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Sustainable Green Roofs: Thermal Insulation & Environmental Assessment

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ABSTRACT:
This research aimed to evaluate both the socio-perceptual drivers and the thermal-energy performance of extensive green roofs in Timişoara, Romania. A mixed-methods approach was employed, combining a survey of 400 residents to assess awareness, willingness, and perceived barriers to adoption, along with dynamic building energy simulations using IES-VE software. A five-story residential building was modeled to compare a conventional roof with an extensive green roof system integrated with five insulation materials: glass wool, foamed glass, rock wool, expanded polystyrene (EPS), and polyurethane. The simulation results demonstrated that green roofs significantly improved thermal performance, with polyurethane insulation achieving the lowest U-value (0.07 W/m²·K), reducing summer indoor temperatures by approximately 1°C, and lowering carbon emissions by up to 33% compared to the base case. Energy savings reached 14.56 MWh annually. Concurrently, the survey revealed that residents' willingness to adopt green roofs was positively influenced by environmental awareness, supportive regulations, and financial incentives, with cost remaining a primary barrier. In conclusion, extensive green roofs, particularly when combined with high-performance insulation such as polyurethane, offer a viable strategy for enhancing urban sustainability in temperate climates. Their broader implementation can be facilitated through targeted policies, public awareness campaigns, and financial support mechanisms.

Keywords: Green Roof; Urban Heat Island (UHI); Thermal Insulation; Energy Performance; Irrigation,

INTRODUCTION

Urban areas across the globe are experiencing mounting pressures from climate change, rapid urbanization, and deteriorating environmental quality. Rising surface temperatures, declining air quality, and increasing energy demand for heating and cooling have made cities particularly vulnerable to ecological and public health challenges (Feijó-Muñoz et al., 2019). Within this context, nature-based solutions have emerged as promising strategies to reconcile urban growth with environmental resilience (Bush & Doyon, 2019; Castelo et al., 2023; Colléony & Shwartz, 2019; Kabisch et al., 2016; Scott et al., 2016).

Among these, green roofs stand out as an innovative and multifunctional approach that *integrates* vegetation into the built environment, offering benefits that *extend* across ecological, social, and economic dimensions (Ashinze et al., 2024; Bosch et al., 2023; Cascone, 2024; Ibáñez Gutiérrez & Ramos-Mejía, 2019; Teotónio et al., 2018). Green roofs (*GFs*) can be broadly categorized into intensive and extensive systems. Intensive roofs, characterized by deeper substrates and diverse vegetation, provide higher ecological performance but are costly and structurally demanding. Extensive roofs, in contrast, employ thinner substrates and hardy plant *species*, making them lighter, more affordable, and adaptable to a wider range of building typologies (Love, 2020; Massey, 2025). Their lower maintenance requirements and feasibility for retrofitting have positioned extensive green roofs as a practical solution for cities seeking scalable and cost-effective climate adaptation measures. Beyond aesthetics, they deliver tangible environmental services such as reducing the urban heat island (*UHI*) effect, enhancing stormwater management, and improving thermal performance by acting as additional insulation layers.

Previous research has substantiated these benefits across various climates. For instance, studies in temperate European climates have demonstrated that green roofs can reduce building energy consumption for air conditioning by up to 75% in summer and lower heating demand in winter, highlighting their year-round utility. Research in Mediterranean regions has further confirmed the cooling potential of green roofs, with recorded surface temperature reductions of up to 30°C compared to conventional roofs (Evangelisti et al., 2020). Systematic reviews have consolidated evidence that green roofs contribute to significant energy savings, carbon emission reductions, and enhanced urban biodiversity, solidifying their role in sustainable urban design (Berardi et al., 2013; Aleksejeva et al., 2024).

Figure Error! No text of specified style in document.. **Different types of Green Roofs (Jungels, 2013)**

Despite these advantages, the adoption of extensive green roofs is influenced not only by their technical and environmental performance but also by social perception and willingness to embrace such innovations. Studes in Europe and beyond suggest that public acceptance, awareness of benefits, and trust in long-term performance significantly shape adoption trends. Therefore, a comprehensive understanding of both environmental performance and community perceptions is essential to inform urban sustainability policies (Benedetta Barozzi et al., 2016).

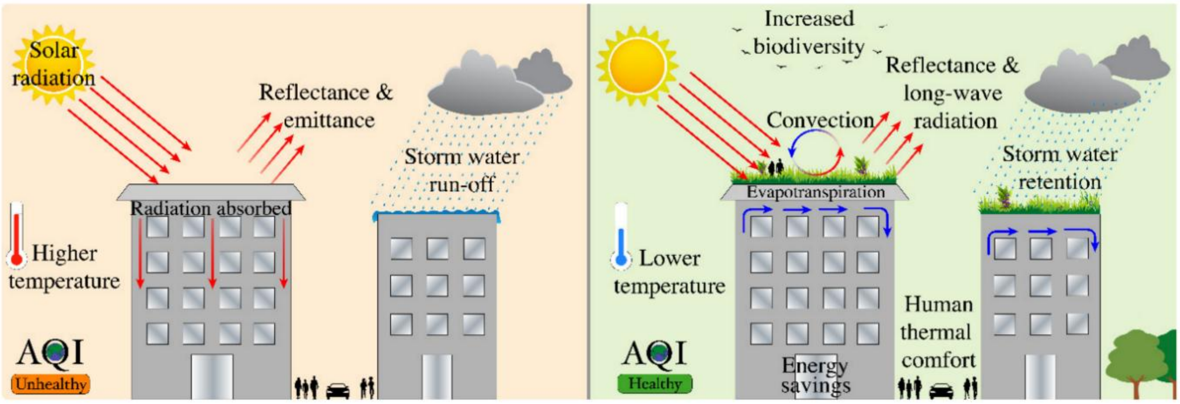


Figure 2. Green roofs as sustainable alternative (Yan & Zhu, 2025)

