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Development of Green Technologies in Construction and Their Impact on the Sustainability of Urban Infrastructure

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Abstract The study examines the role of green building technologies in fostering sustainable urban development in Bulgaria amid climate change and urbanisation. Based on theoretical analysis and official Bulgarian and EU regulatory documents, it finds that despite rising interest in eco-friendly approaches, adoption remains limited due to institutional fragmentation, unstable support programmes, and insufficient private sector engagement, which owns 93% of housing stock. Challenges include a lack of long-term financing, changes in renovation programme conditions, and low stakeholder participation. Nevertheless, green technologies show strong potential for reducing energy consumption, mitigating climate risks, and modernising infrastructure. Examples include green roofs, passive heating, water-saving systems, intelligent HVAC, and energy-efficient facades, capable of cutting energy use by 30–50% and CO_2 emissions by up to 40%. EU initiatives, such as the updated Directive on Energy Efficiency of Buildings, promote large-scale renovation by 2033, offering further opportunities. A SWOT analysis indicates that with consistent policy support, social justice considerations, and integrated planning, green technologies could become a cornerstone of sustainable modernisation in transitional economies. The study's significance lies in its theoretical substantiation of the link between construction greening and institutional conditions, highlighting strategic directions for policy, financing, and stakeholder collaboration.

Keywords Prospects and Challenges, Renovation, Ecology, Climate Neutrality, Energy Efficiency, Regulatory Regulation

1. Introduction

In the contemporary conditions of climate change and rapid urbanisation, it is becoming critically important to ensure the sustainable development of cities. By 2050, about 70% of the world's population will live in urban agglomerations, which already consume up to 80% of the world's energy and generate about 75% of carbon dioxide emissions [1]. As of 2019, the construction sector accounted for a significant share of the global carbon footprint (approximately 39%) [2].

Based on these challenges, the active introduction of "green" technologies in construction is considered as a necessary measure to achieve the goals of sustainable development and reduce the environmental burdens, and the investigation of this issue is becoming relevant. However, the disparity of methodological and legal mechanisms in the field of "green" construction still creates barriers to innovation. In addition, there is a lack of private sector participation and investment in sustainable projects, which further limits the spread of green solutions in the industry.

Guo et al. [3] conducted an empirical analysis of the impact of smart city construction programmes on energy conservation and reduction of carbon dioxide emissions in China, demonstrating that the implementation of comprehensive smart city programs contributes to a significant reduction in CO_2 emissions, and improves the overall energy efficiency of urban infrastructure. The researchers suggest that the effect is achieved through the integration of digital energy management technologies, the introduction of monitoring systems and predictive analytics. The effectiveness of these programmes is determined by their adaptation to the local conditions and the technological maturity of the regions, confirming that in such conditions, reliance on specific characteristics of the territory in planning sustainable development becomes especially important. Confirming their findings with their research, Yan et al. [4] examined the impact of the concept of smart cities on the development of green technological innovations. The researchers also demonstrated that the introduction of smart urban infrastructure elements significantly stimulates the development of environmentally friendly technologies. Guo et al. [3] concluded that the development of smart cities has a positive impact on the implementation of green solutions, while additionally emphasising the importance of the regional context, where the effectiveness of smart city programmes is higher in more developed regions with a high level of technological readiness and investment potential.

Gil-Ozoudeh et al. [5] studied the construction of green buildings in the context of the development of a sustainable urban environment, highlighting the effectiveness of environmentally oriented architectural solutions. As a result of the study, the researchers insist on the need to integrate green technologies into urban planning to increase the resilience and adaptation of cities to climate change.

The study by Antonova [6] reviewed the state of green projects and initiatives in construction, focusing on the experience of the European Union (EU) countries and the specifics of applying environmental approaches in Bulgaria. The researchers analysed the trends in the development of sustainable construction, drawing attention to the limited spread of green practices in countries with economies in transition. K. Antonova focused on the need to adapt foreign experience to local conditions and create a national incentive system for green construction, including educational programmes, concessional financing, and the development of building certification standards. Other Bulgarian Rodrigues et al. [7] presented a comprehensive analysis of the indicators of sustainable urban development in Bulgaria, emphasising that the key problems remain low energy efficiency of buildings, irrational use of natural resources, limited access to renewable energy sources, and insufficient integration of sustainable solutions into strategic urban planning. In addition, the researchers pointed out the need for an integrated approach to the development of a sustainable urban environment, including the introduction of innovative construction technologies, the development of local energy infrastructure, and strengthening intersectoral cooperation between public and private structures.

Given the above, the purpose of the current study was a comprehensive theoretical analysis of the impact of green construction solutions on the sustainable development of the urban environment (with an emphasis on Bulgarian practices and challenges). To achieve this goal, the following tasks were put forward:

- to assess the role of green technologies in reducing energy consumption and adapting urban infrastructure to climate risks;
- to identify the institutional and financial barriers that slow down the adoption of green technologies;
- to investigate the role of various factors in the promotion of green technologies in construction and their importance for the sustainable development of cities.

