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Potential and Benefit of Green Roof Energy Renovation of Existing Residential Buildings with a Flat Roof in Belgrade

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Abstract: Green roofs are considered to be one of the optimal tools for saving energy and protecting the environment in developed countries. In this paper, an analysis of the possible application of green roofs on existing residential buildings with flat roofs is presented. In the economic analysis, models of existing buildings in Belgrade, with two different types of green roofs, are studied. A key indicator of investment profitability in this investigation is the net present value (NPV) of the green roof project. Besides the private economic impact, other aspects of green roof applications, significant for sustainable development, have been highlighted. The values of the reductions in the annual energy needed for heating and cooling are compared for different scenarios. A maximum energy saving of 22% in the heating season is determined in the building energy simulation program for the model with an intensive green roof. Life cycle profit analysis was based on the probabilistic approach. The corresponding variance-based sensitivity analysis determined the impact of various parameters on the final result. In all models, the first order sensitivity index, which measures the impact of the number of residential units on the NPV, ranges from 12.2% to 63.6%. Sensitivity analysis showed that the benefit of property value increase has the highest influence on the calculated NPV in scenarios that account for this benefit. The obtained results in those scenarios indicate that the most probable NPV at the end of the life cycle is EUR 43/m^2 and EUR 82/m^2 for extensive and intensive green roofs, respectively.

Keywords: green roof; life cycle cost; energy renovation; sensitivity analysis

1. Introduction

The building sector is responsible for about 40% of total global final energy use in some developed countries as well as 40% of total greenhouse gas emissions [1]. Additionally, in the Republic of Serbia, residential households have a 35% share in the total amount of energy consumption [2]. It is therefore clear that significant improvement in energy savings can be achieved by the increase in energy efficiency in this sector.

Despite the unnatural environment of modern cities, they should provide comfort to their inhabitants. The goal of optimizing energy consumption and protecting the environment should also be accomplished. New solutions have emerged in the construction strategy as a result of growing populations in cities [3]. Their aim is to reduce the impact of considerable energy needs while maintaining or improving citizens' quality of life. Due to the constant increase in urbanization, it is necessary to optimize building areas and their use. Fulfilling these demands can generally be achieved through various approaches. Retrofitting measures in residential buildings with different aspects and challenges with the importance of cost-effectiveness are discussed in references [4,5]. However, greenery systems provide additional social and environmental value, with great potential to mitigate

some negative aspects of urban housing. An overview of different greenery systems and the effectiveness of their application in different climates are presented in reference [6].

Green roofs, the practical tool of the urban greening concept, are structures that are covered with a vegetation layer. The growth of different forms of vegetation on top of buildings thus provides aesthetic, environmental, and economic benefits [7,8]. Additionally, green roofs have a positive effect on improving the global microclimate in cities, reducing noise levels and purifying rainwater and air inside the building. They are also a living space for various animals and insects, and they can be used for food production. It is important to emphasize that green roofs can improve the thermal performance of buildings, so they are a great option for potential energy savings [9] through reducing energy consumption for heating and cooling [10]. Even though validation of the results of the simulation model [11] is valuable confirmation in research on green roofs, reference [12] argued that there is a lack of experimental results in terms of energy savings in the literature. Data for measuring the effects of green roofs are further discussed in the Section 2.

There are three types of green roofs, depending on usage, maintenance requirements, and structural considerations: intensive, semi-intensive, and extensive. Green roofs consist of the following layers (from bottom to top of the construction): protective board, waterproof membrane, drainage layer, filter, vegetation substrate, and plants. Besides the essential layers, green roofs can include additional filters [7], root barriers, thermal insulation, and irrigation systems (above or inside the soil layer).

Since growing medium represents a relatively thin layer in the case of extensive green roofs, they are easily feasible and lightweight. Consequently, they serve aesthetic, remedial, or technical purposes, and, compared to other types of green roofs, their maintenance and construction costs are lower. In addition to traditional green areas, intensive green roofs can provide similar amenities, usually arranged as parks or gardens. However, their initial and maintenance costs are considerably higher due to their significant weight and irrigation requirements. Furthermore, their waterproofing layers are more reliable, and the energy efficiency of the adjacent spaces of building is substantially improved.

Besides all the above advantages, an important aspect of the applying of green roofs is reflected in the economic benefits. Many studies, such as [7,13,14], claim that the probability of profit of a green roof is much higher than its potential financial losses. Thereby, the study conducted in reference [13] should be emphasized, whose probabilistic net present value (NPV) analysis shows that there is a low financial risk for installing any type of green roof. Additionally, many other investigations [14–16] demonstrate that at the end of its lifetime, the NPV for the green roof is significantly lower when compared with conventional roofs. Determination of NPV of green roofs is usually analyzed through private or social (and environmental) benefits or taking into account both economic impacts, which often implies considering diversified cost and benefit effects. This paper deals with the analysis of the impact of green roofs on the energy performance of the existing building in the center of Belgrade. The potential private benefits of installing a green roof on such a flat roof are indicated.

It can be said that green roofs are not widely represented in Serbia and that there is great potential for its application. This includes, among other things, the conversion of flat roofs to green rooftops on the existing buildings. According to a recent investigation [17], the distribution of the flat roof in the building stock in the Republic of Serbia is about 20%. However, in the central urban area of the capital city of Belgrade, that number reaches as much as 40%. Therefore, the economic feasibility of applying of a green roof system to this type of building is presented in this paper.