This research situated itself within this dual perceptive. The selected case study building in Timisoara, Romania, represents a relevant urban context where energy efficiency and ecological resilience are pressing policy concerns. Although the building does not currently feature an extensive green roof, it serves as a model for applying simulation-based analyses. By integrating quantitative assessments with qualitative insights, this research explores 2 critical and important dimensions that include: (i) perceptions and willingness of people toward adopting extensive green roofs, and (ii) comparative environmental extensive green roofs, against traditional insulating materials. This dual inquiry allows for an enriched understanding of both human and technical factors that influence adoption pathways.

Positioning the buildings as a reference model enables the evaluation of insulation effects under realistic architectural and climate conditions. Such comparative analysis offers evidence for whether extensive green roofs can function as viable alternatives or complementary solutions to traditional thermal insulation materials. Coupling these findings with survey-based insights on community willingness provides all-inclusive foundation to support policy recommendations, particularly in contexts where economic feasibility, climate mitigations, and public engagements converge (Hitayezu, 2021; Martin, 2017; Nampushi, 2015; Rockabrand, 2025; Singh et al., 2024).

This study contributes to the broader discourse on sustainable urban development by bridging technical performance analysis with socio-cultural acceptance. It underscores the role of extensive green roofs as a practical tool for enhancing building performance while also addressing the social dimensions that determine their broader diffusion. By focusing on the Timisoara case, the study provides both localized insights and transferable lessons that may guide green infrastructure adoption in similar urban contexts across Europe and beyond.

Therefore, this study aims to fill the gap by conducting a comprehensive assessment of extensive green roofs, combining technical-thermal performance analysis with an evaluation of social perceptions in specific urban contexts. The main objective is to investigate the effectiveness of green roofs combined with various traditional insulation materials in improving the energy efficiency and thermal comfort of a building in Timisoara, Romania, as well as to analyze the social factors that influence citizens' willingness to adopt this technology. Thus, the benefit of this study is that it provides strong empirical evidence for policymakers, urban planners, and property developers regarding the potential of green roofs as a technically feasible and socially acceptable green infrastructure solution. These findings are expected to drive more effective policymaking, such as financial incentives and supportive regulatory frameworks, to accelerate the adoption of extensive green roofs, ultimately contributing to more sustainable, climate-resilient, and community-well-being-oriented urban development.

METHOD

The methodology adopted for the achievement of the study aims is defined in this chapter. It establishes a systemized means for the study's goals i.e. Checking of citizen perception on the implications of green roofs in Timisoara, Romania, and assess the thermal and energy performance of extensive green roofs with alternative insulation materials using dynamic simulation tools.

The methodology integrated both primary survey data and building performance modeling to create a comprehensive understanding of adoption drivers, energy efficiency, and climate mitigation potential. This dual approach allows for the triangulation of social and technical findings, providing a foundation for policy and design recommendations.

RESULTS AND DISCUSSION

Model X

The baseline stimulation was carried out on the Timisoara case study building to assess its thermal and energy performance. Climate data for zone II (heating) and zone III (cooling) were applied in IESVE.

The structure, built of reinforced concrete panels with AAC insulation, was assigned to a thermal mass of 120kJ (m^2.k). Windows performance was set with U-values of1.4 W/m2K and g-value of 0.39. The roof, modeled as an extensive green roof with a waterproofing membrane, substrate, vegetation layer, and 245mm Rockwool insulation, achieved a u-value of 0.15 W/m^2K. External walls with 4 layers result in a U-value of 0.20W/m^2K.

Table 1. Analysis of external wall construction layers on IESVE software

Material Description	Thickness (mm)	Thermal Conductivity W/(m·K)	Density (kg/m³)	Specific Heat (J/kg·K)	Thermal Resistance (m²K/W)	Vapour Resistivity (GN·s/kg·m)	Classification
Rainscreen Panel	66	49.80	7,790	455	0.0013	–	Metal

Cellular Glass (ASHRAE)	111	0.051	138	805	2.176	49,800	Insulating Material
Glass Fibre with Organic Binder (ASHRAE)	13	0.037	102	995	0.351	10.2	Insulating Material
Waterproof Membrane	3	0.998	1,105	1,005	0.0030	–	Asphalt & Roofing Layer
Insulated Steel Stud Cavity (OC 16, ASHRAE)	151	0.084	31	995	1.786	51.0	Insulating Material
Structural Steel	274	49.9	7,805	482	0.0055	3,000,100	Metal
Steel Siding – HF – A3	71	0.352	7,685	420	0.202	3,000,050	Metal
Plasterboard (Type I)	16	0.212	705	995	0.075	0.0	Plaster
Plasterboard (Type II)	15	0.211	702	1,000	0.071	0.0	Plaster

Source: Simulation data processed by the authors.