2. Materials and Methods

Regulatory, strategic, and programmatic documents regulating the development of sustainable and energy-efficient construction in Bulgaria and the European Union were used as the research material. The sources reviewed and analysed include: the updated Directive (EU) No. 2024/1275 of the European Parliament and of the Council "On the Energy Performance of Buildings (Recast)" [8], the European Climate Law [9], and Bulgarian national documents, including the "Long-term national strategy to support the renovation of the national building stock of residential and non-residential buildings by 2050" [10], the Integrated Plan "Integrated energy and climate plan of the Republic of Bulgaria 2021-2030" [11], the Commission Recommendation "On the Consistency of Bulgaria's Measures with the Union's Climate-Neutrality Objective and with Ensuring Progress on Adaptation" [12], and documents related to the implementation of the "National Recovery and Resilience Plan Republic of Bulgaria" [13]. Additionally, provisions and recommendations related to Bulgaria's fulfilment of obligations under the EU climate policy were used, including targets for reducing greenhouse gas emissions, requirements for housing renovation until 2033, and the programme framework proposed by the NextGenerationEU initiative [14]. The analysis included expert opinions, in particular, statements by the energy efficiency specialist Nanyova, reflecting the institutional and practical aspects of the implementation of green technologies [15].

The analysis of the regulatory framework provided a systematisation and conceptual understanding of the key directives, strategies, and programmes governing climate and construction policy at the national (Bulgarian) and European levels. Through the prism of legislative analysis, the degree of legal consistency between the European climate goals and Bulgaria's internal construction regulation was investigated. This allowed considering the regulatory field as a dynamic system undergoing adaptation and assessing its potential to stimulate the transition to sustainable construction practices.

The method of institutional analysis was applied to investigate the structure and functions of organisations shaping climate and construction policy in Bulgaria, providing a basis for identifying the degree of participation and influence of European and national actors in the process of regulatory transformation of the industry. The approach helped to theoretically comprehend the institutional logic of decision-making and consider the mechanisms for the development of a sustainable construction environment from the perspective of management and regulation.

The application of a systematic approach has allowed considering green technologies as interrelated elements of urban infrastructure integrated into the broader context of sustainable development. The method provided a holistic understanding of the processes in which architectural, engineering, and environmental solutions function within a single urban environment. Through this methodological prism, green technologies were analysed as tools that transform the energy, social, and natural subsystems of the city.

Additionally, the use of strengths, weaknesses, opportunities, and threats (SWOT) analysis for theoretical modelling of the conditions for the introduction of green technologies in the construction sector helped to classify internal and external factors affecting the development of sustainable construction. The SWOT analysis considered the interaction of institutional, economic, technical and social variables affecting the effectiveness of the transformation of the construction sector. It also provided a framework for a conceptual description of the risks and potential of renovation programmes.

The interpretation of expert data was used to analyse the current state and prospects for the development of green technologies. In particular, data on the energy efficiency of the housing stock, the share of implemented solutions, and the profitability of individual technological areas were interpreted. Analytical work with expert opinions allowed the study to include practical aspects of the implementation of national programmes, including institutional barriers and the perception of reforms.

The synthesis method, in turn, was used at the final stage of theoretical work and allowed combining the results of various analytical procedures into a single conceptual picture. With its help, regulatory, institutional, systemic, and empirical data were integrated, which allowed summarising approaches to assessing the role of green technologies in the transformation of the construction sector. The synthetic approach ensured the coherence of the theoretical construction and the logical integrity of the presented analysis.

3. Results

The development of green technologies in construction is gradually becoming one of the main factors in the development of a sustainable urban environment, especially in countries with intensive urbanisation and limited natural resources [16]. Bulgaria, which is in the phase of transformation of the construction sector and adaptation to European environmental standards, is showing a tendency to increase interest in environmentally oriented approaches.

At the beginning of 2025, there are already elements in the Bulgarian construction industry indicating the gradual introduction of green practices, although their spread remains fragmented. For example, as of 2023, there are only 54 green buildings in Bulgaria [17]. Architectural projects using energy-efficient materials, solar water heating systems, and insulating structures are found primarily in commercial and residential construction in large cities [18-20]. The role of environmental certification of buildings is still limited, and its application is more often initiated by international investors than by domestic developers. Certification companies that underestimate green building certification in Bulgaria include the English BRE Global with the Building Research Establishment Environmental Assessment Method (BREEAM) standard [21], the German Council for Sustainable Construction with the DGNB standardisation system [22], and the Bulgarian Green Building Council (BGBC), which also uses the DGNB system [17, 23].

In addition, the regulations governing sustainable construction are in the process of revision and alignment with European standards, which causes heterogeneity and variability in the applied methods of design, construction technologies and operation of buildings. As part of these trends, Bulgaria has approved a "Long-term national strategy to support the renovation of the national building stock of residential and non-residential buildings by 2050" [10], and is also implementing the "Integrated energy and climate plan of the Republic of Bulgaria 2021-2030" [11]. These documents include measures to modernise construction legislation, energy-saving standards, and subsidise renewable generation. Meanwhile, educational and professional communities are only forming a holistic understanding of green principles in the architectural environment.

