermal power from the geothermal resource at B.V. Selo (VS-2/H) site is calculated for the following scenario:

- passive geothermal system with plate heat exchanger
- covering peak-load demands
- first cascade stage (temperature reduction for heating)
- second cascade stage (for balneological purposes, for bathing)
- temperature reduction, $\Delta T = 19$ °C, which is adopted to meet temperature conditions for bathing (35 °C).

The calculation of disposable thermal energy from the geothermal borehole VS-2/H was performed according to the Equation (1).

$$E = 4.2 \text{ kJ/kg/°C} \times 12 \text{ l/s} \times 19°C$$

which brought around 950 kW of thermal power.

The first cascade level of exploitation provided energy for facilities heating, and the second level was provided a warm bath for balneological purposes. After geothermal waters pass through the heat exchanger, what remained disposable was water at 12 L/s at 35 °C, which is the most frequent temperature of healing waters used for curative purposes.

3.2. Architectural Design

Architectural design (general layout, massing, orientation, thermal zoning and materialization) was developed through a holistic approach and the consistent application of the design principles described in "Methodology". The result was a model for developing wellness and spa facilities, as well as public baths that were applicable at various sites and satisfied site conditions, sustainability goals and development scenarios.

3.2.1. Modularity

Structuring the program into modular units proved to be a very powerful and effective design tool for accomplishing the several design goals set for this study. While easily enabling programmatic diversification and flexibility, the modular approach also opened the door for local production of prefabricated elements by small and medium enterprises.

Carefully planned and positioned modules allowed for phase execution, which significantly reduced initial construction costs. This is even more important when the local community is funding or co-funding the facility since the median value of overall costs for 20 proposals included in the study (excluding the land, which is already publicly owned) is estimated to be approximately 1,500,000 euros. Only two of them were designed as single multifunctional buildings (total area 300 m^2 and 1000 m^2) due to the specific site and programmatic conditions.

Interconnected modules, which can be individually included or excluded from the facility's current operation, allow for very economical operation in reduced capacity as well, which is very important, having in mind that 15 out 20 facilities were characterized as being significantly seasonal, meaning that with this concept all of them may remain open to the public year round with optimized operational costs.

The modular approach, which visually and functionally brings together nearly isolated open-door and enclosed spaces (Figure 11), provides a layout with a high level of privacy, which minimizes contact among users of different treatments while allowing optimal hygiene and maintenance intervals during operating hours.

Figure 11. Visualization of proposed model for wellness and spa facilities.

The modular design also permits capacity expansion beyond the initial plans while retaining original design features or remaining at a reduced number of constructed modules for long periods in case of unfavourable economic, social or climate conditions. Expansions can be anticipated mainly along the east–west axes in two basic scenarios.

(1) Planning phases: Capacity is anticipated during the development period as the majority of auxiliary and technical spaces are planned according to the final capacity, and the modular units and adjacent programs (medical and hospitality) are executed in stages.

(2) Open development: The majority of auxiliary and technical spaces are planned according to initial capacity, and the main layout features are designed to support additional extensions until reaching a given site's full capacity.

Simple layout and structure of individual modules makes them very flexible, allowing for partial adaptations, changes in use, or even regaining functionality after an extreme catastrophic event and severe material damage.

3.2.2. Sizing and Positioning of Open-Air and Indoor Features

The general placement and interconnection of open-air features with built-up structures was proposed through a holistic design approach, taking into consideration functional demands, passive design principles [32,44], and the advantages of the modular approach as described in the previous section. The design strategies presented were developed bearing in mind the specific nature and demands of the wellness and spa features that incorporate balneotherapy as well as the geothermal potential of those sites.

Open-air and indoor features were purposely sized and organized in a way that allowed a shared use of auxiliary spaces like reception, changing rooms, lockers, and service rooms (Figure 7). The therapy functions are distributed throughout the open-air and enclosed spaces in a way that facilitates compatibility and provides a continuity of various treatments in different weather scenarios. This enables extended operation time, mitigating the sensitivity to seasonal or annual variations in climate while optimizing running costs.

Most open-air features are rather small, following the general concept of modularity and phase execution and operation. The width i of intermediate open-air spaces O may vary in regard to the height of the neighbouring modules M (Figure 7) for functional and privacy requirements. Additional screens may be added for enhanced privacy and additional sun protection of intermediate open spaces.

The modest capacities of both enclosed and open-air spaces allow the local production of most common types and enable less demanding maintenance, which may be one of the preconditions for sustainability of such features in small communities.

3.2.3. Passive Design Strategies

Striving for high level of energy efficiency and climate-responsive design, a series of passive design strategies were proposed to support the overall design goals.

Placement and orientation: Placement of all open-air features and enclosed spaces was done in a way that provided optimal daylight, solar exposure and shading. North-facing sections were used for technical rooms like storage and sanitary spaces. Circulation corridors connecting the modules were also placed on the northern side, leaving the south-facing open-air spaces between the modules to be sheltered and functionally supported by the side volumes. Longitudinal circulation space can be open or enclosed with glazed south-facing walls to serve as a buffer space for modules.