Commonly, governments have a leading role in the implementation of green roofs. Therefore, the lack of institutional incentives can be a potential barrier to the implementation of a green roof system, especially for existing buildings. For the greenery project implementation, the barriers are similar to standard renovation projects. They are categorized as market, organizational, and economic related, and even in developed countries, policies are different for overcoming these issues [18]. In order to decrease the energy

efficiency gap, reference [19] emphasizes that barriers' inner complex relations and transforming nature must be approached dynamically. Additionally, these obstacles could be further amplified in green roof implementation in countries with an undeveloped green industry. Fortunately, there are many examples of good practices in the world in terms of policies, programs, and projects that encourage the development and implementation of green roofing [20–22]. In Belgrade, the policy of supporting the use of green roofs is reflected through the strategic goals of the Development Strategy of the City of Belgrade 2021 and the pilot project "Green roof of public buildings in the city of Belgrade". In green roof implementation, policies are categorized as direct and indirect financial incentives but also ecological compensation measures with the aim to be integrated into standard development strategies, as presented in ref. [23]. In ref. [22], the incentive policies (mainly concentrated in Europe and North America) were classified into six different categories: tax reductions, financing, construction permits, sustainability certification, obligations by law, and agile administrative processes. In the distinct analysis for southeast Europe [24], state building typology, climate, period of construction, building service, and user behavior are determined as the main considerations for building retrofit packages. In this paper, the focus is on existing residential buildings with a flat roof in the urbanized area, with the presumption that the conclusions could be applied to some extent to other categories of residential buildings with a flat roof. The purpose of this type of research is also to provide background for the possible large-scale implementation as the cost-benefit analysis is regarded as helpful in raising awareness of environmental goods and in increasing the transparency of policymaking [25].

2. An Overview of the Impacts of Green Roofs

Private benefits of green roofs are categorized as buildings' increased aesthetic value, improved sound insulation, extended membrane longevity, and reduced consumption of energy. Further, they enable LEED certification bonuses [26], along with bringing psychological and health benefits. In addition to the individual level, green roof installations also affect the public (environmental and social benefits).

Constructing a green roof can lead to a decrease in energy needed for cooling and heating, which may vary depending on the analyzed climate zone, green roof type, and building envelope. In [27], results are categorized according to their location, where maximum energy savings are obtained in intensive green roofs comparison to black roofs, especially over non-insulated roofs, reaching to 84% energy savings in the cooling season and 48% in the heating season. Similar comparison (white, black, and green roofs) is analyzed in but these types of roofs are not widely spread in the location of the presented analysis. In this paper, the impact of green roofs is investigated in Belgrade, where the climate is considered to be Cfa according to and to Koppen–Geiger climate classification system [28]. It should be emphasized that the presented data from the literature mainly reflect energy savings only for the floor under the green roof, which is also taken into account in the economic analysis in the presented paper. Ref. [29] found that the installation of a rooftop garden in a building in Singapore could result in a saving of up to 15% in the annual energy consumption. Total energy savings in the range of 24 to 35% were the result of investigation performed in hot-humid climate areas [30]. The comparison presented in [31] ranks green roof performance above the traditional roof with an insulation layer (5–14% energy saving) in the experimental analysis performed during the cooling season in Spain. A specific study in cold and hot climate zones [32] concluded that application of green roofs leads to an annual reduction in heating load by 36.5% to 55% and an annual reduction in cooling load by 27.7% to 35.8%. Based on a comprehensive literature review related to this topic, ref. [6] concluded that the maximum energy savings of greenery systems are found during summer. In contrast, for winter conditions, the results can vary and are dependent on the conditions in which the research was conducted.

The high absorption of solar radiation in urban areas may cause heat island effects. As a consequence, the temperature in the city center is significantly higher than in the

surrounding rural areas [33]. This temperature difference is usually larger at night than during the day and this urban heat island (UHI) effect indirectly increases building cooling demand [34]. Still, the effects of UHI have been recognized since the 19th century [35], and today, how their negative impacts are reflected in the social, economic, and environmental aspects is especially considered. Compared to standard flat roofs, this effect could be mitigated due to the reduction in heat flux in the green roof structure. Consequently, for buildings that are not heavily insulated, the reduction in the peak indoor temperature can reach 7 °C [36] during the cooling season. Feng [26] presented the results of the simulations indicating that the green roof concept in Toronto and New York can reduce the average temperature of the roof by 1–2 °C. In addition, in ref. [37], it is calculated that in Venice, the temperature could be 4 °C lower if the green permeable surface were used instead of existing roofs. The numerical model for Belgrade [38] showed that with a different type of green roof structure, the reduction in temperature varies from 0.5 to 1.5 °C and 0.5 to 1.8 °C for the roof and pedestrian level, respectively. In the recent study of the summer thermal performance of a lightweight extensive green roof system with rock mineral wool substrate in Belgrade [39], a maximum outdoor roof surface temperature reduction of 27.5 °C was observed, while the average air temperature decrease was 1.6 °C.