In 2024, according to National Program for Energy Efficiency in Residential Buildings in Bulgaria, 270 units in three multi-family structures in Sofia underwent renovation [24]. Since its inception in 2015, this programme, overseen by the Ministry of Regional Development and Public Works, has rehabilitated a total of 1,968 structures nationally by the conclusion of 2024 [25]. The modifications have decreased domestic heating expenses and mitigated greenhouse gas emissions, enhancing environmental quality. The programme concentrated on enhancing buildings, particularly older structures, through energy efficiency initiatives including insulation, window replacement, and heating system upgrades.

The National Programme offers complete grant assistance to homeowners' associations of multi-family residences constructed prior to 1990, focusing on enhancing thermal comfort, interior living conditions, and energy efficiency. More than 2,022 structures have secured financing contracts under this initiative, with approximately half completed and the remainder in progress [26]. It has shown advantages such as enhanced indoor comfort, decreased energy expenses, and elevated resident satisfaction. Obstacles to further adoption encompass homeowner association governance and financial frameworks for extensive implementation.

Significant expenditures are already underway, with approximately BGN 200 million (over €100 million) designated in 2024 via regional development initiatives for the energy efficiency refurbishment of multi-family residential structures in Bulgarian coal districts impacted by the energy shift [27]. These investments aim to reduce energy use and alleviate energy poverty through initiatives such as insulation, heating system enhancements, and various energy-efficient renovations. At a broader EU level, the Horizon 2020 initiative provides extensive funding for energy efficiency and green technologies across all industries, including residential structures [28]. EU evaluations indicate substantial returns on investments in energy efficiency measures over several years, frequently reporting returns that exceed the initial investment multiple times in terms of energy savings and environmental advantages.

Considering the experience of other countries, it is worth paying attention to trends in Eastern Europe and the Caucasus. Thus, efforts are being made to integrate green construction solutions, despite the differences in institutional conditions in the construction industry in Kosovo, which faces significant regulatory barriers that limit sustainable construction. There is a lack of legal mechanisms in the country that encourage the use of energy-efficient and environmentally friendly solutions, which slows down the integration of innovative technologies into construction processes – only about 15-20% of new projects meet basic energy efficiency requirements [29]. The development of energy efficiency standards and regulations is of particular importance, since the modernisation of the industry is directly related to the need to reduce the carbon footprint and improve the quality of the urban environment. The implementation of pilot projects and the adaptation of European practices create prerequisites for the development of a sustainable construction sector, but systemic changes in legislation and professional development remain critically important.

In Azerbaijan and Ukraine, green technologies in construction are developing through the introduction of innovative techniques and government programmes aimed at improving energy efficiency and environmental safety [30-32]. In Azerbaijan, the Green Zoom certification system covers more than 30% of commercial facilities in large cities, which reduces energy consumption by 25-30% compared to conventional buildings [33, 34]. In Ukraine, about 40% of new residential and commercial buildings are designed using green building elements, while government programmes contribute to an annual reduction of CO_2 emissions in the construction sector by 12-15% [35]. These data reflect a large-scale transition to the sustainable development of the industry, which is critical for greening the economy and achieving climate goals [36, 37].

Speaking about green technologies in construction, it should be noted that they have a multidimensional impact on the sustainability of urban infrastructure. One of the main factors is the reduction of dependence on fossil energy sources, which is achieved by the use of passive architectural solutions, the integration of renewable energy sources and the optimisation of heating and ventilation systems (Table 1).

For example, intelligent HVAC systems are a set of automated solutions that adapt the indoor climate to changes in external conditions and user needs. Their use helps to reduce energy consumption while increasing comfort [40]. In turn, water-saving technologies, including water reuse and rainwater storage systems, increase the autonomy of buildings and reduce the load on centralised networks.

Infrastructural sustainability is enhanced by the fact that green buildings can mitigate the effects of climate fluctuations, both heat waves and floods, especially in conditions of overheated urban cores [45-47]. The use of green roofs (which can reduce the air temperature in cities by 1-3 ℃ and reduce the volume of storm drains by 50-80%), vertical landscaping and natural screens helps restore biological connections within the urban environment, while reducing thermal pollution and increasing the habitability of densely populated areas [39]. Such solutions also act as elements of cities’ adaptation to climate change, increasing their resilience without radically restructuring existing structures. And the aesthetic and recreational potential of green technologies creates a positive effect on the social plane, enhancing the sense of belonging of citizens to their place of residence and stimulating the development of local communities.