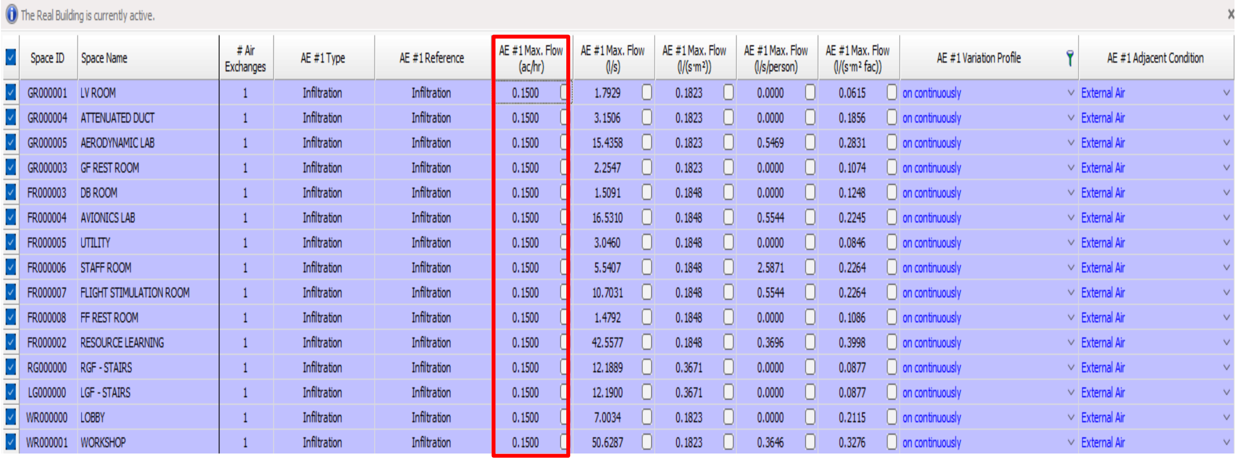
Table 2. Analysis of Roof layers on IESVE software

Material Description	**Thickness (mm)**	**Thermal Conductivity W/(m·K)**	**Density (kg/m^3)**	**Specific Heat (J/kg·K)**	**Thermal Resistance (m^2K/W)**	**Vapour Resistivity (GN·s/kg·m)**	**Classification**
Waterproof Membrane	2	0.998	1,105	1,005	0.0030	–	Asphalt & Roofing Layer
Glass Wool Insulation	246	0.0385	198	675	6.29	6.0	Insulating Material
Metal Deck (ASHRAE Ref.)	199	159.8	2,805	900	0.00125	9,999,500	Metal

Source: Simulation data processed by the authors

According to the standard, the building's air permeability is 5 m^3/(h.m^2) at 50 Pa. with IESVE, this translates to an air infiltration rate of 0.15 ac/hr., derived by dividing permeability by 20.

Table 3. Infiltration rate on IESVE



The Real Building is currently active.

☑	Space ID	Space Name	# Air Exchanges	AE #1 Type	AE #1 Reference	AE #1 Max. Flow (ac/hr)	AE #1 Max. Flow (l/s)	AE #1 Max. Flow (l/(s·m²))	AE #1 Max. Flow (l/s/person)	AE #1 Max. Flow (l/(s·m² fac))	AE #1 Variation Profile	AE #1 Adjacent Condition
☑	GR000001	LV ROOM	1	Infiltration	Infiltration	0.1500	1.7929	0.1823	0.0000	0.0615	on continuously	External Air
☑	GR000004	ATTENUATED DUCT	1	Infiltration	Infiltration	0.1500	3.1506	0.1823	0.0000	0.1856	on continuously	External Air
☑	GR000005	AERODYNAMIC LAB	1	Infiltration	Infiltration	0.1500	15.4358	0.1823	0.5469	0.2831	on continuously	External Air
☑	GR000003	GF REST ROOM	1	Infiltration	Infiltration	0.1500	2.2547	0.1823	0.0000	0.1074	on continuously	External Air
☑	FR000003	DB ROOM	1	Infiltration	Infiltration	0.1500	1.5091	0.1848	0.0000	0.1248	on continuously	External Air
☑	FR000004	AVIONICS LAB	1	Infiltration	Infiltration	0.1500	16.5310	0.1848	0.5544	0.2245	on continuously	External Air
☑	FR000005	UTILITY	1	Infiltration	Infiltration	0.1500	3.0460	0.1848	0.0000	0.0846	on continuously	External Air
☑	FR000006	STAFF ROOM	1	Infiltration	Infiltration	0.1500	5.5407	0.1848	2.5871	0.2264	on continuously	External Air
☑	FR000007	FLIGHT STIMULATION ROOM	1	Infiltration	Infiltration	0.1500	10.7031	0.1848	0.5544	0.2264	on continuously	External Air
☑	FR000008	FF REST ROOM	1	Infiltration	Infiltration	0.1500	1.4792	0.1848	0.0000	0.1086	on continuously	External Air
☑	FR000002	RESOURCE LEARNING	1	Infiltration	Infiltration	0.1500	42.5577	0.1848	0.3696	0.3998	on continuously	External Air
☑	RG000000	RGF - STAIRS	1	Infiltration	Infiltration	0.1500	12.1889	0.3671	0.0000	0.0877	on continuously	External Air
☑	LG000000	LGF - STAIRS	1	Infiltration	Infiltration	0.1500	12.1900	0.3671	0.0000	0.0877	on continuously	External Air
☑	WR000000	LOBBY	1	Infiltration	Infiltration	0.1500	7.0034	0.1823	0.0000	0.2115	on continuously	External Air
☑	WR000001	WORKSHOP	1	Infiltration	Infiltration	0.1500	50.6287	0.1823	0.3646	0.3276	on continuously	External Air