In urban areas, the public (social and environmental) benefits of green roof are indisputable. Managing water runoff quantity, reduction in pollution alongside urban noise, and enabling the preservation of habitats [40,41] represent the most essential public gains. Studies quantifying biodiversity increase with the green roof [42,43] reported green roof limited effect and different factors that influence biodiversity. The comparison of the hydrological and water quality performance of green roofs that are presented in [44], shows that they behave differently in different climate zones. The green roof system shows promising results as a substantial tool for removing the air polluting particles in urban areas, as explained in [45], but a model for indication of removal level in Toronto [46] and Chicago [47] showed limitations of green roof impact as they cannot fully replace the widespread urban removal of green areas. Assessment of health risk caused by air pollution in Belgrade [48] proved high exceedance of level PM_{10} particles, which generally can be modestly mitigated by wider application of green roofs [49].

Besides obvious environmental benefits, the presence in vegetation surroundings is good for mental health, providing general comfort from various aspects. It is noted in [50] that evaluating the mental health aspect of green roof implementation must be a multidisciplinary task as it is influenced by other benefits as well.

3. Costs and Benefits of Green Roof

The economic benefits of applying green roofs are an important aspect of the usage of this technology. Cost-benefit studies can be an essential tool for city planners and public decision-makers in promoting green roofs and support for draft bills [22]. There is a wide range of costs that depend on various factors, such as the type and size of the roof, weather conditions of the location, building characteristics, etc. There are also possible barriers to the application of green roofs [40] primarily related to increasing maintenance, design, and construction cost as well as the possible structural limit exceedance, which can cause serious problems in practice.

Comprehensive research provides multifunction nature of green roofs in both the private and social sectors. In the presented economic model, only the private cost/benefit effect is examined in detail. It is based on the relevant references from literature and also on the consideration of local conditions and practices. For the initial cost of extensive green roofs (EGR), the value varies in different ranges: USD 130–165/m^2 [13], USD 70–100/m^2 [51], USD 60–110/m^2 [14], USD 53–214/m^2 [22], or about USD 172 /m^2, proposed in [52]. The estimated range for the intensive green roof (IGR) is USD 160–540/m^2 [13,22], or USD 100–240/m^2 suggested in [51]. In [9], it is indicated that the cost of retrofitting of the existing building (with EGR) depends in the wide range (USD 60–180/m^2) on the specification but also the condition of the existing waterproofing layer.

According to ref. [13], property value increase is relatively close to installation cost, i.e., it can be evaluated as an increase of 2–5% for EGR to 10–20% for IGR. So, it is estimated that this increase is USD 132–648/m^2, depending on the type of green roof. On the other hand, ref. [53] estimated an increase of 16.2% in rental prices in buildings with green roofs. For property value increase, the most influential parameter is an aesthetic improvement, although it depends on access and ownership regime [54], and it is taken into a calculation as a one-off benefit or annual benefit in the case of renting. Without directly estimating property value, in ref. [26], the aesthetic benefits (USD 2.6–32.2/m^2) and the benefit of acoustic improvement (USD 43/m^2) in the building are separately analyzed and quantified, added up to USD 72.2/m^2/40 years. In the economic analysis conducted in this paper, these types of benefits are considered to be incorporated into property value increase. These benefits are conservatively estimated for the apartment below the green roof, and for the other apartments in the considered building, this value is further reduced by 50%.

For IGR, operating and maintenance cost is one of the main concerns of potential investors, while EGR has minimum operating requirements. These costs have notably dispersed value range in the literature overview. In refs. [13,27], this value ranges from USD 0.7 to 13.5/m^2 per year for different types of green roofs. In ref. [52], this value is set to USD 2.9/m^2, while in ref. [16] this value is universally proposed as USD 5/m^2 per year. For markets and industries that are not yet developed, the higher values are more suitable. Given that green roofs in Serbia are not yet sufficiently represented, the higher value is adopted in the economic model.

The lifespan of the green roof can vary from 40 to 55 years [13,15]. Therefore, in addition to maintenance costs, replacement after the projected lifetime could be included in the analysis. However, the conventional flat roof is usually replaced or reconstructed in 20 years, or twice as often as green roofs. Consequently, the membrane longevity benefit is proposed as much as USD 160/m^2 in ref. [13], although this value is significantly lower (USD 20–43/m^2) in refs. [55–57]. The replacement cost of the green roof at the end of its service life [52] is approximately evaluated as one-third of the green roof installation cost, but it is not included in the presented economic model since the analysis of one life cycle is performed. As it is stated previously, the uncertainty of project cost/benefit outcome is one of the main barriers in the wider application of green roofs. Property value increase due to greenery systems also depends on people's preferences and access [20], so its financial contribution is dependent on a specific type of implementation and pricing models. Furthermore, even neighboring residential areas (with a view to green areas) have this benefit [58] in the case of a substantial greening project. In the investigations presented in refs. [13,14,20,26,59–61], the property value increase is counted as a benefit, while in refs. [7,15,16,30,52] authors do not account it directly or neglect that benefit. Thus, in the analysis presented in this paper both approaches are used to determination the NPV of green roof projects at the end of the life cycle.