Massing, solar gains and shading: Modules are compact to provide a good shape factor for each unit. The same principles were applied to all public and utility spaces except for the longitudinal circulation corridor. Modular units and the corridor were mainly opaque on the north façade for improved thermal performance and almost fully glazed on the South façade to maximize solar gain. Adequate shading was provided by various design features tailored to provide unobstructed views under various weather

conditions (Figure 12) and additionally supported by an adequate choice of glazing and flexible interior shading.
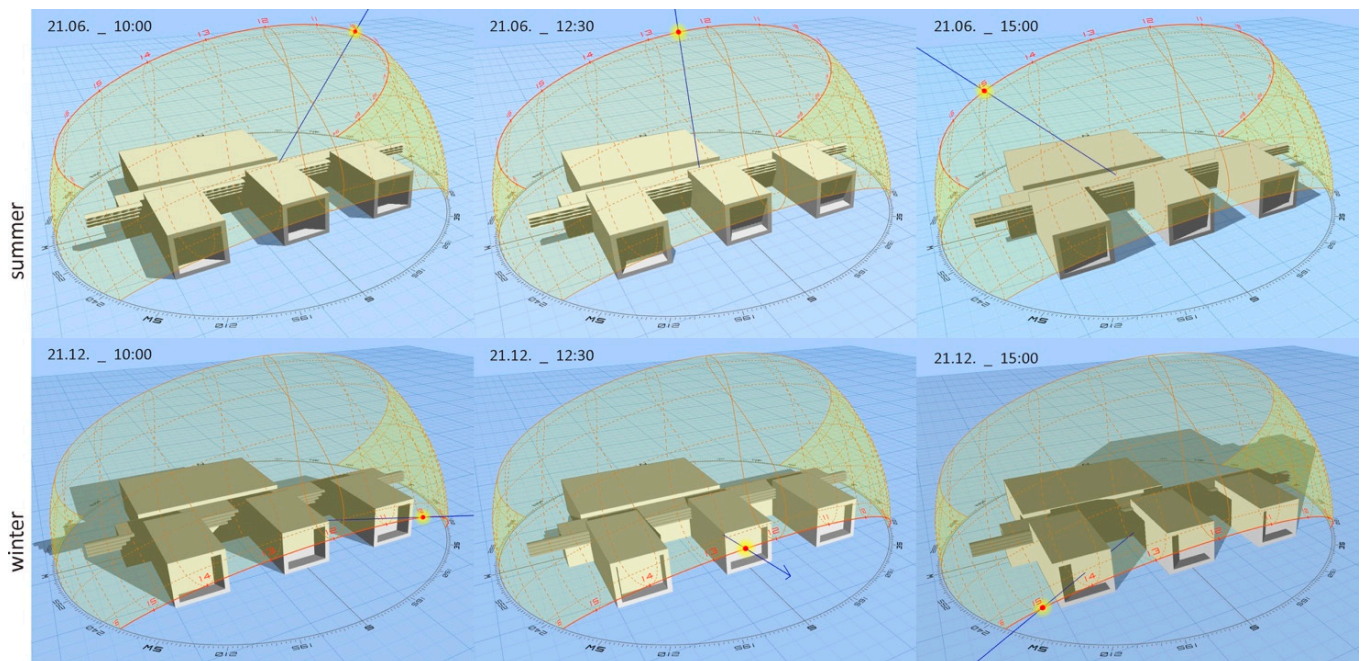

Figure 12. Solar exposure and shading: all glazed surfaces of wellness modules and circulation volume are fully shaded during the summer to prevent overheating (**upper row**) while remaining almost completely exposed during winter (**lower row**), enabling direct passive solar gain.

Natural ventilation and cooling: Glazed surfaces are designed to maximize the share of operable elements with cross-ventilation that are provided for all spaces. The basic layout, as previously described in this chapter, provides very good preconditions for natural ventilation and effective application of night cooling, which are further enhanced by the green areas and water features. Under favourable weather conditions, the glazed façade of the long corridor can be open along the intermediate semi-atrium spaces.

Thermal mass and materials: The modules are designed as lightweight structures where a low thermal mass optimizes comfort and energy efficiency in intermittently used spaces. Enhanced thermal insulation and a high-performance glazed element could significantly contribute to further mitigation of energy demands for cooling and heating. The façade and roof finishing also affect the energy efficiency, but they should be considered case by case. In exposed sites, with peak occupancy in summer season, reflective surfaces or green roofs should be prioritized. In more secluded sites, where structures are surrounded by deciduous trees (naturally shaded in summer and exposed in winter), reflectivity is not so much of an advantage.

3.3. Energy Demands

Energy demands were calculated for 6 cases—3 development stages with different operational capacities and two approaches to thermal envelope materialization. The basic climate data, as defined by the Rulebook on Energy Efficiency [33] for both sites are given in Table 7. The data for Banatsko Veliko Selo are somewhat less favourable (lower temperatures and higher HDD values) and were used as input to calculate the energy needed for heating.