Source: Simulation data processed by the authors

As per BS EN ISO 7730, thermal comfort is defined as a "state of mind that reflects satisfaction with the surrounding thermal environment". It is primarily influenced by parameters such as sir temperature, air velocity, mean radiant temperature, and humidity. In addition, both BS EN ISO 7730 and BS EN ISO 10551 highlight that thermal comfort can be quantified through two indices: the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfaction (PPD).

Simulation on Natural Ventilation and HVAC

Table Error! No text of specified style in document.. **Base Case Model table on ventilation and HVAC, Ground Floor**

Case	U-value (W/m²·K)	Season	Air Temp (°C)	Mean Radiant Temp (°C)	PMV	PPD (%)	Carbon (kgCO₂)	Electricity (MWh)	Energy (MWh)
Base Case – Rockwool (Natural Ventilation)	0.15	**Winter**	6.69	6.82	-2.86	98.27	842	–	–
		Summer	27.81	26.51	1.38	5.00	842	–	–
Base Case – Rockwool (HVAC)		**Winter**	16.00	15.08	-1.17	44.59	5035	37.41	37.41
		Summer	27.82	26.55	1.38	5.01	5035	37.41	37.41

Source: Simulation results from IES-VE

The simulation results for the ground and first floors indicate noticeable differences between natural ventilation and HVAC operation. With the installation of an air-to-air heat pump, the indoor winter temperature improved significantly, from 6.69 °C on the ground floor and 7.48 °C on the first floor to 16 °C in both cases. In contrast, summer conditions showed little to no reduction in indoor temperature. The mean radiant temperature during summer increased slightly under HVAC operation, by 0.04 °C on the ground floor and 0.06 °C on the first floor.

Thermal comfort indicators also showed improvement. The Predicted Mean Vote (PMV) on the first floor rose from -2.70 under natural ventilation to -1.15 with HVAC during winter, while summer values increased marginally by 0.01. For the ground floor, 98.27% of occupants were predicted to be dissatisfied under natural ventilation, but HVAC reduced this figure by 53.68%. Similarly, dissatisfaction levels on the first floor dropped from 96.72% to 33.62% in summer, meaning that approximately 63.1% of occupants reported comfort improvements following HVAC integration.

Based on these findings, the comparative analysis between natural ventilation and HVAC highlights the significant role of active systems in enhancing thermal comfort. To meet the study's broader objectives, further simulations will be conducted to evaluate the performance of green roofs against the base case model, focusing particularly on their potential as high-performing insulation strategies.