4. Application of Green Roof on the Existing Building

While it is certainly beneficial to incorporate green roofs into the initial design of new buildings, it is equally important to explore the feasibility and advantages of retrofitting existing buildings. Even though the share of buildings with flat roofs built in Serbia before 1945 is not high [17], a significant number of these buildings are located in the center of Belgrade. Due to their urban architectural value, these buildings are occasionally protected by city and state regulations and this too applies to the building analyzed in this investigation. Furthermore, the strict city center (Figure 1a) has great potential for wider implementation of the green roofs, according to data obtained during the research performed for this paper. The investigated area covers about 2.82 million square meters, of which (public) green areas are only 0.21 million square meters. By mapping the buildings with flat roofs in this zone (Figure 1), it is concluded that 45% of the buildings have flat roofs, with a total area of about 330,000 m^2. It is indicative that the flat roof area in the observed zone is about 50% larger than the area of the existing parks. In a study from 2016

in Thessaloniki, green roof potential reaches 2.29 km^2 compared to 0.66 km^2 of the existing vegetation areas [62].
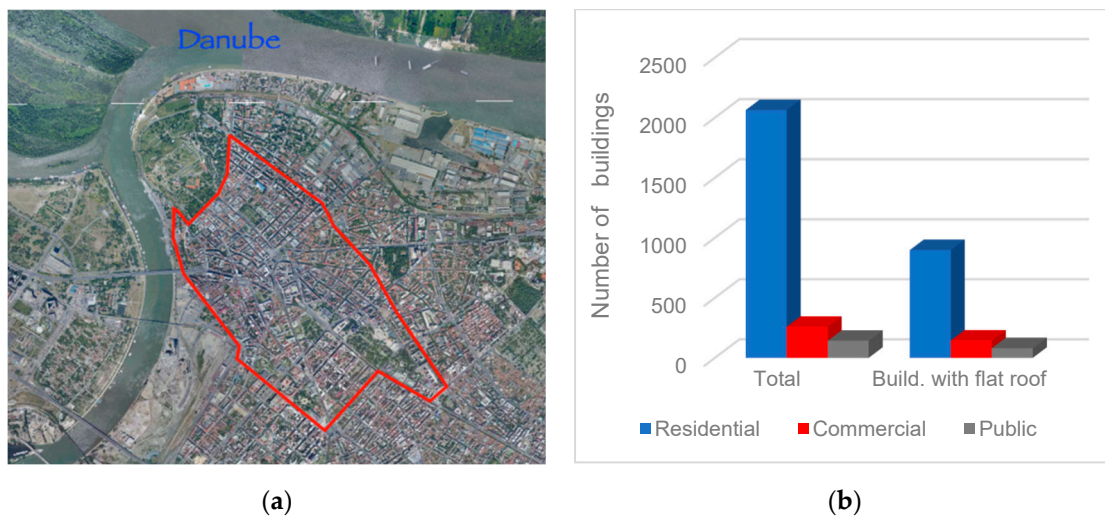

(**a**)   (**b**)

Figure 1. (**a**) City center (red outline) from which detailed data is acquired. (**b**) Summary of the building stock in analyzed zone.

Figure 1b gives a summary of the building stock in the analyzed zone. The highest share in presented data belongs to residential buildings; hence, the absolute highest number of flat roof buildings is detected in that type. About 43% of them have such a roof with a total area of 194,000 m^2. On the other hand, 55% of commercial buildings in this zone have a flat roof (total area 69,000 m^2), as do 56% of public buildings (total area 67,000 m^2). Since current city regulations predict a budget for investing in the greening of public buildings, it is clear that there is great potential for such investments as well.

Model and Parameters

The potential of constructing of green roof on a flat roof is evaluated through project that predicts the removal of layers of the roof structure, enabling additional load on the roof without structural implications. A correlative study in ref. [9] implies that removing traditional paving slabs and gravel on the roof could provide enough capacity for EGR with decent thickness. An additional problem arises if a live load is considered, where ref. [63] proposes a wide range of values of imposed load on accessible flat roofs, depending on National Annexes, up to 2 kN/m^2. Specifically, ref. [64] recommends a live load of up to 4.79 kN/m^2 for accessible roof gardens in a saturated condition, limiting its adequacy for existing roof structures. On the other hand, for inaccessible green roofs, the live load is in the range of 0.5–0.96 kN/m^2 [64], which corresponds to existing capacity according to standards used for analyzed building stock. Data provided in [17,65] revealed flat roof structure typology in Serbia; hence, it can also be relevant for considered urbanized area—the center of Belgrade. Distinct types of roof coverings are observed; still, the overall characteristics are similar and they can be classified (Table 1) on two types according to the top outside layer. Since the weight of various types of green roofs demands different capacities of the roof structure, it can be estimated that for installing EGR, removing all the layers above the concrete laid to fall would be sufficient in certain types of flat roof structures. On the other hand, if that remaining layer is also removed, in some cases it would increase capacity, enabling setting up of semi-intensive or IGR. Table 1 indicates the possibility of installation of IGR (without strengthening the structure) is lower (than EGR). Additionally, ref. [66] argues that an EGR can be the most efficient solution in buildings' greenery concept. Nevertheless, analyzing the IGR economic implications is also important especially in the investigated building that has an even higher capacity (than presented in Table 1) for the vertical load on the flat roof structure. More precisely, the possible

removal of all layers above the surface of the structural plate would provide 4 kN/m^2 of additional weight.

Table 1. Characteristic layers and weight of different types of flat roofs according to [17].