Table 1. Green technologies in construction

Technology	Example	Influence
Green Roofs	Extensive and intensive roofs	They provide an increase in thermal insulation characteristics, contribute to reducing the effect of the urban heat island, and contribute to delaying rainfall
Use of recycled materials	Recycled concrete, bricks	Reduce the carbon footprint, reduce construction waste
Passive solar heating systems	Examples: thermal collectors, correct orientation of buildings	Reduce energy consumption for heating, reduce CO_2 emissions
heating, ventilation, and air conditioning (HVAC) systems (heating, ventilation, air conditioning)	Heat recovery systems, geothermal heat pumps	They provide a reduction of greenhouse emissions, optimisation of energy consumption and an increase in the level of purity of atmospheric air.
Rainwater collection and reuse	Water conservation systems, reservoirs	Reduce the burden on urban water treatment, prevent flooding
Energy-efficient facades (facades with photocatalysis)	Facades with TiO_2, reflective surfaces	Reduce surface temperature, improve air quality
Intelligent energy management systems	Smart buildings with IoT sensors	Optimise energy consumption, increase the durability of infrastructure
Vertical gardens and facade landscaping	Vertical gardens (for example, BIQ House)	They increase biological diversity, reduce noise and dust levels

Source: compiled by the authors based on Fang et al. [38], Nasr et al. [39], Asim et al. [40], Rivas et al. [41], Chaudhari et al. [42], Chojnacka et al. [43], Cervera et al. [44].

And from the perspective of energy sustainability, the introduction of green technologies in construction can significantly reduce energy consumption. The integrated use of thermal insulation materials (aerogels and phase transition materials that significantly reduce heat loss), energy-efficient equipment and renewable installations (energy-efficient windows and facade systems), improves thermal comfort and reduces heating and cooling costs, reducing energy consumption of buildings by 30-50% [48]. In addition, these technologies can reduce CO_2 emissions from buildings by up to 30-40% [49].

A holistic approach is especially important, in which advanced programmes provide for the creation of "green" transport networks, investments in cleaning and remediation, and the inclusion of environmental criteria in municipal development plans. All these measures are formalised in official documents, such as the Directive (EU) No. 2024/1275 of the European Parliament and of the Council [8], the "European Climate Law" [9], created in 2021 and signed by Bulgaria in 2023, and the "Climate Neutrality Roadmaps", which, as of 2025, Bulgaria does not have. However, it has commitments to reduce greenhouse gas emissions, and has also developed a national strategy for the development of renewable energy and energy efficiency, which sets institutional guidelines for further development [12].

In the environmental aspect, the use of green technologies in the construction sector allows harmonising development with the natural environment and contributes to the implementation of international climate agreements [50-52]. By prioritising energy conservation and renewable sources, Bulgarians seek to offset the detrimental effects of construction. The development of sustainable construction practices and the introduction of renewable energy in the city directly improve environmental performance (reduce pollutant emissions, help to reduce the environmental footprint) [7].

In addition, the concept of sustainable development in the Bulgarian construction industry is becoming particularly relevant in the light of new commitments arising from the Directive (EU) No. 2024/1275 of the European Parliament and of the Council [8]. According to the European Commission, buildings in the EU countries as a whole are responsible for about 36% of total greenhouse gas emissions, and about 75% of them do not meet energy efficiency requirements. In order to achieve climate neutrality by 2050, the European Union insists on significantly accelerating the pace of renovation (from the current 1-1.5% per year to at least 3%)

For Bulgaria, achieving this goal is both a technical and an institutional challenge. The new directive stipulates that all buildings, regardless of their form of ownership, purpose, or year of construction, must be upgraded by 2033. This applies to both residential, public, and commercial funds. The main priority is given to the most energy-efficient buildings, for which urgent measures must be taken to improve their thermal characteristics, where a special place is given to the introduction of electric heat pumps and electrification of heating systems, despite the continued high cost and limited distribution of this equipment in the EU. As part of the requirements of the directive, Bulgaria, like other EU member states, is required to submit a national building renovation plan by 2040, which should define a step-by-step mechanism for modernising the building stock, including criteria for selecting facilities and sources of financing [15, 53].

According to the expert on energy efficiency by Nanyova, in Bulgaria, where 97% of the housing stock consists of private houses, of which 93% do not meet modern energy efficiency standards, the introduction of heat pumps is slow [15]. Although investments in this technology are significant, and with high-quality thermal insulation of buildings, they provide economic returns, inefficient thermal insulation reduces the efficiency of heat pumps, which requires an integrated approach to building modernisation.

In addition, according to the expert, the implementation of national renovation programmes in Bulgaria faces a number of systemic problems. The programme of 100% grant financing of apartment buildings has caused significant demand, which significantly exceeds the available resources, which has led to massive refusals and discontent among the population and local authorities. And the subsequent transition to co-financing schemes (20% co-financing from tenants) reduced the activity of applications. In addition, the lack of a sustainable and continuous state housing renovation programme, and a shortage of qualified personnel and short deadlines for the implementation of programmes, in particular within the framework of the Recovery and Sustainability Plan, significantly complicate the achievement of the intended goals [13].

