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Future-Oriented Simulation-Based Strategies for the Sustainable Development of Batıkent, Ankara

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Abstract

The sustainable transformation of existing urban districts requires forward-looking strategies that integrate environmental performance, spatial morphology, and advanced simulation tools. This study explores future-oriented, simulation-based strategies for the sustainable development of Batıkent, Ankara, a large-scale cooperative housing district characterized by diverse building typologies and terrain conditions. Using parametric environmental simulation tools, the research evaluates future development scenarios focusing on topography-sensitive planning, renewable energy integration, and nature-based material solutions. The study examines four representative cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular—under alternative future scenarios, including flat versus sloped terrain conditions, and the integration of solar panels, green walls, and advanced insulation materials. Solar radiation simulations are employed to assess how terrain variation and design interventions influence environmental performance across low-rise, mid-rise, high-rise, and mixed-typology settlements. In addition, before–after visual simulations are used to translate numerical results into spatially interpretable outcomes, supporting design-based decision-making. The results indicate that terrain-responsive configurations generally enhance solar radiation stability and reduce shading conflicts, particularly in mid-rise and high-rise developments. Renewable energy systems and material-based interventions further improve environmental performance without requiring structural reconstruction, demonstrating the feasibility of incremental retrofitting strategies. The findings suggest that sustainable redevelopment in Batıkent should prioritize site-specific, morphology-sensitive, and simulation-informed approaches rather than uniform planning solutions. By focusing on future scenarios rather than existing-condition evaluation, this study contributes a practical framework for guiding sustainable urban redevelopment in cooperative housing districts. The proposed strategies offer transferable insights for similar urban contexts seeking to enhance energy efficiency, environmental resilience, and long-term sustainability through simulation-based planning.

Keywords: Sustainable Urban Development, Parametric Simulation, Future Scenarios, Cooperative Housing, Batıkent, Solar Radiation

1. Introduction

Rapid urbanization, climate change, and increasing energy demand have intensified the need for sustainable development strategies in existing urban environments. Contemporary sustainability discourse increasingly emphasizes that the environmental transformation of cities cannot rely solely on new developments but must also address the performance of established residential districts (Eryıldız, 1996; Eryıldız, 2007). Large-scale housing areas developed during the late twentieth century, particularly cooperative housing settlements, represent a critical challenge in this regard due to their fixed morphology, aging building envelopes, and limited adaptability to current environmental standards (Ratti et al., 2005; Sharifi & Murayama, 2013; Eryıldız & Eryıldız, 2005).

Batıkent, one of Ankara's largest planned cooperative housing districts, exemplifies this condition. Developed through a cooperative-based planning model, Batıkent contains a wide range of residential typologies, including low-rise duplex housing, uniform mid-rise apartment blocks, high-rise residential towers, and mixed-height configurations distributed across both flat and gently sloped terrain (Eryıldız & Eryıldız, 2004). While the original planning approach prioritized housing provision and functional organization, contemporary sustainability goals require a reassessment of how such districts can adapt to current and future environmental challenges, particularly in relation to energy efficiency and climate responsiveness (Jenks & Burgess, 2000; Yeang et al., 2012).

In recent years, simulation-based urban analysis has emerged as a powerful approach for evaluating environmental performance and testing future development scenarios. Parametric tools allow the integration of climatic data, urban geometry, and design variables within a unified analytical framework, enabling the exploration of multiple alternatives under controlled conditions. Compared to conventional evaluation methods, simulation-based approaches provide higher spatial resolution and greater flexibility, making them particularly suitable for scenario-driven planning and sustainability assessment in complex urban contexts (Ng et al., 2012; Robinson et al., 2009; SuSan & Eryıldız, 2023).

Among the various environmental indicators used in urban sustainability studies, solar radiation performance plays a central role due to its direct influence on heating demand, cooling loads, renewable energy potential, and outdoor thermal comfort. The distribution of solar radiation within urban environments is strongly affected by building height, spacing, orientation, and terrain configuration, underscoring the need for spatially explicit and geometry-sensitive analytical methods (Compagnon, 2004; Lobaccaro & Frontini, 2014; Eryıldız, 2005). As cities increasingly pursue low-carbon development pathways, understanding and optimizing solar access at both building and neighborhood scales has become a fundamental planning concern (Yeang et al., 2012).