Type 1—Layers	d [cm]	ρ [kg/m^3]	Weight [kN/m^2]	Weight [kN/m^2]
concrete or stone tiles	3–5	200–2400	above concrete laid to fall layer	above roof plate
sand (or without)	3	1800		
hydro-insulation	1–2	900	q = 1.02–2.51	q = 1.56–3.01
cement screed (or without)	2–3	2100	Whole roof structure Typical U [W/(m^{2}K)]	
thermal insulation (or without)	3–6	100		
concrete laid to fall (or without)	3–5	2400	0.5, 0.85, 1.04, 1.4	
roof plate structure				
Type 2—Layers	d [cm]	ρ [kg/m^3]	Weight [kN/m^2]	Weight [kN/m^2]
asphalt or gravel	2–5	1800–2000	above concrete laid to fall layer	above roof plate
hydro-insulation	1–2	900		
cement screed (or without)	2–3	2100	q = 0.90–1.25	q = 1.71–2.56
thermal insulation (or without)	3–6	100	Whole roof structure Typical U [W/(m^{2}K)]	
concrete laid to fall (or without)	3–5	2400		
bitumen layer (or without)	0.5	900	0.45, 0.7, 0.85, 1.07, 1.4	
roof plate structure				

The object of the analysis is a four-story residential building with eight residential units with a total area of 771 m^2. Given the insufficient thermal insulation in this building, it can be used as an appropriate example for energy efficiency improvement. Contemplated measures are represented in the form of the application of an EGR and IGR, which was previously discussed, only on the part of the existing roof that is flat (Figure 2).

(a)   (b)

Figure 2. Micro location and the possible green roof implementation: (**a**) on the roof of the analyzed building; (**b**) on the entire block of buildings.

The installation of a green roof in the proposed models would be performed after the removal of all non-structural elements above the last slab in the building. Consequently, the weight of the new roof structure would be reduced compared to the weight of the existing roof. The estimated mass of the proposed types (Table 2) of the green roof ranges from 125 kg/m^2 (EGR) to 250 kg/m^2 (IGR). In general, additional capacity can be introduced to account for the increase in load due to the saturation of soil and maintenance loading [59]. Regarding the uniqueness of building typology and condition, structural analysis or survey is recommended in most cases [67], especially in the potentially active seismic area, where the additional load on the roof has global implications on the whole building structure.

Table 2. Properties of EGR and IGR layers in numerical model.

EGR and IGR Green Roof Layers	d [cm]	ρ [kg/m^3]	c [J/kg·K]	λ [W/mK]
Plants—LAI = 1–4	10–30	-	-	-
Vegetative substrate	8–20	900	1000	0.2
Filter layer	0.5	160	2500	0.06
Drainage layer	4–6	800	920	0.08
Waterproof membrane	0.7	1200	920	0.17
Thermal insulation	5–10	90	990	0.035
Vapor control layer	0.3	2500	840	0.055

The configuration of the model of EGR and IGR structures and its properties are shown in Table 2, where the highest values of parameter correspond to the IGR model, and the lowest to EGR model. The thickness of the layer is marked as d, density with ρ, specific heat with c, and thermal conductivity with λ. Thus, the variation in the composition of the green roof layer can give different outcomes in thermal properties and numerical models [68–71], which modifies the peak cooling load and energy consumption. However, since the aim of the paper is a general approach in the profitability of the analyzed project, detailed variation of the layer properties is not performed. As presented later in the conducted sensitivity analysis, the dependence of the calculated energy cost reduction indicated the overall importance of the savings achieved by installing a green roof.

Energy efficiency measures consider different levels of thermal envelope retrofitting, and the effects of those actions are usually determined relative to the current state. Results of greening the roof can additionally improve energy consumption, even after the possible usual measures of energy renovating in the buildings—the so-called business as usual (BAU) scenario. In the model of partial renovation (flat roof renovating excluded) assumed in ref. [65], the BAU scenario predicted 20% of heating energy savings, which can be compared with the energy savings in the presented analysis. On the other hand, in ref. [72], 15% of energy savings represents a low renovation scenario, and 45% of energy savings represents a moderate renovation scenario. Furthermore, for the analyzed building, potential additional thermal envelope retrofitting is limited because the design of the street façade of the analyzed building is protected due to its urban architectural value. In addition, a significant part of the external walls represents the party wall with surrounding buildings which may be the obstacle for other buildings in the urbanized center.

For verification of different rehabilitation measures, distinct scenarios are proposed in Table 3. A probabilistic Monte Carlo simulation [73] is performed to calculate the life cycle NPV of different projects. These calculated values represent the possible investment profitability indicator from the point of view of different residential unit owners, expressed in EUR/m^2 of green roof area compared to the current state of the building thermal envelope.

Table 3. Scenarios for economic analysis.

Effect on Residential Unit		Current State Reference Scenario
RU under green roof (property value increase excluded)	EGR	1 EGR
	IGR	1 IGR
Other RU (property value increase excluded)	EGR	2 EGR
	IGR	2 IGR
RU under green roof (property value increase included)	EGR	3 EGR
	IGR	3 IGR
Other RU (property value increase included)	EGR	4 EGR
	IGR	4 IGR

Although various social (public) benefits could be accounted for in the economic analysis, the local circumstances in practice do not strongly support this type of expectation, especially for residential buildings. The existing city development strategy includes activities and a budget for green roof projects of public buildings, but detailed plans have not been completed, so some values are not easy to determine. Therefore, in the presented analysis of energy renewal of the existing object, only personal (private) benefits are taken into account, as given in Table 4. The outcome of the following analysis could also represent the indication for the level of public financial subsidy programs after evaluating the feasibility of the proposed projects as shown at the end of this section. The benefits relate to the apartment under the green roof predominately, but other residential units are also interested in this type of project. As explained in ref. [74], the influence in other adjacent zones of the building is manifested in the reduction in the peak of cooling energy demand to some extent. However, this impact of the green roofs is neglected in the calculation of benefits for other residential units (models 2 and 4). It is important to emphasize that models for NPV calculation are determined by uniformly dividing the costs (marked with * in Table 4) of investment, maintenance and, consequently, the roof membrane longevity value (as a benefit) to all residential units. These adjusted prices used in the economic analysis represent a realistic scenario, according to the local city regulation on housing, where investment and maintenance costs are distributed equally among all apartments.