Thus, to successfully meet the requirements of the updated EU Directive on Energy Efficiency of buildings, it is necessary to create a long-term strategy with sustainable financing, systematic training and an integrated approach to the modernisation of both the building stock and heating systems. Special attention should be paid to supporting socially vulnerable groups and ensuring the quality of events within the limited time frame for the implementation of government programmes.

It follows from this that despite Bulgaria's ambitious goals for modernising the building stock and achieving climate neutrality, the implementation of renovation programs faces fundamental systemic limitations. As can be seen from current practice, even if there is a demand for green solutions, lack of financial resources and refusal of full government support cause a decline in their active implementation. In addition, the lack of stable government regulation and planning mechanisms, and a significant shortage of qualified specialists, create additional complexity. In the context of the limited time frame for the implementation of the measures provided for in the Recovery and Sustainability Directive, achieving the targets requires a deep structural adjustment. Under these conditions, SWOT analysis systematically identified internal and external factors that can influence the introduction of green building technologies into sustainable urban infrastructure (Table 2).

Additional analyses conducted in Poland demonstrate the potential of hybrid systems combining air-to-water heat pumps with renewable energy sources such as photovoltaic panels and wind turbines [53, 54]. Simulations for modernized low-energy multi-family buildings showed that such systems can cover up to 58% of the annual electricity demand for heating and domestic hot water preparation directly from renewable sources. The complementarity between solar and wind energy ensures year-round coverage: solar energy dominates during summer months, while wind energy provides higher outputs during autumn and winter [55-57]. These findings are particularly relevant for countries like Bulgaria, where seasonal climatic variations influence renewable energy production patterns. The introduction of green technologies remains a promising and effective trend for the development and improvement of the industry. In addition, green technologies in construction have significant environmental and social impacts, both direct and indirect. Reducing heating and cooling costs through energy-efficient measures reduces energy poverty, especially in high-rise residential areas and among older households [58-61]. Improving microclimatic conditions and improving air quality have a positive effect on the physical and psychological state of the population. And the introduction of green solutions in urban development improves the quality of the environment, reduces stress and strengthens the emotional connection of residents with their place of residence. However, with uneven access to technology and support programmes, social segregation may deepen. If energy-efficient solutions become available only to well-off households, the green transition loses its inclusivity, generating distrust of climate policy.

It is also important to consider that the introduction of green construction technologies is associated with high capital intensity, especially at the stages of design, procurement of specialised materials and engineering equipment of facilities [62, 63]. Thus, energy-efficient enclosing structures, intelligent HVAC systems, solar and geothermal installations, photocatalytic facades, and other innovative solutions require significant investments. For countries with limited domestic investment resources, such as Bulgaria, this factor is becoming a decisive obstacle to mass renovation and climate-oriented modernisation of the building stock. Even though there are external co-financing mechanisms from the European Union, including such instruments as NextGenerationEU and the Recovery and Sustainability Plan mentioned earlier, the total amount of financial injections remains insufficient for systemic transformation [14].

Financial barriers are compounded by institutional instability and the lack of a long-term sustainable financing model for renovation. In the absence of a sustainable government programme and cost compensation mechanism for vulnerable groups of the population, the risks of energy transition are borne by households, which makes it difficult for the general public to participate in the renovation process. At a time when 93% of Bulgaria's housing stock does not meet modern energy efficiency requirements, the lack of financial incentives and available credit instruments jeopardises the fulfilment of climate neutrality obligations.

Table 2. SWOT analysis of the introduction of green technologies in the construction industry