Table 7. Basic climate data for Ljuba and Banatsko Veliko Selo.

	Average Temperature [1]	Design Temperature [2]	Heating Days	HDD
Ljuba	5.4 °C	−15 °C	184	2686
Banatsko Veliko Selo	4.9 °C	−15.3 °C	183	2763

[1] Average temperature during the hating season. [2] Design temperature for sizing the heating system, HDD—Heating degree-days.

The calculated annual energy needs for heating are presented in Table 8. The potential reduction of energy demand resulting from an improved thermal envelope are 40.35%, 35.74% and 35.98% for stages 1–3, respectively. While the enhanced model shows notably better energy performance, the results still remain within the EPC class C (50–100 kWh/m^{2}a).

Table 8. Annual energy needed for heating.

	Stage 1		Stage 2		Stage 3	
	Base Case	**Enhanced**	**Base Case**	**Enhanced**	**Base Case**	**Enhanced**
Heat losses (kWh)						
Transmission	51,597.94	35,625.64	75,290.03	52,198.15	100,799.42	69,786.58
Ventilation	15,675.93	15,675.93	23,436.22	23,436.22	30,824.67	30,824.67
Total losses (kWh)	67,273.87	51,301.57	98,726.25	75,634.37	131,624.09	100,611.25
Heat gains (kWh)						
Solar	21,189.90	18,541.00	31,567.60	27,621.50	42,303.60	37,015.80
People	3316.48	3316.48	4956.10	4956.10	6503.62	6503.62
Appliances	6309.89	6309.89	9429.41	9429.41	12,373.71	12,373.71
Total gains (kWh)	30,816.27	28,167.37	45,953.11	42,007.01	61,180.93	55,893.13
$Q_{H,nd}$ **(kWh/a)**	36,457.60	23,134.20	52,773.14	33,627.36	70,443.16	44,718.12
$Q_{H,nd}$ **(kWh/m^{2}a)**	83.46	53.37	80.86	51.96	82.25	52.66

The monthly heating energy demands for all six scenarios is shown in Figure 13. It can be observed that the values of "enhanced case" for one stage almost correspond to the values of "base case" for a smaller stage. Stage 3 enhanced case is lower than Stage 2 base case and Stage 2 enhanced case is just slightly above Stage 1 base case (lower in March). These findings indicate that the heating system and materialization should be chosen to correspond to seasonal sensitivity and the anticipated capacity of the final stage to achieve a balance between the initial costs and the effects throughout the facility's lifespan.
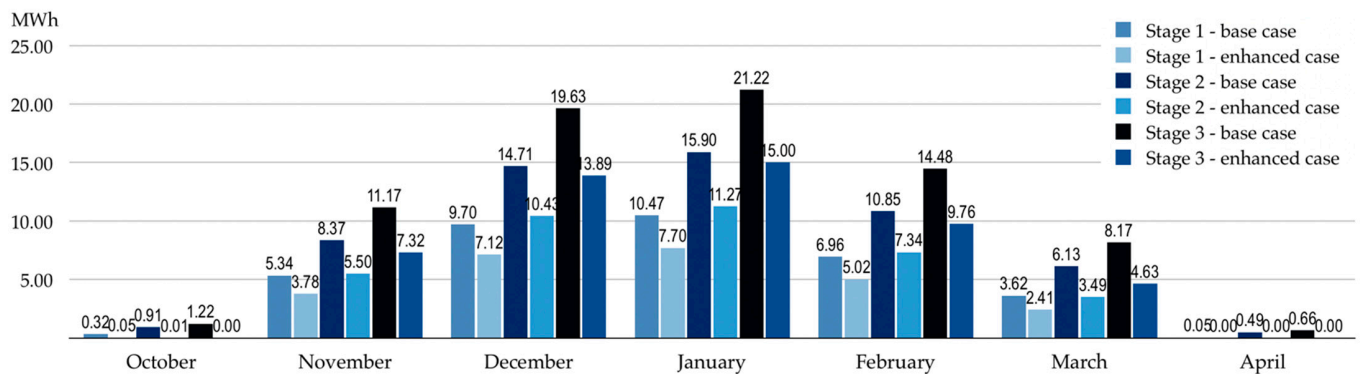

Figure 13. Energy needed for heating.

Cooling energy is not calculated since the model was designed to enable natural ventilation whenever necessary. In July and August, the average temperature is 23.9 °C and maximums are 28.7 and 28.9 °C, respectively (Table 1), which means that the cooling

systems (if any) should be designed primarily to meet the specific medical and therapy-related demands of a particular facility or specific modules within the facility.

The power demands *P* for heating were calculated for two different outside temperature settings:

- *Pa*—for average outside temperature (per the procedure for establishing EPC class), and
- *Pd*—for design temperature (per the procedure for sizing the overall capacity of a heating system).