Table 4. Input parameters and their function in probabilistic analysis.

Type	EGR [EUR/m^2]	IGR [EUR/m^2]	Function	Type	Time Frame
* Old roof removal	10–20	20–35	triangular	cost	one time
* Installation	80–140	120–170	uniform	cost	one time
Property value	30–80	60–120	uniform	benefit	one time
Cooling	0.25	0.65	constant	benefit	annual
Heating	2	2.5	constant	benefit	annual
* Membrane longevity	30–50	30–50	uniform	benefit	one or two times
* Operation & Maintenance	3–8	5–12	uniform	cost	annual

* cost or benefit divided to all residential units

In summary, for models 1 IGR and 1 EGR, all parameters from Table 4 are used, except parameter 3. For models 2 IGR and 2 EGR, only parameters 1, 2, 6, and 7 are used in the LCC and sensitivity analysis. For models 3 IGR and 3 EGR, all parameters 1–7 from Table 4 are used. Models 4 IGR and 4 EGR include parameters 1, 2, 6, 7, and 50% of the parameter 3 value.

The variation of different cost and benefit values in the analysis, presented in Table 4, is based on the previous overview of different sources. The life cycle of the green roof is also varied from 40 to 55 years, and the discount rate is assumed in a uniform variation range of 4–8% in the economic analysis. As is already mentioned, scenario models 2 and 4 (all residential units except RU under the green roof) do not have the benefit of reduced energy for heating and cooling due to green roofs. Furthermore, the property value benefit for model 4 is reduced to 50% compared to the corresponding model 3. Based on the reviewed economic analysis from the literature [13,30,55,75], and the local tariff system, the price of the energy reduction is adopted as 0.08 EUR/kWh.

5. Results and Discussion

EnergyPlus 9.1.0 software with the EcoRoof model [76] was used for the computation of the heating and cooling energy needs. Different outcomes for the reduction in the building's annual energy need for cooling and heating (for the last floor) are demonstrated in Table 5 and Figure 3. As a result of the currently insufficient thermal insulation, the analyzed apartment can potentially reduce the consumption up to 22% of heating and 21% of cooling energy with the implementation of IGR compared to the current state (Figure 3b), which is in the range of savings obtained in BAU scenario measures. On the other hand, IGR models reduce the need for cooling energy significantly more than the proposed EGR model. In the corresponding economic analysis, the yearly benefits of heating and cooling energy reductions, for models with EGR and IGR, are presented in Table 5.

Table 5. Energy need reduction and results from probabilistic analysis for different scenarios.

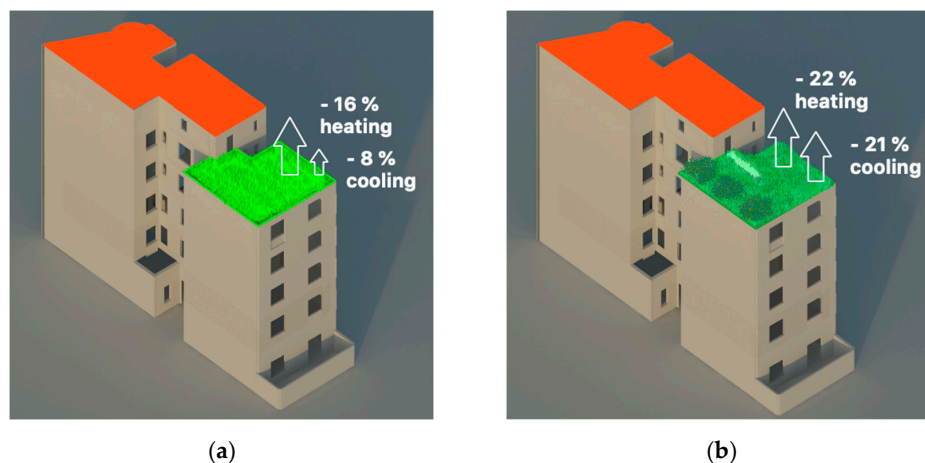| Model	Energy [kWh/m²]/% Heating	Energy [kWh/m²]/% Cooling	Min	NPV [EUR/m²] Most. Prob.	Max
1 EGR	25 kWh/m²/16%	3 kWh/m²/ 8%	−16	−7	3
1 IGR	34 kWh/m²/22%	8 kWh/m²/ 21%	−12	−2	10
2 EGR	-	-	−34	−27	−20
2 IGR	-	-	−48	−38	−29
3 EGR	25 kWh/m²/16%	3 kWh/m²/8%	17	42	83
3 IGR	34 kWh/m²/22%	8 kWh/m²/21%	53	83	132
4 EGR	-	-	−19	6	26
4 IGR	-	-	−16	9	23

Figure 3. Reduction in energy need (percentage) for cooling and heating compared to the current state of the apartment under the (green) roof obtained with: (**a**) EGR and (**b**) IGR.