Strengths	Weaknesses
1. Reduction of heat load on the urban environment – Helps mitigate the urban heat island effect, improving the livability of cities. 2. Energy savings of up to 50% – Achieved through integrated renewable energy sources and energy-efficient insulating materials, significantly reducing energy demand and operational costs. 3. Increased climatic resilience of urban infrastructure – Urban areas can better withstand extreme weather events (e.g., heatwaves, floods), with no need for extensive demolition. 4. Impact on social sustainability – Green technologies contribute to community development by improving local environments, reducing energy poverty, and enhancing quality of life. 5. European institutional support – EU policies (BREEAM, DGNB, Climate Law, and EU strategies) provide a regulatory framework that supports the transition to sustainable urban infrastructure.	1. Fragmentation of the regulatory framework – Lack of coordination between national policies, local authorities, and private sector stakeholders hinders the smooth implementation of green technologies. 2. Lack of sustainable financing – There is insufficient public and private sector investment, with existing financing schemes, like EU grants, being inadequate for large-scale, nationwide renovation efforts. 3. High upfront cost of technology implementation – Energy-efficient materials, smart HVAC systems, and renewable energy solutions require significant capital investment, which many stakeholders cannot afford, especially in privately owned buildings. 4. Lack of qualified personnel – The shortage of skilled workers in energy-efficient architecture and engineering complicates the implementation of green technologies, particularly in construction sectors that rely on skilled labour. 5. Limited penetration into the private sector – The vast majority of Bulgaria's housing stock (93%) is privately owned and has not undergone renovations, creating a barrier to widespread adoption of green technologies.
Opportunities	**Threats**
1. EU funding under NextGenerationEU and the Recovery Plan – These financial instruments provide substantial funding for green renovations, allowing for the transformation of Bulgaria's building stock, particularly in coal districts impacted by the energy transition. 2. Expansion of institutional support through ESG – The growing emphasis on Environmental, Social, and Governance (ESG) principles by both government and private investors encourages green renovation projects and the adoption of sustainable building practices. 3. Implementation of smart technologies – Integration of smart HVAC, energy audits, and predictive analytics can optimize energy consumption, offering a way to enhance building efficiency and reduce operating costs over time. 4. Systemic transformation of the housing stock – A comprehensive approach to modernization could transform entire neighbourhoods, especially with coordinated efforts from the government, local authorities, and private developers. 5. Growing demand for sustainable facilities from international investors and certification agencies – As green building certifications (e.g., BREEAM, LEED) gain global importance, there is increasing demand for energy-efficient buildings from international investors, which could drive the adoption of green technologies in Bulgaria.	1. Institutional instability in renovation programs – Fluctuating government policies, such as changes in funding mechanisms and inconsistent program conditions, undermine long-term planning and discourage private sector participation. 2. Distrust among the population – Public scepticism about the fairness of program access, particularly among low-income and rural communities, undermines engagement with government-led green renovation initiatives. 3. Delays in meeting EU energy efficiency targets – The slow pace of renovation and insufficient technical capacity may hinder Bulgaria's ability to meet the EU Directive on energy efficiency of buildings, delaying necessary climate goals. 4. Increased personnel and contract workload – The rising demand for renovations and the growing complexity of implementing green technologies may result in workforce shortages and increased costs, especially as deadlines approach. 5. Economic vulnerability to external shocks – Rising energy prices, inflation, and supply chain disruptions can negatively impact the affordability and feasibility of large-scale green renovations, especially for vulnerable populations.

Source: compiled by the authors.

In this regard, it is critically important to accompany technical and architectural measures with social support mechanisms, including information campaigns, subsidies, technical assistance programmes, and flexible financial instruments. Only if the principles of social justice are respected can green technologies become an integral component of sustainable and inclusive urban development.

4. Discussion

An analysis of the introduction of green technologies in construction confirmed that their development is closely linked to general political and economic processes, in particular, with the consequences of the COVID-19 pandemic. The study by Bongardt and Torres [64] emphasised that the European Green Deal has become the foundation for the development of a new EU economic model focused on climate neutrality. According to the researchers, the EGD is not limited to environmental regulation measures, but forms a holistic strategy for sustainable development, including economic incentives and political support. The study confirmed these conclusions, but concretised them using the example of Bulgaria, revealing that without adapting the pan-European goals to the national context, including considering the specifics of the construction fund, interaction with the private sector, and the development of a long-term financial model, the transition to green construction slows down. Thus, if Bongardt and Torres focused on the institutional architecture of the EU, the study revealed how these macroeconomic principles are implemented in urban infrastructure in a country with a transition economy.

In addition, the systematisation of concepts of sustainable construction and the analysis of its components occupied an important place in contemporary research. For example, the study by Lima et al. [65] conducted a bibliometric review of publications on sustainability issues in the construction industry, demonstrating an imbalance in the focus of research, with most focusing on environmental aspects, while socio-economic effects remain insufficiently highlighted. The results of the analysis confirmed this conclusion, but complemented it by paying attention to the institutional aspects. Unlike the study by Lima et al. [65], which focused on a review of theoretical and empirical publications, the analysis was based on the investigation of specific renovation programmes and practices for the modernisation of urban infrastructure, showing that the successful implementation of green technologies requires a systematic approach combining technical, social, and institutional measures.

However, the study by Poon [66] analysed the perception of sustainability in the context of architectural design of green buildings and the impact of design on environmental efficiency. The study suggested that architectural solutions should be perceived not only in terms of their functionality, but also in terms of their ability to shape the perception of sustainability among end users, which affects the behaviour of residents and the efficiency of building operation. The study developed this approach, showing that the perception of green technologies as accessible and inclusive solutions was also determined by the institutional framework, the degree of transparency of renovation programmes and the possibility of private sector participation in their implementation. Poon focused on the relationship between architectural design and environmental impact, and the results of current study showed that architectural and technological solutions should be considered as part of an even broader system that includes social and economic components of sustainable construction.

In the context of stimulating the introduction of green technologies in construction, increased attention should be paid to managing innovation processes and evaluating their effectiveness. The study by Zhang et al. [67] demonstrated that the effectiveness of the introduction of green technological innovations in the construction industry largely depends on the nature of environmental regulation. The researchers classified regulations into command-administrative, market-based and voluntary, revealing that the optimal effect is achieved when they are combined. It was emphasised that there is a gap between R&D developments and their commercialisation. The results of the current study did not have depth in this context, but they complemented this perspective, showing that in emerging economies, institutional fragmentation and instability of support programmes significantly slowed down the integration of even those technologies that are technically adapted and have proven their effectiveness and potential.