The power demands *Pd* for the heating with regard to the outside design temperature were calculated based on *Pa*, using the following formula

$$Pd = \frac{Pa \times (t_i - t_d)}{(t_i - t_a)} \tag{2}$$

where t_i is the designed interior temperature, t_d is designed exterior temperature and t_a is the average exterior temperature.

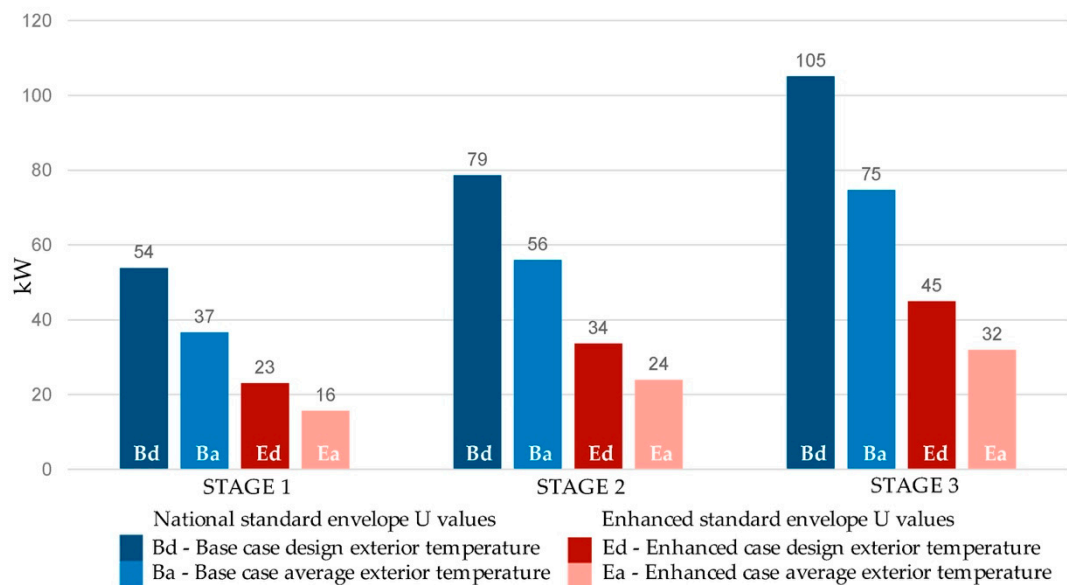The resulting power demands for the study cases are shown in Figure 14.

Figure 14. Power needed for heating.

During initial research, after developing the modularity-based approach, the modules were formed as single-purpose entities (one module for one type of balneological treatment—Figures 7, 11 and 12). This approach was rather successful in many cases, where it provided more options for interaction with the natural environment and versatility of outdoor balneological treatments on semi-private or private patios. However, extending such a concept to more units would be rather demanding because land occupancy, daily operation, supervision and other issues would have to be considered on case-by-case basis. The model used for the calculations is somewhat more compact with paired wellness modules (Figure 8). The initial module would obviously show higher energy demands for heating, but it is expected to be used in facilities that operate only during the summer. In both cases, special attention is dedicated to passive measures for thermal comfort during the summer, thereby minimizing mechanical ventilation and air conditioning while addressing the well-being of users, in addition to enhancing hygiene standards, new occupancy protocols and energy efficiency issues.

Exploring energy performance of three development stages in two types of materialization provided six scenarios where some additional observations can be made regarding thermal envelope components:

1. The share of the components' surface area in the overall thermal envelope area remained mostly constant throughout the development stages (Figure 15a). The ratio between the opaque and glazed elements was approximately 3:2 in all three stages, and the only component that showed a significant increase was the interior wall-to-unheated space as unheated technical modules are added.
2. The glazed surfaces accounted for more than half of heat transmission losses even in enhanced cases (Figure 15b). This component is key not only for energy efficiency but also for thermal comfort throughout the year, so the exact sun exposure and anticipated occupancy regime of particular facility should be specified on a case-by-case basis.
3. The materialization of opaque components reflects on the overall energy performance but further studies should be performed regarding the feasibility of using the enhanced option; the production of panels with more than 30 cm of thermal insulation (Table 3) requires technology and resources that might be more challenging for local companies. The composition of interior walls to unheated spaces may remain as proposed for the base case in all scenarios since their share in heat transmission losses is almost irrelevant (0.5–1.5%)
4. Since flat roofs cover a significant area, mounting PV units as additional renewable energy resources might cover the energy needs of electrical equipment.
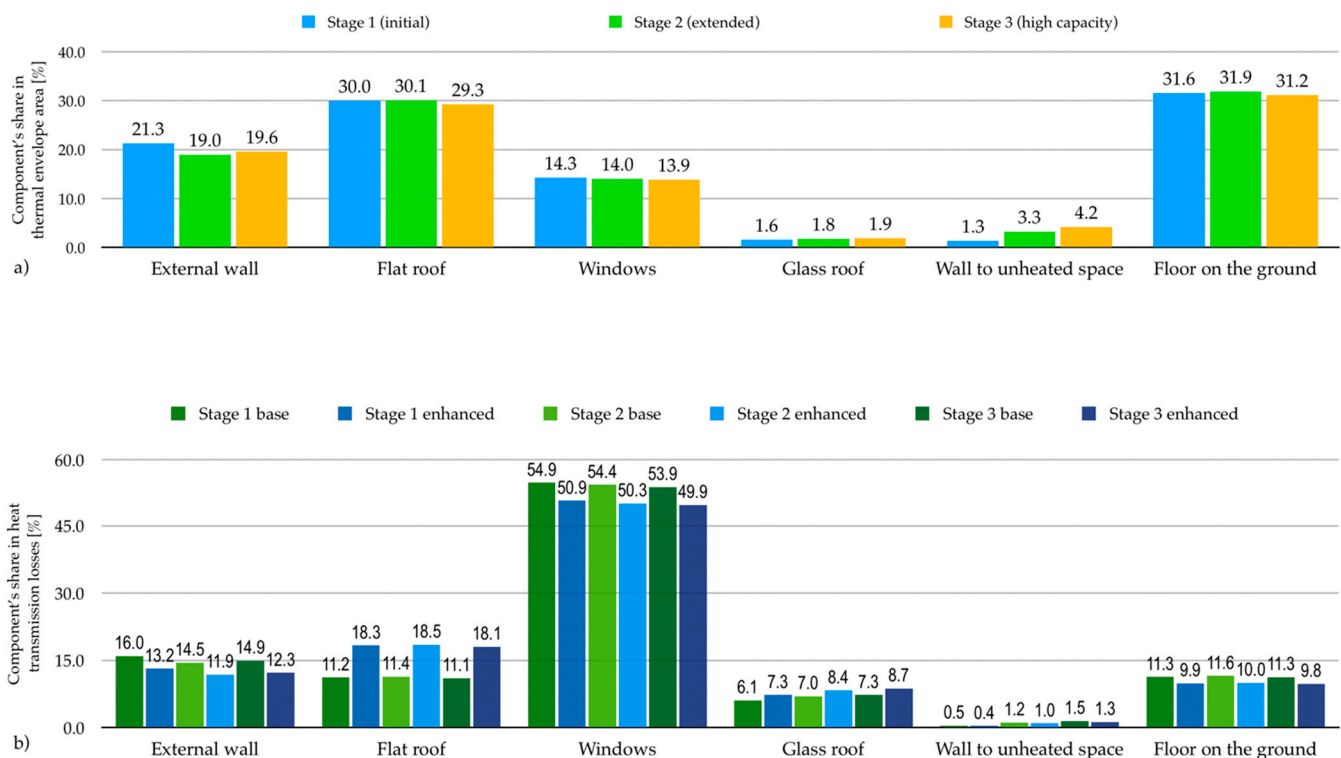

Figure 15. Distribution of thermal envelope components: (**a**) per surface area and (**b**) per contribution to heat transmission losses.

Regardless of the capacity of the location and the materialization variant, all development models consumed significantly less energy for heating than the geothermal potential provides. At Ljuba, the site with the lower capacity, development model 3 (maximum size) in the basic code-compliant state of materialization, and taking into account extreme external temperatures, yielded 35% of geothermal capacity; at Banatsko Veliko Selo 2, it was only 11%. In the improved variants, these needs are reduced to 13% and 4.7%, respectively.

Developed modules reached a significant level of energy efficiency, not only in heating demands but also in the sustainable use of groundwater. More than 50% of flow capacity was reduced in all three module stages between the base average exterior temperature and the enhanced average exterior temperature (Figure 16). The efficiency calculation was done for the Banatsko Veliko Selo site, where a cascade system with a constant ΔT value (19 °C) was adopted. The lower flow capacity may lead to less power consumption by circulation pumps and a low operational cost. In addition, these beneficial effects reflect resource preservation and sustainable exploitation.
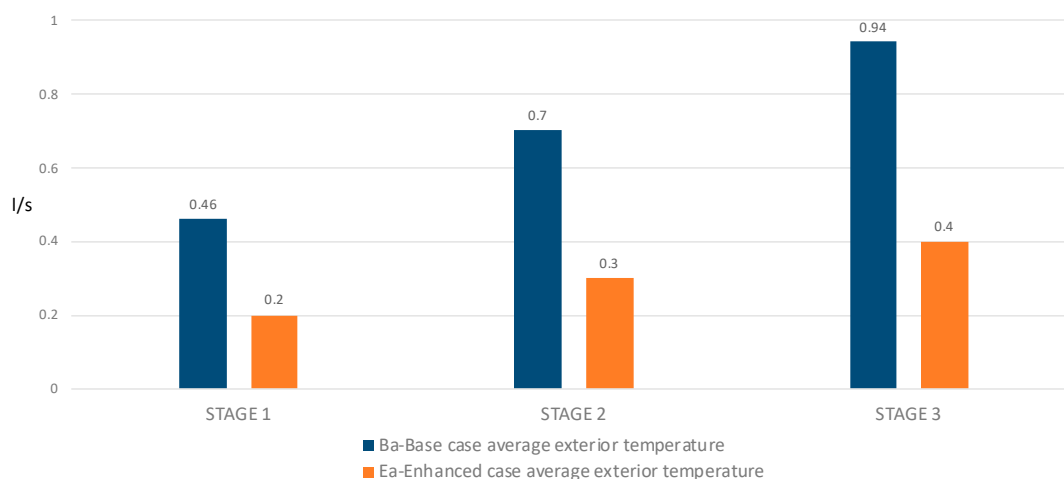

Figure 16. Modeled flow capacities—heating demand.