The results of the economic analysis are presented in Table 5. Based on the presented input data for the apartment under the green roof, the life cycle NPV for model 3 is computed in the range of EUR 17/m^2 to EUR 132/m^2, depending on the type of the roof when the property value increase is accounted as a benefit. By analyzing the models without this benefit, it can be said that there are dominantly negative outcomes of NPV values for scenarios 1 and 2, which may be the case with similar location and envelope properties. It is important to emphasize that the analyzed object has eight residential units, and for similar energy performance buildings with a higher number of RU, individual users (investors) could have lower installation costs but lower benefits from membrane longevity as well. Therefore, sensitivity analysis evaluated the impact of this parameter. Since the social benefits, but also the costs, are excluded from the NPV model in this paper, corresponding life cycle assessment analysis should incorporate the negative aspects of old roof disposal aspects as well.

Since the uniform variations included an estimated green roof lifespan of 40 to 55 years, in Figure 4, the most probable result for NPV of the life cycle projected to 47 years is presented for all models. These results indicate that energy savings are not the crucial aspect of the economic benefits of investment, even for the model with the IGR. Based on the calculation, it is clear that the payback period is not more than one year for the models incorporating this benefit. This outcome is expected because the increase of the property value has become significantly higher than the initial costs—if it is distributed on all residential units of the building. An analogous observation is in accordance with sensitivity analysis. Moreover, the property value increase broadly determines the outcome of the NPV at the end of the life cycle, and the shape of the LCC curve is depicting the asymptotic tendency of the final result (Figure 4.). The influence of a number of residential units is analyzed through sensitivity analysis. For the different numbers of RU, the NPV value curve tends to increase or decrease with a high rate for all models, which will be indicated in the sensitivity analysis. For an individual investor (number of RU = 1) in the equivalent model, the NPV value would further decrease to EUR −176/m^2, EUR −254/m^2, EUR −124/m^2, and EUR −170/m^2, for models 1 EGR, 1 IGR, 3 EGR, and 3 IGR, respectively. LCC analysis can present different results depending on the climate and economic parameters, but various costs and benefits that are included in the calculation could alter the results as well. In ref. [14], the most probable NPV for installation of EGR on detached house was calculated as USD 351/m^2, with significant benefits obtained by thermal envelope improvement. In the first scenario in ref. [55], where property with a constructed green roof is being used after construction, the most probable NPV is calculated as USD 173/m^2 and USD 213/m^2 for EGR and IGR, respectively. In the second scenario where property is being sold after construction, the most probable NPV is calculated as USD −16/m^2 and USD −41/m^2 for EGR and IGR, respectively The most probable NPV calculated in ref. [13] was USD 291/m^2 and USD 611/m^2 for EGR and IGR, respectively. However, it should be noted that the corresponding analysis, presented in ref. [13], included additional benefits in the form of avoidance of infrastructure cost. Moreover, in compared results from the literature [13,14,55], the distribution of costs on other RUs was not analyzed.

Sensitivity analysis was based on the variance-based method [77] that was implemented in the Python library [78]. Sensitivity analysis is one of the tools in the impact assessment procedure recommended by regulatory documents [79]. The proposed method enables the calculation of the first (S_i) and the second order (S_{ij}) sensitivity indices, as well as total effects index. Besides parameters from Table 4, additional significant factors are taken into account in Table 6. First-order sensitivity indices of parameters for NPV indicate the greatest influence of the property value increase on the outcome, while the benefit of the heating energy reduction is only significant for models 1 EGR and 1 IGR. This is due to the poor current state of the thermal envelope of the building, but this effect is less pronounced in models 3 EGR and 3 IGR. As is the case with similar numerical analyses, the discount rate also has a notable impact on the formation of NPV results given that the life cycle of a green roof is high. Second-order sensitivity indices, which determine

interactions between parameters, are insignificant for the presented analysis and hence the total sensitivity indices are close to the first-order.
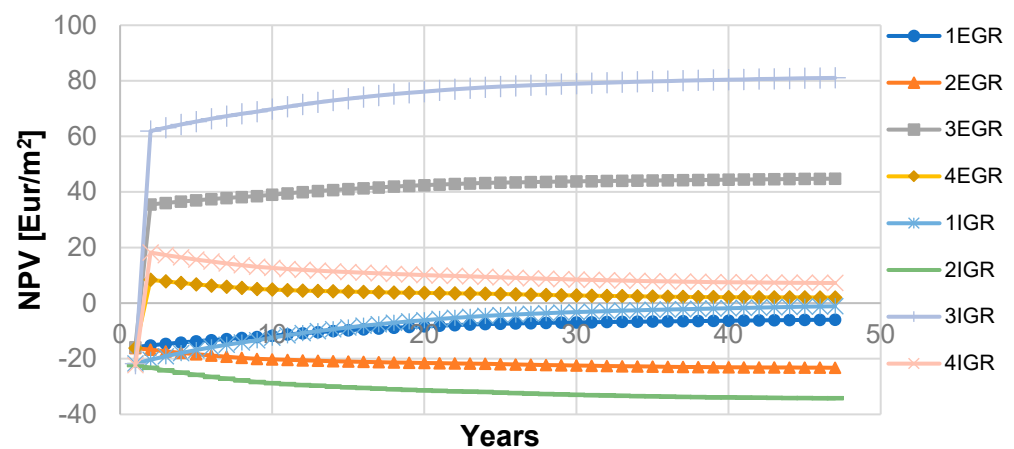

Figure 4. The life cycle of green roof—N = 47 years—calculated NPV for proposed models—most probable scenario for different models.