At the same time, sustainable urban development strategies are expanding beyond energy generation alone to include nature-based solutions and advanced building materials that enhance environmental performance without requiring extensive structural intervention. Green façades, high-performance insulation materials, and renewable energy systems are increasingly recognized as effective retrofitting measures capable of improving thermal comfort, reducing energy consumption, and mitigating urban heat effects in dense residential areas (Perini et al., 2011; Santamouris, 2014; Eryıldız, 2007). These approaches are particularly relevant for cooperative housing districts, where large-scale demolition or reconstruction is often impractical (Eryıldız & Eryıldız, 2005).

Within this broader context, the present study adopts a future-oriented, simulation-based perspective to explore sustainable development strategies for Batıkent, Ankara. Rather than focusing on the evaluation of existing conditions alone, the research investigates how Batıkent could perform under alternative future scenarios shaped by terrain-sensitive planning, renewable energy integration, and material-based interventions, consistent with principles of ecological urbanism and urban ecology (Eryıldız, 1996; Yeang et al., 2012). Four representative cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular—are selected to reflect the district's morphological diversity and to enable comparative analysis across low-rise, mid-rise, high-rise, and mixed-typology settlements (Eryıldız & Eryıldız, 2004).

The study is structured around three interconnected analytical dimensions. First, it examines the influence of topography by comparing flat and sloped terrain scenarios, recognizing terrain as a potential environmental asset rather than a planning constraint (Toparlar et al., 2017; Eryıldız, 2005). Second, it evaluates the integration of renewable energy systems and nature-based solutions, including solar panels and green walls, as feasible strategies for enhancing environmental performance in existing residential contexts (Santamouris, 2014; SuSan & Eryıldız, 2023). Third, it employs visual before–after simulations to translate numerical results into spatially interpretable outcomes, strengthening the link between quantitative analysis and design-oriented decision-making (Yeang et al., 2012).

By focusing on future scenarios and simulation-informed strategies, this research contributes to the growing body of literature that frames sustainability as an adaptive and transformative process rather than a static performance benchmark. The findings from Batıkent provide transferable insights for similar cooperative housing districts and mass-housing developments seeking to improve environmental performance through incremental, context-sensitive, and technologically informed interventions.

2. Research Tools and Method

This study adopts a simulation-based, scenario-oriented methodological framework to explore future strategies for the sustainable development of Batıkent, Ankara. Rather than evaluating existing conditions alone, the methodology is designed to test alternative future configurations under controlled environmental assumptions, allowing the assessment of how spatial form, terrain, and technological interventions may influence long-term environmental performance. The approach combines parametric modeling, climatic data integration, and visual simulation to support evidence-based urban design and planning decisions.

2.1. Case Study Selection

Batıkent was selected as the case study due to its significance as a large-scale cooperative housing district and its morphological diversity. Four representative cooperative areas were chosen to reflect different building typologies and spatial configurations within the district:

- 3D Dubleks (Site A): Low-rise duplex housing with open courtyards and high spatial permeability.
- Harp-İş (Site B): Uniform mid-rise (5-story) apartment blocks with linear arrangements.
- Tez-Koop (Site C): High-rise (10-story) residential blocks representing vertical density.
- Ortadoğulular (Site D): A mixed configuration combining duplex units and 8-story apartment blocks.

The selection of these sites enables comparative analysis across low-rise, mid-rise, high-rise, and mixed typologies, which is essential for evaluating the transferability of future-oriented sustainability strategies.