Additionally, the results indicated the possibility of the further use of the investigated geothermal potentials, primarily to provide energy for other facilities (healthcare, hospitality) or to heat complementary facilities, even larger pools or other aquatic venues.

4. Conclusions

Balneological usage presents one of the driving forces for the activation of geothermal resources in modern medical and rehabilitation practices. This paper addressed two sites chosen from previous interdisciplinary research conducted in the Vojvodina region that have different geothermal resources and placed within different urban contexts. Coupling the identified and analyzed geothermal potential with a purposely formulated architectural model for balneological application based on sustainable and green design strategies, the paper illustrated a possible development concept that could serve as an implementation tool for activation at various locations.

The developed architectural model showed good potential both for phase development and for effective and efficient use with adaptable capacities during the low season. The modular approach in placing indoor and outdoor balneotherapy as well as ancillary spaces enables a high level of flexibility with minimized operational costs. The base model was designed as a structure of approximately 500 m^2 of gross area, encompassing all basic wellness and spa activities with proper support spaces (e.g., reception, examination room, changing rooms and technical room). It was a modest start, but rather feasible for the local municipality that met all contemporary standards for this type of program. The largest structure was some 1000 m^2 as the result of preliminary design research, which indicated that for larger sites a different design approach should be explored to overcome certain functional shortcomings.

As far as materialization of thermal envelope was concerned, practically all variations remained within the boundaries of EPC class C, but enhanced envelope proposals were very close to EPC class B (for the smallest, initial case it was just below the threshold). Having in mind the abundance of geothermal energy at both sites, the pursuit of enhanced

energy efficiency might be questionable unless the NZEB (nearly zero-energy buildings) standard is targeted. However, Serbia has not yet established any formal NZEB definition.

The abundance of geothermal resources broadens the scope of the wellness and balneotherapies that can be offered within the facility. In this context, further feasibility studies should be conducted to explore more development options for health tourism in the province of Vojvodina.

On the other hand, the focus of further research regarding the architecture of wellness and spa/medical facilities in the Vojvodina region should be on enhanced comfort (while optimizing the construction and operation costs), building technologies that are based on local production, and flexibility of development and operation. The proposed model also includes a set of structured open spaces that were not developed in detail in this study. Some future research should address options for the multifunctional use of such spaces and the potential for their enclosure to provide extended use throughout the year.

Depending on the business model, we can consider this starting model to be not economically demanding and able to serve as a demonstration model to attracting further investment and multiplication in other locations.

Author Contributions: Conceptualization, N.Ć.I. and A.V.; methodology, D.M. and A.V. (hydrogeology and energy resources); N.Ć.I. and D.I. (architecture and energy needs), validation, D.I. (energy efficiency); investigation, D.M. and A.V.; resources, A.V. and O.K.; writing—original draft preparation, N.Ć.I. (architecture and energy needs), and A.V. (hydrogeology and energy resources); writing—review and editing, D.I.; visualization, N.Ć.I. (architecture and energy efficiency); supervision, D.M. and N.Ć.I. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Morrone, P.; Algieri, A. Integrated Geothermal Energy Systems for Small-Scale Combined Heat and Power Production: Energy and Economic Investigation. *Appl. Sci.* **2020**, *10*, 6639. [CrossRef]
2. Ilzarbe, J.M.B.; Malpartida, J.G.; Chandro, E.R. Recent Patents on Geothermal Power Extraction Devices. *Recent Patents Eng.* **2013**, *7*, 2–24. [CrossRef]
3. IRENA (International Renewable Energy Agency). Available online: https://www.irena.org/geothermal (accessed on 28 May 2020).
4. Stegnar, G.; Staničić, D.; Česen, M.; Čižman, J.; Pestotnik, S.; Prestor, J.; Urbančič, A.; Merše, S. A framework for assessing the technical and economic potential of shallow geothermal energy in individual and district heating systems: A case study of Slovenia. *Energy* **2019**, *180*, 405–420. [CrossRef]
5. Kljajić, M.V.; Anđelković, A.S.; Hasik, V.; Munćan, V.M.; Bilec, M. Shallow geothermal energy integration in district heating system: An example from Serbia. *Renew. Energy* **2020**, *147*, 2791–2800. [CrossRef]