Base Model Y - Roof Improvement with Green Roof

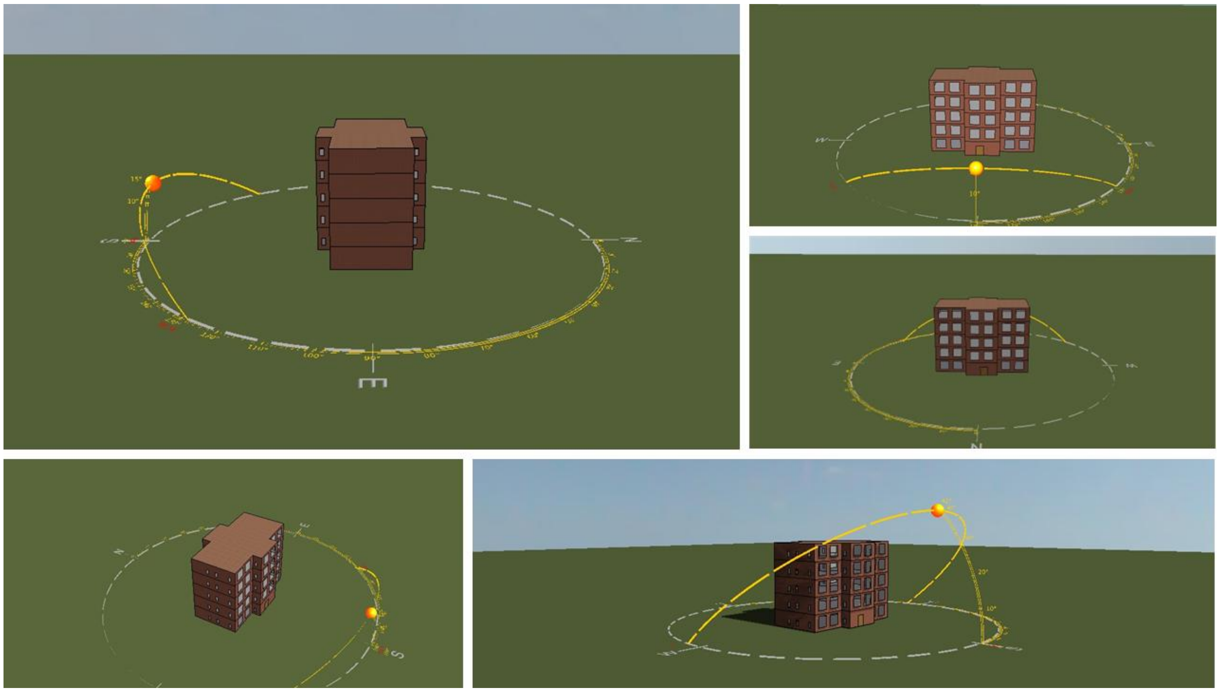


Figure 3. Sectional drawing of Base case model

Source: Author's own illustration.

Analysis with Inorganic Glass wool Insulation

The simulation carried out a green roof incorporating glass wool insulation shows improvements in U-values, thermal comfort, and energy efficiency. As presented in table 4.12, the u values decreased, by 0.04. In terms of thermal comfort, the indoor air temperature on the 1st floor dropped by 1.08 C compared to the results shows in 4.13. during summers, the mean radiant temperature slightly increased from 25 .06 to 25.22 C with the green roof system, The OMV showed a decline from 1.17 to 1.10 in summer, while the PPD was reduced by 4.03% on the ground floor and 0.88% on the first floor.

From an energy perceptive, the green roof exhibited superior performance by significantly lower carbon emissions, recording a reduction of 1380 kgCO^2 (equivalent to a 33% decrease). Additionally, electricity and energy consumption were reduced, with savings of approximately 14 MWH achieved through the application of green roof with glass wool insulation.

Table 5. Analysis of construction layers on IESVE for glass wool insulation

Material	Thickness (mm)	Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)	Thermal Resistance (m²K/W)	Vapour Resistivity (GN·s/kg·m)	Category
Cultivated Clay Soil	150	1.18	1,800	1,250	0.22	250	Soil, Sand & Stone Mix
Gravel-Rich Soil	100	0.52	2,050	185	0.19	250	
Glass Wool Insulation (Layer 1)	150	0.040	200	670	3.75	6.0	Insulation
Glass Wool Insulation (Layer 2)	150	0.040	200	670	3.75	6.0	
Gypsum/Plasterboard (ASHRAE Ref.)	50	0.21	800	840	0.24	45	Plaster
Medium-Weight Cast Concrete (BS EN 1745)	300	1.40	1,900	1,000	0.21	500	Concrete

Source: Material library and simulation data

Table 6. Ground and First Floor, Glasswool insulation

Floor Level	Season	Parameter	Value
Ground Floor	Winter	U-Value (W/m²·K)	0.11
		Air Temperature (°C)	16.00
		Mean Radiant Temp (°C)	15.09
		PMV	-1.17
		PPD (%)	5.00
		Carbon (kgCO₂)	3355
		Electricity (MWh)	23.41
		Total Energy (MWh)	23.41
	Summer	U-Value (W/m²·K)	0.11
		Air Temperature (°C)	27.36
		Mean Radiant Temp (°C)	26.56
		PMV	1.31
		PPD (%)	40.65

Floor Level	Season	Parameter	Value
		Carbon (kgCO₂)	3355
		Electricity (MWh)	23.41
		Total Energy (MWh)	23.41
First Floor	Winter	U-Value (W/m²·K)	0.11
		Air Temperature (°C)	16.00
		Mean Radiant Temp (°C)	15.27
		PMV	-1.15
		PPD (%)	5.00
		Carbon (kgCO₂)	3355
		Electricity (MWh)	23.41
		Total Energy (MWh)	23.41
	Summer	U-Value (W/m²·K)	0.11
		Air Temperature (°C)	26.74
		Mean Radiant Temp (°C)	25.22
		PMV	1.10
		PPD (%)	32.74
		Carbon (kgCO₂)	3355
		Electricity (MWh)	23.41

Source: Simulation results from IES-VE

Analysis with Inorganic Foamed Glass Insulation

The Construction layer has a thickness of 900mm, a U-value of 0.14 W/m2.K, and an R-value of 6.452 m2.K/W.

Table 7. Analysis of Foamed Glass Insulation using IESVE

Material	Thickness (mm)	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific Heat Capacity (J/kg·K)	Thermal Resistance (m²·K/W)	Vapour Resistivity (GN·s/kg·m)	Category
Cultivated Clay Soil	150	1.18	1795	1245	0.218	252	Sands, Stones, and Soils
	100	0.52	2045	185	0.192	248	
Foamed Glass	150	0.051	137	805	2.95	50,200	Insulating Materials
Gypsum / Plasterboard (ASHRAE)	150	0.051	137	805	2.95	50,200	
Cast Concrete (Medium Weight, BS EN 1745)	50	0.21	800	835	0.238	46	Plaster
	300	1.40	1905	1005	0.214	505	Concretes