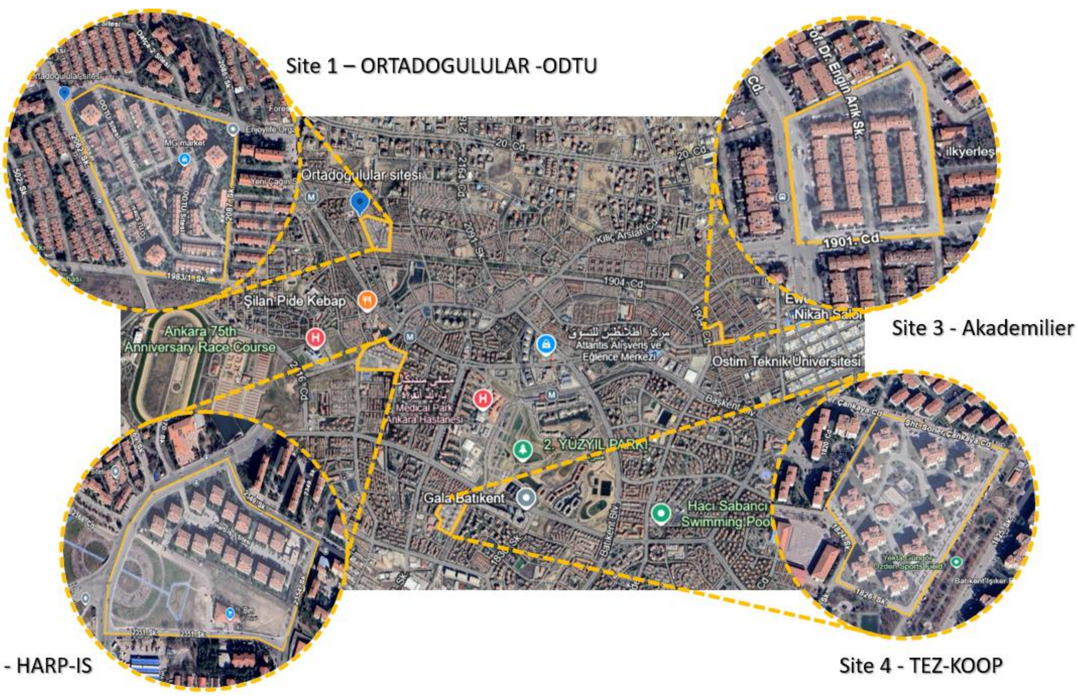

Figure 1: Locations in Batıkent-Ankara

2.2. Simulation Tools and Climatic Data

Parametric environmental simulations were conducted using Grasshopper as the core modeling platform, with Ladybug Tools employed for solar radiation analysis. These tools allow the integration of geometric parameters, orientation, and terrain conditions with real climatic data. Climate inputs were obtained from the EnergyPlus Weather (EPW) file for Ankara, ensuring that simulations reflect long-term local solar conditions rather than hypothetical or generalized climate assumptions.

Solar radiation was selected as the primary environmental performance indicator due to its direct relevance to energy efficiency, renewable energy potential, and thermal comfort. Incident radiation values (kWh/m^2) were calculated for each site under multiple scenarios, enabling numerical comparison across different spatial and terrain configurations.

2.3. Terrain-Based Scenario Development

To assess the influence of topography on future environmental performance, two terrain scenarios were developed for each cooperative area:

1. Flat Terrain Scenario: All buildings are positioned on a uniform horizontal plane, reflecting conventional planning practices that prioritize land leveling and standardized layouts.
2. Sloped Terrain Scenario: Buildings follow natural topographical gradients, introducing elevation differences between blocks and façades. This scenario allows the evaluation of terrain-sensitive massing and its impact on solar exposure and shading behavior.

By keeping all other variables constant, the comparison between flat and sloped terrain scenarios isolates the effect of topography on environmental performance.