6. Soltani, M.; Kashkooli, F.M.; Dehghani-Sanij, A.; Kazemi, A.; Bordbar, N.; Farshchi, M.; Elmi, M.; Gharali, K.; Dusseault, M.B. A comprehensive study of geothermal heating and cooling systems. *Sustain. Cities Soc.* **2019**, *44*, 793–818. [CrossRef]

7. Soltani, M.; Kashkooli, F.M.; Dehghani-Sanij, A.; Nokhosteen, A.; Ahmadi-Joughi, A.; Gharali, K.; Mahbaz, S.; Dusseault, M. A comprehensive review of geothermal energy evolution and development. *Int. J. Green Energy* **2019**, *16*, 971–1009. [CrossRef]

8. Mahbaz, S.; Dehghani-Sanij, A.; Dusseault, M.; Nathwani, J. Enhanced and integrated geothermal systems for sustainable development of Canada's northern communities. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100565. [CrossRef]

9. Kinney, C.; Dehghani-Sanij, A.; Mahbaz, S.; Dusseault, M.B.; Nathwani, J.S.; Fraser, R.A.; Sanij, D. Geothermal Energy for Sustainable Food Production in Canada's Remote Northern Communities. *Energies* **2019**, *12*, 4058. [CrossRef]

10. Schmerler, K. *Medical Tourism in Germany: Determinants of International Patients' Destination Choice*; Springer: Cham, Switzerland, 2018.

11. Proticć, D. *Mineral and Thermal Waters of Serbia*; Geoinstitut—Special editions; Geoinstitut: Belgrade, Serbia, 1995; Volume 17, p. 35. (In Serbian)

12. Dokmanović, P.B.; Krunić, O.Ž.; Martinović, M.K.; Magazinović, S.M. Hydrogeothermal Resources in Spa Areas of Serbia: Main Properties and Possible Improvement of Use. *Therm. Sci.* **2012**, *16*, 21–30. [CrossRef]

13. Republic Agency for Spatial Planning of the Republic of Serbia. *Spatial Plan of the Republic of Serbia 2010–2020*; Official Gazette of the Republic of Serbia no. 88/10; Republic Agency for Spatial Planning of the Republic of Serbia: Belgrade, Serbia, 2010. (In Serbian)

14. Institute for Urbanism of Vojvodina. *Regional Spatial Plan of the Autonomous Province of Vojvodina*; Official Gazette of APV no. 22/11; Institute for Urbanism of Vojvodina: Novi Sad, Serbia, 2011. (In Serbian)

15. Zwaan, V.D.B.; Longa, D.L. Integrated assessment projections for global geothermal energy use. *Geothermics* **2019**, *82*, 203–211. [CrossRef]

16. DiPippo, R.; Renner, J.L. Geothermal Energy. In *Future Energy, Improved, Sustainable and Clean Options for Our Planet*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 471–492.

17. Kaczmarczyk, M.; Tomaszewska, B.; Operacz, A. Sustainable Utilization of Low Enthalpy Geothermal Resources to Electricity Generation through a Cascade System. *Energies* **2020**, *13*, 2495. [CrossRef]

18. Marović, M.; Djoković, I.; Peić, L.; Radovanović, S.; Toljić, M.; Gerzina, N. Neotectonics and Seismicity of the Southern Margin of the Pannonian Basin in Serbia. In *Neotectonics and Surface Processes: The Pannonian Basin and Alpine/Carpathian System*; EGU Stephan Mueller Special Publication Series; Cloetingh, S.A.P.L., Horvath, F., Bada, G., Lankreijer, A.C., Eds.; European Geosciences Union: Munich, Germany, 2002; Volume 3, pp. 277–295.

19. Rman, N.; Lenuța, B.L.; Bobovečki, I.; Gál, N.; Jolović, B.; Lapanje, A.; Marković, T.; Milenić, D.; Skopljak, F.; Rotár, S.A.; et al. Geothermal sources and utilization practice in six countries along the southern part of the Pannonian basin. *Environ. Earth Sci.* **2020**, *79*, 1–12. [CrossRef]

20. Nádor, A. (Ed.) *Cascades and Calories: Geothermal Energy in the Pannonian Basin for the 21st Century and Beyond*; Faculty of Mining and Geology, Belgrade University: Belgrade, Serbia, 2019; 130p.

21. Nádor, A.; Sebess, Z.L.; Rotár, S.Á.; Gulyás, Á.; Markovic, T. New methods of geothermal potential assessment in the Pannonian basin. *Neth. J. Geosci.* **2020**, *98*, e10. [CrossRef]

22. Lenkey, L.; Dövényi, P.; Horváth, F.; Cloetingh, S.A.P.L. Geothermics of the Pannonian basin and its bearing on the neotectonics. *EGU Stephan Mueller Spec. Publ. Ser.* **2002**, *3*, 1–12. [CrossRef]

23. Horváth, F.; Musitz, B.; Balázs, A.; Végh, A.; Uhrin, A.; Nádor, A.; Koroknai, B.; Pap, N.; Tóth, T.; Wórum, G. Evolution of the Pannonian basin and its geothermal resources. *Geothermics* **2015**, *53*, 328–352. [CrossRef]

24. Kostić, A. *Thermal Evolution of Organic Matter and Petroleum Generation Modelling in the Pannonian Basin (Serbia)*; Faculty of Mining and Geology, Belgrade University: Belgrade, Serbia, 2010; ISBN 978-86-7352-221-0.