Source: Material library and simulation data

Table 8. Ground and First Floor - Foamed Insulation

Parameter	Ground Floor	First Floor
U-Value (W/m^2·K)	0.14	0.14
Air Temperature – Winter (°C)	16.00	16.00
Air Temperature – Summer (°C)	27.36	26.74
Mean Radiant Temp – Winter (°C)	15.09	15.24
Mean Radiant Temp – Summer (°C)	26.55	25.16
PMV – Winter	-1.17	-1.15
PMV – Summer	1.31	1.11
PPD – Winter (%)	5.00	5.00
PPD – Summer (%)	40.65	32.87
Carbon Emissions (kgCO_2)	3410	3410
Electricity (MWh)	23.77	23.77
Total Energy (MWh)	23.77	23.77

Source: Simulation results from IES-VE

The simulation results of this analysis, present in the tables above shows that a marginal improvemnet compared with the analysis of glass wool done in above section, the U-values decreased slightly by 0.01. During summer, the first-floor aim temperature dropped by 1.08 °C, while the mean radiant temperature rose marginally by 0.10 °C.

Analysis with Inorganic Rockwool Insulation

The application of inorganic rockwool insulation at a thickness of 900mm demonstrate strong thermal resistance. The system achieves a U-values of 0.10 W/m2.K, shows that minimal heat transfer is going on, while the corresponding R-values of 9.0238 m2.K/W reflects its high insulating capacity.

Table 9. Analysis with Rockwool Insulation

Material	Thickness (mm)	Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (J/kg·K)	Thermal Resistance (m^2·K/W)	Vapour Resistivity (GN·s/kg·m)	Category
Cultivated Clay Soil	150	1.18	1802	1248	0.217	252	Sands, Stones, and Soils
Gravel-Based Soil	100	0.52	2048	185	0.192	249	
Rockwool	150	0.036	31	1005	4.17	6.1	Insulating Materials
Gypsum / Plasterboard (ASHRAE)	50	0.21	800	835	0.238	46	Plaster
Cast Concrete (Medium Weight, BS EN 1745)	300	1.40	1905	1002	0.214	505	Concretes

Source: Material library and simulation data

Table 10. Ground and First Floor – Rockwool insulation

Category	Indicator	Season	Ground Floor	First Floor
Envelope	U-Value (W/m²·K)	–	0.11	0.11
Indoor Conditions	Air Temperature (°C)	Winter	16.00	16.00
		Summer	27.35	26.73
	Mean Radiant Temp (°C)	Winter	15.10	15.27
		Summer	26.58	25.23
Comfort Indices	PMV	Winter	-1.16	-1.14
		Summer	1.30	1.12
	PPD (%)	Winter	5.01	5.00
		Summer	40.60	32.72
Energy & Emissions	Carbon Emissions (kgCO₂)	Annual	3,325	3,325
	Electricity (MWh)	Annual	23.25	23.25
	Total Energy (MWh)	Annual	23.25	23.25

Source: Simulation results from IES-VE

The results shows that U-value with rock wool decreased by 0.05 w/m^2.K compared to Model X, performing better than glass wool and foamed glass. Summer air temperature on the first floor dropped by 1.07, while winter showed little changes. PMV stayed the samen, but PPD improved by 0.92%. Carbon emission fell by 33.9% and energy use dropped by 37.9%.

Analysis With Organic Expanded Polystyrene Insulation (Cibse)

The expanded polystyrene insulation, with a thickness of 900mm, achieves a U-values of 0.10 W/m^2.K and corresponds to an R-values of 9.0238 m^{2}K/W.

Table 11. Analysis with Expanded Polystyrene Insulation

Material	Thickness (mm)	Thermal Conductivity (W/m·K)	Density (kg/m³)	Heat Capacity (J/kg·K)	Thermal Resistance (m²K/W)	Vapour Resistivity (GN·s/kg·m)	Category
Cultivated clay soil	150	1.18	1800	1250	0.22	250	Natural soils and aggregates
Gravel-based soil	100	0.52	2050	184	0.19	250	Natural soils and aggregates
Expanded polystyrene (EPS)	150	0.035	25	1400	4.29	200	Thermal insulation material
Expanded polystyrene (EPS) layer	150	0.035	25	1400	4.29	200	Thermal insulation material
Gypsum/plasterboard (ASHRAE std.)	50	0.21	801	837	0.24	45	Finishing/Plaster
Cast concrete (medium weight)	300	1.40	1900	1000	0.21	500	Concrete (structural)

Source: Material library and simulation data

Table 12. First Floor and Ground Floor – EPS

Floor Level	Material	Parameter	Winter	Summer
Ground Floor	Green roof – Expanded Polystyrene	U-Value (W/m^2·K)	0.10	0.10
		Air Temperature (°C)	16.00	27.36
		Mean Radiant Temp (°C)	15.09	26.57
		PMV	-1.17	1.31
		PPD (%)	5.00	40.66
		Carbon Emissions (kgCO_2)	-	3327
		Electricity (MWh)	-	23.23
		Total Energy (MWh)	-	23.23
First Floor	Green roof – Expanded Polystyrene	U-Value (W/m^2·K)	0.10	0.10
		Air Temperature (°C)	16.00	26.75
		Mean Radiant Temp (°C)	15.28	25.25
		PMV	-1.15	1.11
		PPD (%)	5.00	32.69
		Carbon Emissions (kgCO_2)	-	3327
		Electricity (MWh)	-	23.23
Total Energy (MWh)			-	23.23

Source: Simulation results from IES-VE.