Table 6. First-order sensitivity indices for different parameters in life cycle analysis.

	Type	1 EGR	1 IGR	2 EGR	2 IGR	3 EGR	3 IGR	4 EGR	4 IGR
S1 [%]	Old roof removal	0.136	0.2478	0.313	0.49	0.065	0.095	0.19	0.28
S2 [%]	Installation	7.14	6.7	16.9	13.55	3.49	2.57	10.5	7.7
S3 [%]	Operation and Maintenance	4.9	6.5	11.8	12.9	2.5	2.5	7.3	7.4
S4 [%]	Property value	0	0	0	0	50.4	59.3	39.1	44.4
S5 [%]	Membrane longevity	0.0833	0.042	0.24	0.113	0.053	0.015	0.14	0.063
S6 [%]	Heating	39.7	34	0	0	19.14	12.9	0	0
S7 [%]	Cooling	0.6	2.29	0	0	0.3	0.88	0	0
S8 [%]	Number of RU.	26.7	31.7	63	63.6	12.85	12.2	39.2	36.26
S9 [%]	Discount rate	18.2	16.7	5.7	7.46	11.6	8.7	2.33	2.85
S10 [%]	Gr. roof lifespan [years]	0.5	0.43	0.0417	0.062	0.3	0.16	0.0248	0.034

It is clear that the estimated life cycle period, within a range from 40 to 55 years, also does not significantly affect the outcome, although the membrane longevity parameter has a higher probability to occur twice for a green roof with a longer lifespan. That remark is consistent with the shape of the NPV curve presented in Figure 4, which is almost constant after 40 years. For models 2 and 4 (without the benefits of energy reduction), the most dominant factor is the number of RUs and the increase in the value of the properties, respectively. Although installation cost is a parameter with the highest value in all models, it is not the most influential since it is distributed to all residential units. The most influential economic factors in sensitivity analysis in [13] was discount rate, while the property value was the most important non-economic factor in LCC model from private perspective. In the first scenario in [55], the most influential parameters were discount rate and energy savings, while in the second scenario, initial cost and property value increase were the most decisive parameters in the NPV calculation. On the other hand, in ref. [14], the most important factors for NPV were maintenance cost and discount rate.

Based on the results obtained in sensitivity analysis, the presented approach could be extended to different typologies of buildings in future research as it would give different absolute and relative values of parameters in life cycle analysis.

6. Conclusions

This paper presented the analysis of the potential application of green roofs in urban areas and the economic effects for private users on a specific example of a building in Belgrade. Since the city center is always the most affected by the UHI effect, the significant potential for increasing the current state of the green area is revealed. This possibility is perceived through the high percentage of buildings with a flat roof in the observed area, and their capacity for additional loading after removing current layers of the roof structure. Energy efficiency calculation is performed in the EnergyPlus 9.1.0 software, and it referred to the energy savings of the apartment under the proposed green roof. In the presented study, application of green roofs reduces the energy need for heating and cooling up to 22% and 21%, respectively. Those results are in the agreement with those reported in the literature. Since the variance-based approach is used in sensitivity analysis, a relatively small difference in parameter values is amplified, resulting in the reduction in cooling energy being insignificant in comparison to the heating energy reduction. Although this approach is efficient and enables calculation of second-order effects in the sensitivity analysis, no such dependence on factors is observed.

The economic profitability analysis took into account other relevant benefits and costs for the private users through a probabilistic lifecycle approach. This paper aimed to emphasize personal gain by focusing on individual benefits for different users as it predominantly affects investment comprehension. Hence, the presented investigation also provided insight into economic interest from the perspective of distinct RUs of existing buildings that aim for green roof renovation. By examining the top floor of such a building, it becomes evident that implementing a green roof can enhance energy efficiency to a comparable or even greater extent than traditional energy renovations (as per the BAU scenario). The proposed concept of cost distribution led to a positive life cycle NPV even for other residential units if the property value increase is counted as a benefit. Moreover, positive implications are identified at the public level, which should activate local authorities to significantly stimulate green roof implementation projects for existing and new buildings. The relevance of the number of residential units taking part in the investment is determined, and it is concluded that for the individual investor, the NPV of the project would decrease substantially. Although in the presented analysis, property value increase is conservatively estimated, it is the most influential factor in NPV models that include this benefit, with a high probability of negative values in all other models. Therefore, in those models, additional social benefits must be included in the project to be profitable. Moreover, in future research, this benefit must be determined precisely with an appropriate pricing model and market analysis for existing buildings. The presented typology of flat roofs indicates EGR as the most practical solution for existing buildings, as was concluded in analogous research. According to data related to the load capacity of existing roofs, it can be seen that there is limited possibility for installing IGR. Nevertheless, its environmental impact and higher NPV (in most cases) could motivate investors and decision-makers to support these types of projects.

These conclusions imply the existence of the influential role of local authorities and government in generating such projects through a subsidy policy, tax abatements, and official programs for different social benefits in both the public and private building sectors.

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