25. Milenić, D.; Vranješ, A. Evaluation of Geothermal Potential of the AP Vojvodina. In Proceedings of the XV Serbian Symposium of Hydrogeologist with International Participation, Kopaonik, Serbia, 14–17 September 2016; pp. 283–289.

26. Milenić, D.; Vranješ, A.; Krunić, O. *Balneology Potential of the Territory of AP Vojvodina—Resources Research, Multiparameter Valorisation and Development Projections, Scientific Study*; Faculty of Mining and Geology, Belgrade University: Belgrade, Serbia, 2017; unpublished.

27. Milenić, D.; Vranješ, A.; Krunić, O. Preliminary Assessment of the Balneological Potential of the Territory of AP Vojvodina. In Proceedings of the 17th Serbian Geological Congress (National Congress with International Participation), Vrnjačka Banja, Serbia, 17–20 May 2018; Volume 2, pp. 439–444.

28. Royden, L.H.; Horvaáth, F. (Eds.) The Carpathian-Pannonian Region with Names and Locations in the Basins. In *The Pannonian Basin, A Study in Basin Evolution*; American Association of Petroleum Geologists Memoiry 45; AAPG: Tulsa, OK, USA, 1988.

29. The Serbian Ministry of Natural Resources and Environmental Protection. *Geological Atlas of Serbia 1:2.000.000 No. 1 Geological Map*, 2nd ed.; The Serbian Ministry of Natural Resources and Environmental Protection: Belgrade, Serbia, 2002.

30. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; Resolution adopted by the General Assembly on 25 September 2015. A/RES/70/1; United Nations: New York, NY, USA, 2015.

31. Climate Data. Available online: https://en.climate-data.org/europe/serbia/vojvodina-483/r/july-7/ (accessed on 11 February 2021).

32. Szokolay, S. *Introduction to Architectural Science: The Basis of Sustainable Design*; Architectural Press: Oxford, UK, 2004.

33. *Rulebook on Energy Efficiency of Buildings*; Official Gazette of RS, No. 61/2011; Official Gazette of RS: Belgrade, Serbia, 2011. (In Serbian)

34. Passive House Institute. *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard*; Passive House Institute: Darmstadt, Germany, 2016.
35. *Rulebook on Conditions of Content and Manner of Issuing Certificates on Energy Properties of Buildings*; Official Gazette of RS, no. 69/2012 and 44/2018; Official Gazette of RS: Belgrade, Serbia, 2018. (In Serbian)
36. Knaufinsulation Serbia. Available online: https://www.knaufinsulation.rs/knaufterm-2-pro-srbija (accessed on 5 June 2020).
37. Statistical Office of the Republic of Serbia. *2011 Census of Population, Households and Dwellings in the Republic of Serbia*; Bulletin #540; Statistical Office of the Republic of Serbia: Belgrade, Serbia, 2011.
38. Marović, M.; Toljić, M.; Rundić, L.; Milivojević, J. *Neoalpine Tectonics of Serbia*; Serbian Geological Society: Belgrade, Serbia, 2007; ISBN 86-86053-03-3.
39. Toljić, M.; Matenco, L.; Ducea, M.N.; Stojadinović, U.; Milivojević, J.; Đerić, N. The evolution of a key segment in the Europe–Adria collision: The Fruška Gora of northern Serbia. *Glob. Planet. Chang.* **2013**, *103*, 39–62. [CrossRef]
40. Lesicć, V.; Maárton, E.; Cvetkov, V. Paleomagnetic detection of Tertiary rotations in the Southern Pannonian Basin (Fruška Gora). *Geol. Carp.* **2007**, *58*, 185–193.
41. Allen, A.; Milenic, D. Low enthalpy geothermal heat resources from ground water in fluvioglacial gravels of buried valleys. *J. Appl. Energy* **2003**, *74*, 9–19. [CrossRef]
42. D'Amore, F.; Scandiffio, G.; Panichi, C. Some observations on the chemical classification of ground waters. *Geothermics* **1983**, *12*, 141–148. [CrossRef]
43. Milenić, D.; Vasiljević, P.; Vranješ, A. Criteria for use of groundwater as renewable energy source in geothermal heat pump systems for building heating/cooling purposes. *Energy Build.* **2010**, *42*, 649–657. [CrossRef]
44. Konstantinou, T.; Prieto, A. Environmental Design Principles for the Building Envelope and More Passive and Active Measures. In *Energy Resources and Building Performance*; Konstantinou, T., Ćuković Ignjatović, N., Zbasnik-Senegacnik, M., Eds.; TU Delft Open: Delft, The Netherlands, 2018; pp. 147–180.