2.4. Future-Oriented Intervention Scenarios

Beyond terrain conditions, the methodology incorporates future-oriented design interventions aimed at improving sustainability without requiring structural reconstruction. Three categories of interventions were simulated and evaluated:

- Renewable Energy Integration: Rooftop and façade-based solar panels were proposed based on building height, orientation, and surface availability across the four sites.
- Nature-Based Solutions: Green walls were introduced on selected façades to improve thermal regulation, reduce surface temperatures, and enhance environmental quality, particularly in dense mid-rise and high-rise contexts.
- Material-Based Envelope Enhancement: The advanced insulation materials was applied as a façade treatment to improve thermal, acoustic, and fire performance. Its suitability for retrofitting existing buildings made it a key component of future redevelopment scenarios.

These interventions were applied consistently across sites, allowing comparative evaluation while accounting for typological differences.

2.5. Visual Simulation and Comparative Analysis

To complement numerical outputs, before–after visual simulations were generated for each site. The “before” condition represents the existing spatial configuration, while the “after” condition illustrates the proposed future scenario incorporating terrain adaptation and sustainability interventions. This visual approach enhances interpretability and supports the translation of simulation results into design-oriented insights.

Comparative analysis was conducted by examining differences in solar radiation values across scenarios and sites, supported by qualitative interpretation of visual outcomes. The methodology prioritizes relative performance trends rather than absolute optimization, aligning with the study's focus on strategic guidance rather than prescriptive design.

2.6. Methodological Scope and Limitations

The methodology is intentionally focused on future scenarios and solar radiation performance as a central indicator. While other environmental factors such as airflow and thermal comfort are relevant, they are addressed conceptually rather than through full multi-variable simulation to maintain methodological clarity and feasibility. The results should therefore be interpreted as strategic indicators rather than definitive performance predictions. Overall, this methodological framework enables a structured exploration of how Batıkent's cooperative housing areas could evolve toward sustainability through simulation-informed, terrain-sensitive, and intervention-based strategies.

3. Future-Oriented Strategies for the Sustainable Development of Batıkent

The sustainable development of Batıkent cannot be addressed solely through the evaluation of existing environmental performance; rather, it requires a forward-looking framework that integrates future design scenarios, terrain conditions, and advanced environmental technologies. Building on the comparative analyses and simulation results presented in the previous sections, this chapter shifts the focus from assessment to strategic projection, exploring how Batıkent's residential environments can evolve under alternative spatial, technological, and material-based interventions. The chapter emphasizes the role of topography-sensitive planning, renewable energy integration, and innovative façade and surface solutions in enhancing long-term environmental resilience and energy efficiency. By employing parametric simulations under varying terrain conditions and proposed design enhancements, the future perspective presented here aims to support informed decision-making for sustainable redevelopment, retrofitting strategies, and climate-responsive urban design across the four cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular.

3.1. Future Performance Scenarios under Different Terrain Conditions

Topography plays a decisive role in shaping long-term environmental performance in residential settlements, particularly in districts such as Batıkent where both flat and gently sloped terrains are present. While conventional planning approaches often treat terrain as a constraint to be neutralized through leveling, contemporary sustainability-oriented design recognizes topography as a spatial and environmental asset. In this context, the present section explores future performance scenarios for Batıkent by comparing flat terrain and sloped terrain conditions using parametric solar radiation simulations for the four cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular. The objective is to evaluate how terrain configuration influences solar exposure patterns and to identify forward-looking strategies for terrain-responsive urban redevelopment.

The flat terrain scenario represents a conventional planning assumption in which all buildings are positioned on a uniform horizontal plane. Under this condition, solar radiation performance is largely dictated by building orientation, height, and spacing. The simulation results show that settlements with open layouts or significant vertical differentiation perform more effectively, while uniform mid-rise arrangements experience notable reductions in solar access due to mutual shading.