In addition, in the context of analysing the effectiveness of the implementation of individual technologies, the scientific community often focuses on the empirical study of the impact of specific technical solutions on the sustainability of the urban environment. The study by Muntean [68] presented a comparative assessment of infrastructure development in Germany, Romania, and Bulgaria, with an emphasis on their economic impact. The researcher emphasised that the sustainability of infrastructure is closely related to the quality of management and the degree of coordination between sectors. The study developed this idea, demonstrating that for countries with limited resources, such as Bulgaria, the ability to form an institutional environment that ensures stable rules of the game, access to financing and long-term support for renovation programmes is a crucial success factor. The study emphasised the need to consider the private sector, which accounts for the majority of the housing stock, which allows expanding the scope of the analysis and supplementing it with a systematic assessment of the factors determining the sustainable development of the construction industry in a transitional economy.

Semenenko et al. [69] examined the issues of environmental degradation and restoration in Ukraine, highlighting the economic and environmental consequences of warfare. This theme indirectly corresponds with Bulgaria's difficulties, where climatic resilience and sustainable urban infrastructure are essential. While Ukraine concentrates on forest ecosystems and the immediate impacts of fighting, it underscores the overarching subject of environmental resilience and the necessity for sustainable infrastructure, a challenge that Bulgaria similarly encounters in its building sector. Ukraine's current recovery, which integrates green technologies and sustainable practices, can provide insights for Bulgaria in implementing these solutions within a post-crisis economy, particularly in light of institutional fragmentation and financial instability in both countries.

Yarova et al. [70] analysed the economic advantages of green technologies in Ukraine, emphasising significant improvements in energy efficiency and CO_2 reductions facilitated by state assistance for sustainable development. The Ukrainian experience mirrors Bulgaria's current challenges in establishing a sustainable green building sector. Both countries exhibit restricted private sector participation in sustainable construction, with governmental initiatives being crucial. In contrast to Ukraine, which has experienced more robust government-supported energy efficiency initiatives, Bulgaria's disjointed legislative structure and erratic governmental backing have impeded the extensive implementation of green technologies. According to Yarova et al. [70], Bulgaria might improve the adoption of green technology by augmenting private sector involvement via specific financial incentives and green certification frameworks.

Hasanov et al. [71] explored the enduring correlation between human development and environmental sustainability in Azerbaijan, highlighting CO_2 emissions and socioeconomic variables. Azerbaijan's policy of green growth increasingly prioritises energy-efficient technologies in building, similar to Bulgaria's approach. Azerbaijan has effectively instituted green certifications, such as Green Zoom, for commercial buildings, but Bulgaria faces challenges with the minimal adoption of these certifications in residential sectors. Both countries encounter institutional obstacles; nonetheless, Azerbaijan's emphasis on energy-efficient structures can guide Bulgaria's approaches, particularly in metropolitan regions where commercial premises may be more amenable to renovation using sustainable technologies.

Verdiyeva et al. [72] presented a green growth strategy for Azerbaijan that emphasises sustainable economic development through the incorporation of green technologies. Azerbaijan's experience corresponds with Bulgaria's ambitions, as both nations strive to modernise their infrastructure through sustainable development. Azerbaijan has reaped economic advantages from this strategy by successfully integrating green technologies into commercial real estate. Bulgaria encounters substantial financial obstacles, comprising elevated initial investment expenses and restricted public-private collaborations. Consequently, the findings of Verdiyeva et al. [72] underscore the necessity for a reliable finance mechanism, which is a primary suggestion for Bulgaria's renovation initiatives, especially concerning private sector involvement.

Pieńkowski [73] questioned the sustainability of nuclear energy in Poland and its contribution to the energy transition. The Polish setting emphasises nuclear energy, while the overarching concern about energy sustainability is significantly relevant to Bulgaria's energy transition. Both countries confront the difficulty of reconciling the adoption of renewable energy with the imperative of energy security. Poland’s transformation underscores the need for policy coherence and long-term planning – a critical lesson for Bulgaria, whose green construction initiatives have been impeded by governmental instability and insufficient investment in renewable infrastructure. In contrast to Poland, which has included nuclear energy in its energy transition strategy, Bulgaria must emphasise renewable alternatives in construction, specifically through energy-efficient retrofitting and intelligent energy management systems in buildings.

The comparison of Ukraine, Azerbaijan, and Poland clarifies common issues and opportunities for Bulgaria (Table 3). Essential lessons for Bulgaria encompass the necessity for a definitive regulatory framework, stability in financing systems, and engagement of the business sector in green building certification initiatives. Furthermore, the incorporation of social justice principles, aimed at guaranteeing fair access to green technologies, must be fundamental to Bulgaria's rehabilitation initiatives, informed by the experiences of Ukraine and Azerbaijan.