The simulation results of insulation materials, as presented in table above, shows consistent result with those of previous cases in terms of U-values, thermal comfort and energy performance. Despite variations in density, specific heat capacity, and vapor resistivity when compared with both above table, the overall outcome remains unchanged. Therefore, it can be inferred that booth Rockwool and Expanded Polystyrene provide comparable thermal performance, maintaining similar effects on indoor temperature, energy consumption, and carbon emission.

Analysis of Organic Polyurethane Insulation Board

1. Thickness – 900mm
2. U-value 0.07W/m^2. K
3. R-value 12.4524 m^2K/W

Table 12. Analysis of Polyurethane Insulation using IESVE

Material	Thickness	Conductivity	Density	Specific Heat Capacity	Thermal Resistance	Vapour Resistivity	Category
Cultivated clay soil	150 mm	1.28 W/m·K	1800 kg/m^3	1250 J/kg·K	0.32 m^2K/W	240 GN·s/kg·m	Sands, stones & soils
Gravel-based soil	100 mm	0.58 W/m·K	2050 kg/m^3	185 J/kg·K	0.19 m^2K/W		
Polyurethane insulation	150 mm	0.025 W/m·K	30 kg/m^3	1450 J/kg·K	6.00 m^2K/W	450 GN·s/kg·m	Insulating material
Gypsum / plasterboard (ASHRAE)	50 mm	0.25 W/m·K	801 kg/m^3	827 J/kg·K			

Source: Simulation results from IES-VE

Table 13. First Floor and Ground Floor - Polyurethane Insulation

Parameter	Winter	Summer
U-Value (W/m²·K)	0.07	
Air Temperature (°C)	16.00	27.36
Mean Radiant Temp (°C)	15.09	26.58
PMV	-1.17	1.31
PPD (%)	5.00	40.67
Carbon (kgCO₂)	3268	3268
Electricity (MWh)	22.85	22.85
Energy (MWh)	22.85	22.85

Source: Simulation results from IES-VE

Table 14. Results for Base Model X and Y (Ground-floor)

Case Study / Material	U-Value (W/m²·K)	Air Temp (°C) – Winter	Air Temp (°C) – Summer	Mean Radiant Temp (°C) – Winter	Mean Radiant Temp (°C) – Summer	PMV (Winter)	PMV (Summer)	PPD (%) – Winter	PPD (%) – Summer	Carbon (kgCO₂)	Electricity (MWh)	Energy (MWh)
Base Case – Rockwool (Natural Vent.)	0.15	6.69	27.81	6.82	26.51	-2.86	1.38	5.00	98.27	842	–	–
Base Case – (HVAC)	0.15	16.00	27.82	15.08	26.55	-1.17	1.38	5.01	44.59	5035	37.41	37.41
Glass Wool	0.11	16.00	27.36	15.09	26.56	-1.17	1.31	5.00	40.65	3355	23.41	23.41
Foamed Glass	0.14	16.00	27.36	15.09	26.55	-1.17	1.31	5.00	40.65	3	–	–

Source: Compiled simulation results from IES-VE

Table 15. Results for Base Model X and Y (First-floor)

Scenario / Insulation Type	U-Value ($W/m^2·K$)	Air Temperature (°C) – Winter	Air Temperature (°C) – Summer	Mean Radiant Temp (°C) – Winter	Mean Radiant Temp (°C) – Summer	PMV (Winter)	PMV (Summer)	PPD (%) – Winter	PPD (%) – Summer	Carbon Emissions ($kgCO_2$)	Electricity (MWh)	Total Energy (MWh)
Rockwool (Natural Vent.)	0.15	7.48	27.37	7.60	25.00	-2.70	1.16	5.01	96.72	842	–	–
Rockwool (HVAC)	0.15	16.00	27.82	15.28	25.06	-1.15	1.17	5.27	33.62	5035	37.41	37.41
Glass Wool	0.11	16.00	26.74	15.27	25.22	-1.15	1.10	5.00	32.74	3355	23.41	23.41
Foamed Glass	0.14	16.00	26.74	15.24	25.16	-1.15	1.11	5.00	32.87	3410	23.77	23.77
Rockwool	0.10	16.00	26.75	15.28	25.25	-1.15	1.11	5.00	32.70	3327	23.23	23.23
Expanded Polystyrene	0.10	16.00	26.75	15.28	25.25	-1.15	1.11	5.00	32.69	3327	23.23	23.23
Polyurethane	0.07	16.00	26.74	15.31	25.32	-1.14	1.11	5.00	32.55	3268		

Source: Compiled simulation results from IES-VE

The findings from above both tables indica that the discussion is primarily based on the results of first floors. It is evident that green roofs outperform traditional roofing systems in reducing U-values, with polyurethane showing the most significant improvement, achiveing a decrease of 0.08 W/m2.K. in terms of thermal comfort, ondoor air temperature was lowered by 1 C, while carbon emissions dropped by 33%. Futhermore, energy and electricity consumption decclined, recording a total saving of 14.56 MWh. These outcomes align with the conclusions of (Silva et al., 2023), which highlight the potential of green roofs in reducing emergy demand, cutting carbon emissions, and enhancing both urban biodoversity and outdoor thermal comfort.