Table 1: Solar Radiation Results under Flat Terrain Conditions for the Four Study Sites

	Incident Radiation [kWh/m2]							
	Site A		Site B		Site C		Site D	
	Original	Randomized	Original	Randomized	Original	Randomized	Original	Randomized
1	985.97	1002.65	948.92	979.41	995.55	996.97	988.66	998.9
2	887.37	902.39	858.61	887.35	899.88	897.8	889.79	899.01
3	788.78	802.12	768.3	795.29	804.22	798.63	790.93	799.12
4	690.18	701.86	677.98	703.24	708.55	699.46	692.06	699.23
5	591.58	601.59	587.67	611.18	612.89	600.29	593.2	599.34
6	492.98	501.33	497.36	519.12	517.22	501.12	494.33	499.45
7	394.39	401.06	407.05	427.06	421.56	401.95	395.46	399.56
8	295.79	300.8	316.74	335.01	325.89	302.77	296.6	299.67
9	197.19	200.53	223.43	242.95	230.23	203.6	197.73	199.78
10	98.6	100.27	136.11	150.89	134.25	104.43	98.87	99.89
11	0	0	45.8	58.83	38.9	5.26	0	0

The flat terrain results highlight clear performance distinctions among the four sites. High-rise configurations, such as Tez-Koop, benefit from unobstructed upper-level exposure, while low-rise but permeable layouts, such as 3D Dubleks, achieve comparable performance through horizontal openness. In contrast, Harp-İş, characterized by uniform 5-story blocks, consistently demonstrates lower radiation values, indicating sensitivity to shading accumulation in flat-grid configurations. These findings suggest that, under flat terrain assumptions, solar efficiency depends heavily on either vertical advantage or generous spacing—conditions not equally present across all cooperatives.

To extend this evaluation into a future-oriented framework, a sloped terrain scenario was introduced to examine how elevation differences influence solar radiation distribution. Rather than leveling the terrain, this scenario allows buildings to follow natural topographical gradients, creating vertical offsets between blocks and façades.

Table 2: Solar Radiation Results under Sloped Terrain Conditions for the Four Study Sites

	Incident Radiation [kWh/m2]							
	Site A		Site B		Site C		Site D	
	Original	Randomized	Original	Randomized	Original	Randomized	Original	Randomized
1	987.37	1002.95	987.59	987.59	999.47	997.95	986.14	998.69
2	888.63	902.65	888.83	888.83	899.53	898.15	887.53	898.82
3	789.9	802.36	790.07	790.07	799.58	798.36	788.91	798.95
4	691.16	702.06	691.31	691.31	699.63	698.56	690.3	699.08
5	592.42	601.77	592.55	592.55	599.68	598.77	591.69	599.21
6	493.68	501.47	493.79	493.79	499.74	498.97	493.07	499.34
7	394.95	401.18	395.04	395.04	399.79	399.18	394.46	399.48
8	296.21	300.88	296.28	296.28	299.84	299.38	295.84	299.61
9	197.47	200.59	197.52	197.52	199.89	199.59	197.23	199.74
10	98.74	100.29	98.76	98.76	99.95	99.79	98.61	99.87
11	0	0	0	0	0	0	0	0

The sloped terrain simulations reveal a generally more stable and, in several cases, improved solar performance compared to the flat scenario. This improvement is particularly evident in mid-rise and mixed-typology settlements. For Tez-Koop, the sloped condition enhances radiation consistency by reducing shading interactions between adjacent towers, especially at lower interfaces. The elevation gradient effectively increases sky exposure for lower façades without requiring additional building height. From a future planning perspective, this suggests that high-rise developments in Batıkent can achieve better environmental outcomes when aligned with topography rather than imposed on flattened terrain.

For Ortadoğulular, which combines duplex units with 8-story blocks, the sloped terrain scenario produces a more balanced radiation distribution across building types. Elevation differences mitigate the shadowing impact of taller blocks on adjacent low-rise units, supporting a more equitable solar environment. This finding is particularly significant for future redevelopment strategies in mixed-morphology areas, indicating that terrain-sensitive design can improve performance without altering building typology.

The 3D Dubleks site shows minimal variation between flat and sloped terrain scenarios. This stability confirms that open, low-rise configurations are inherently resilient to topographical change. From a future perspective, such layouts offer strong adaptability for redevelopment in sloped zones, as their performance does not depend on artificial leveling or complex height manipulation.