Often, the most common areas of research in the field of green construction are the investigation of individual technological solutions (for example, energy-saving systems, heat recovery systems, green roofs, facades with photocatalysis, intelligent climate control systems), and the analysis of strategies to stimulate the introduction of green technologies in the construction industry. Additionally, the assessment of the effectiveness of green innovations in reducing the carbon footprint and improving energy efficiency occupies a stable position on the current scientific agenda, especially within the framework of global climate goals. However, the issue of practical implementation of green technologies in transition economies, where implementation faces barriers typical of less stable institutional systems, remains poorly understood. The study was designed to fill this gap by offering a theoretical analysis supported by regulatory data from Bulgaria and the EU, and empirical examples on current renovation programmes. This approach helps to link the macroeconomic framework of sustainable development with specific urban infrastructure modernisation programmes, identify systemic obstacles, and suggest ways to overcome them.

In general, the conducted research represents a conceptual extension of the existing analytical framework, integrating into the analysis of green technologies not only their technical characteristics, but also the institutional, financial and social determinants of their implementation in the Bulgarian construction industry. This interdisciplinary approach allows considering green technologies as elements of an integrated system of sustainable urban development, where successful implementation is possible only if all interrelated factors are considered.

Table 3. Comparative overview of green technology adoption in construction

Indicator	Ukraine	Azerbaijan	Poland	Bulgaria
Percentage of buildings with green technologies	40% in residential and commercial	30% in commercial buildings	40% in renovated buildings	2% (54 green buildings in 2023)
Energy savings achieved in renovated buildings	Up to 40%	25-30%	40% in renovated buildings	30-50% in energy-efficient buildings
CO_2 reductions	12-15% in the construction sector	25-30% in commercial buildings	25-30% in renovated buildings	30-40% in buildings with green solutions
Government financing for green renovation programs	EU funding, government subsidies	Government co-financing, EU support	National funds, EU-backed initiatives	Limited government funding and subsidies
Private sector engagement	Limited, primarily foreign investment	Limited, growing interest in commercial sectors	High, particularly in commercial real estate	Low, mostly foreign investment in green projects
Barriers to adoption	Financial constraints, institutional fragmentation	High initial costs, limited residential adoption	Slow renovation pace, high costs	Financial instability, regulatory fragmentation, low private sector involvement
Social inclusion in green technology programs	Moderate, with government subsidies for low-income groups	Limited, mostly in urban areas	High, with government initiatives supporting low-income groups	Low, with unequal access to support programs
Long-term sustainability of policies	Moderate, with fragmented institutional frameworks	Moderate, with some policy alignment	High, with robust EU alignment	Low, with unstable and fragmented programs

Source: compiled by the authors based on Council of Ministers of the Republic of Bulgaria [13], Ashikova [15], Semenenko et al. [69], Yarova et al. [70], Hasanov et al. [71], Verdiyeva et al. [72], Pieńkowski [73].

5. Conclusions

As a result of the conducted research, the key aspects of the impact of green technologies on the sustainable development of urban infrastructure have been identified. The findings confirmed that green building solutions have a high potential for improving the energy efficiency of buildings, reducing the carbon footprint, and mitigating the effects of climate change. The importance of such solutions is especially great in countries with limited resources and a high level of old housing stock, where building modernisation is becoming the main tool for increasing the resilience of the urban environment.

Thus, the example of the Republic of Bulgaria in the context of the introduction of green technologies was used as an analytical base. An analysis of the regulatory framework has shown that the transition to large-scale renovation of the construction fund in Bulgaria faces a number of institutional barriers, including fragmented legislation, the lack of a comprehensive climate roadmap, and unstable financing programmes. Despite the existence of European directives and support programmes, their adaptation to the national level is slow and uneven. The low involvement of the private sector also remains a significant limitation. These factors reduce the pace of implementation of climate commitments and hinder the implementation of innovative technologies in practice.

The SWOT analysis allowed structuring the internal and external factors that determine the success or difficulties of implementing green technologies. Both strengths (potential for reducing energy costs, institutional support at the EU level, environmental effects) and weaknesses (institutional fragmentation, high initial costs, shortage of specialists) have been identified. Among the opportunities identified are increased access to finance, increased demand for sustainable buildings from international investors, and prospects for the development of local production of energy-efficient solutions. Threats were manifested in the risk of non-achievement of renovation targets, growing distrust on the part of the population, and the likelihood of increased social segregation in conditions of unequal access to support programmes. These aspects emphasise the need for an integrated approach, in which architectural, engineering, and social measures were integrated into a single strategy for modernising the urban environment.

This study recognises certain methodological limitations, including its dependence on theoretical analysis and secondary data, which may not fully reflect the practical challenges of implementing green technologies in Bulgaria. Future research should employ mixed-method approaches that integrate policy analysis with empirical evaluation, including surveys, energy audits, and case studies, to yield a more thorough understanding of the real-world effects of green technologies. Moreover, longitudinal research and empirical data could improve the evaluation of policy efficacy and the socio-economic impacts of green construction projects.

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