CONCLUSION

This study highlights the substantial benefits of extensive green roofs in temperate climates like Timisoara, Romania, where integration with insulation materials—particularly polyurethane—outperformed conventional roofs by achieving a low U-value of 0.07 W/m²·K, reducing summer indoor temperatures by about 1°C, cutting carbon emissions by up to 33% (1767 $kgCO_2$), and saving 14.56 MWh annually, positioning green roofs as key energy-efficient components beyond mere aesthetics. Survey data further reveal that while residents acknowledge environmental advantages, adoption hinges on awareness, economic viability, and supportive policies, with cost as the primary barrier, necessitating incentives, regulations, and public education for broader uptake through stakeholder collaboration. Future research should conduct longitudinal field trials across diverse global climates to validate these findings and explore cost-optimization strategies using recycled or bio-based insulation materials.

REFERENCES

Aleksejeva, J. V. G., & G. A. (2024). Systematic review of the climatic and non-climatic benefits of green roofs in urban areas. *Urban Climate, 58*, 102133. https://doi.org/10.1016/j.uclim.2024.102133

Ashinze, U. K., Edeigba, B. A., Umoh, A. A., Biu, P. W., & Daraojimba, A. I. (2024). Urban green infrastructure and its role in sustainable cities: A comprehensive review. *World Journal of Advanced Research and Reviews, 21*(2), 928–936.

Barozzi, B., Bellazzi, A., & Pignatta, M. C. (2016). The energy impact in buildings of vegetative solutions for extensive green roofs in temperate climates. *Buildings, 6*(3), 33. https://doi.org/10.3390/buildings6030033

Bosch, M., Lacasta, A. M., Berigüete, F. E., Alva, A., & Cantalapiedra, I. R. (2023). Green roofs and other nature-based solutions in Barcelona: Environmental benefits, and physical and mental well-being. In *Building engineering facing the challenges of the 21st century: Holistic study from the perspectives of materials, construction, energy and sustainability* (pp. 511–532).

Bush, J., & Doyon, A. (2019). Building urban resilience with nature-based solutions: How can urban planning contribute? *Cities, 95*, 102483.

Cascone, S. (2024). Eco-innovative construction: Integrating green roofs design within the BIM framework. *Sustainability, 16*(5), 1967.

Castelo, S., Amado, M., & Ferreira, F. (2023). Challenges and opportunities in the use of nature-based solutions for urban adaptation. *Sustainability, 15*(9), 7243.

Colléony, A., & Shwartz, A. (2019). Beyond assuming co-benefits in nature-based solutions: A human-centered approach to optimize social and ecological outcomes for advancing sustainable urban planning. *Sustainability, 11*(18), 4924.

Evangelisti, L., et al. (2020). On the energy performance of an innovative green roof in the Mediterranean climate. *Energies, 13*(19), 5163. https://doi.org/10.3390/en13195163

Feijó-Muñoz, J. P. C., et al. (2019). Energy impact of air infiltration in residential buildings in the Mediterranean area of Spain.

Hitayezu, E. (2021). *Understanding the role of forum for unity and reconciliation in post-genocide* *peacebuilding Rwanda: Case of Gasabo District* [Unpublished thesis]. University of Rwanda.

Ibáñez Gutiérrez, R. A., & Ramos-Mejía, M. (2019). Function-based and multi-scale approach to green roof guidelines for urban sustainability transitions: The case of Bogotá. *Buildings, 9*(6), 151.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., & Stadler, J. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society, 21*(2).

Love, V. L. (2020). *A study on the effects of species, plant density, population size and species mixture on the morphological, physiological and thermal performance of six woody shrubs growing on rooftops in Sheffield, UK* [Doctoral dissertation]. University of Sheffield.

Martin, S. P. (2017). *Young people's sexual health literacy: Seeking, understanding, and evaluating online sexual health information* [Doctoral dissertation]. University of Glasgow.

Massey, T. (2025). *RHS resilient garden: Sustainable gardening for a changing climate*. Dorling Kindersley Ltd.

Nampushi, J. S. (2015). *Perceptions of leadership and sustainable tourism in emerging economies: Narok County, Kenya* [Doctoral dissertation]. Clemson University.

Rockabrand, R. (2025). *How artificial intelligence will power emergency preparedness and response for small modular reactors* [Doctoral dissertation]. Capitol Technology University.

Scott, M., Lennon, M., Haase, D., Kazmierczak, A., Clabby, G., & Beatley, T. (2016). Nature-based solutions for the contemporary city. *Planning Theory & Practice, 17*(2), 267–300.

Singh, S., Dutta, A., Mudoi, D. J., & Karmakar, S. (2024). Assessing sustainable urbanization: A comparative study on Kolkata and New Town, West Bengal. In *Sustainable development goals: A handbook based on media perspective* (p. 128).

Teotónio, I., Silva, C. M., & Cruz, C. O. (2018). Eco-solutions for urban environments regeneration: The economic value of green roofs. *Journal of Cleaner Production, 199*, 121–135.