In contrast, Harp-İş benefits noticeably from the sloped terrain condition. The introduction of elevation differences reduces continuous shadow corridors formed under flat terrain assumptions, leading to improved radiation values across multiple rows. This outcome suggests that underperforming mid-rise settlements can achieve meaningful environmental gains through terrain-responsive reconfiguration rather than full-scale reconstruction.

Overall, the comparison between flat and sloped terrain scenarios demonstrates that topography-sensitive planning offers clear environmental advantages for Batıkent's future development. Flat terrain conditions tend to amplify the negative effects of dense and uniform block arrangements, while sloped terrain introduces spatial differentiation that enhances solar access, particularly in mid-rise and high-rise contexts. These results indicate that future redevelopment strategies should avoid excessive land leveling and instead adopt stepped massing, slope-aligned orientation, and terrain-integrated block layouts.

In conclusion, future performance scenarios based on terrain variation confirm that topography should be treated as an active design parameter rather than a passive constraint. By integrating slope-aware planning principles into Batıkent's redevelopment and infill strategies, it is possible to improve solar efficiency, reduce shading conflicts, and support long-term energy resilience across all four cooperative areas. This approach provides a critical foundation for subsequent future scenarios involving renewable energy systems and material-based interventions discussed in the following sections.

3.2. Integration of Renewable Energy and Nature-Based Solutions

Achieving long-term sustainability in Batıkent requires the integration of renewable energy systems and nature-based solutions that complement the existing urban morphology while enhancing environmental performance. Building on the terrain-sensitive future scenarios discussed in Section 4.1, this section explores three key intervention strategies—solar panels, green walls, and the advanced insulation material—as complementary measures to improve energy efficiency, thermal comfort, and environmental resilience across the four cooperative sites (3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular). These strategies were selected due to their adaptability to different building typologies and their potential to be implemented through retrofitting rather than full-scale reconstruction.

3.2.1. Green Walls as Nature-Based Climate Moderators

Green walls constitute a nature-based solution that addresses multiple environmental challenges simultaneously, including thermal regulation, air quality improvement, and visual enhancement of dense urban façades. In the context of Batıkent, green walls are particularly relevant for mid-rise and high-rise blocks, where limited ground-level green space restricts conventional landscaping options.

Simulation-based projections indicate that green walls can significantly reduce surface temperatures by limiting direct solar absorption on façades, thereby decreasing cooling loads during summer periods. This intervention is especially valuable for Site B (Harp-İş) and Site C (Tez-Koop), where façade shading is more critical due to block density and building height. For Ortadoğulular, green walls can function as transitional elements between duplex units and taller blocks, contributing to microclimatic balance. In 3D Dubleks, green walls primarily serve as complementary features that enhance outdoor comfort and biodiversity rather than as primary thermal regulators.

Beyond thermal benefits, green walls contribute to acoustic buffering and visual softening of rigid building envelopes, improving residents' perception of environmental quality. Their modular nature allows phased implementation, making them feasible within cooperative-based redevelopment frameworks.

3.2.2. Advanced Insulation Material: Concept and Application

A key innovative component of the future development strategy is the integration of advanced fire insulation material, a perlite-based plaster and coating system that provides thermal insulation, acoustic performance, and fire resistance. Advanced Insulation material is free from chemical emissions, does not degrade under solar exposure, and contributes to indoor air quality while enhancing exterior durability. Thermal imaging evidence demonstrates its capacity to maintain significantly lower surface temperatures compared to untreated materials, even under extreme heat exposure.

Figure 2: Advanced Fire Insulation material

3.2.3. Easy Application

1. Advanced fire insulation coating is applied after the application of surface adhesion mortar on surfaces such as brick, gas concrete, lightweight concrete blocks, and concrete.
2. Advanced Insulation material is applied to the surface using 2.5-centimeter anode rods after proper mixing. Due to high plaster adhesion, the consumption is low, and application is easy.
3. It is recommended to use a mesh before applying the final coat of mineral decorative coating or paint. The mesh is applied by pressing it onto the surface of the coating that has been previously applied.
4. After applying the mesh, the desired decorative plaster or paint application completes the process.

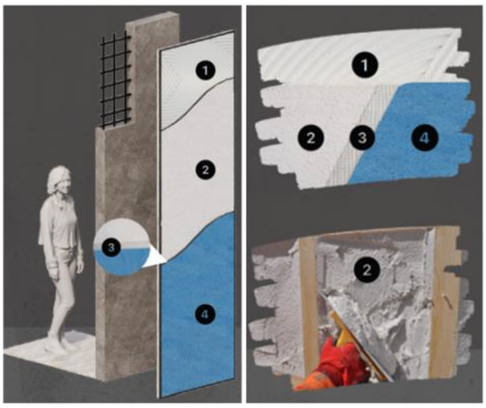

Figure 3: Advanced material Application

3.2.4. Free From Chemical Emissions

Advanced insulation material does not undergo chemical changes when exposed to sunlight and does not release harmful gases or chemicals into the air on the applied surface. This increases the durability of the exterior while maintaining indoor air quality.

3.2.5. Acoustic Effect

While absorbing noise with its sound insulation, Advanced insulation material also prevents sound from echoing indoors and provides acoustic comfort. This enables the creation of a quieter indoor environment or achieving desired sound characteristics.

3.2.6. Noise Insulation

Advanced insulation material limits the transmission of noise from outside to inside or from one room to another with the superior sound insulation it provides. Thus, it creates quieter and more comfortable interior spaces by reducing noise pollution. It reduces sound by 42 decibels in 3 cm thick applications.

Figure 4: Advanced material Specifications

Figure 5: How to install it

From a sustainable development perspective, Advanced insulation material is particularly suitable for retrofitting existing buildings in Batıkent. Its application process—surface preparation, plaster application, mesh reinforcement, and final coating—allows it to be integrated without structural alteration. This makes it highly applicable to Harp-İş and Ortadoğulular, where improving envelope performance is critical to compensating for lower solar efficiency. In Tez-Koop, Advanced insulation material can be combined with façade-mounted PV systems to enhance overall envelope performance, while in 3D Dubleks, it supports indoor comfort and fire safety without compromising architectural openness.

3.2.4. Permeable Outdoor Surfaces

In addition to façade applications, Advanced insulation material -compatible systems can be combined with permeable outdoor flooring solutions, such as self-draining surfaces, to improve stormwater management and thermal behavior in open spaces. These systems allow rainwater infiltration, reduce surface runoff, and mitigate urban heat accumulation—an increasingly important consideration under climate-change conditions.

Figure 6: Paving Stones and Building Components

Lack of drainage causes rainwater to spread uncontrollably into urban infrastructure, leading to environmental problems. Flash floods threaten life and property on streets and roads, while excess water accumulation that cannot be removed from retaining walls can threaten structural integrity. These situations highlight the importance of effective drainage systems and demonstrate their necessity for environmental sustainability and infrastructure safety.

Introducing the ecological paving stones, distinguished by their inherent water permeability. This innovative product combines aesthetics and durability while allowing rainwater to seep into the soil.

3.2.7. Cellular Drainage Technology (CDT)

Traditional paving stones have limited rainwater absorption capacity and, due to their generally hard surfaces, prevent water from penetrating the soil. However, this problem is eliminated with ecologically permeable paving stones. This special design, utilizing Cellular Drainage Technology, allows rainwater to directly seep into the soil, contributing to the natural water cycle and offering an environmentally friendly option.

This eco-friendly paving stone has a wide range of applications including landscaping, retaining walls, walkways, parking lots, pool sides, and car/carpet washing areas. If you are looking for an environmentally friendly and aesthetically pleasing solution for any of your outdoor projects, this specially designed paving stone will be the ideal choice for you.

Such applications are particularly relevant for courtyard spaces in 3D Dubleks and Ortadoğulular, as well as pedestrian zones in Harp-İş, where surface sealing currently limits environmental performance. Integrating permeable materials strengthens Batıkent's capacity to adapt to extreme weather events while reinforcing ecological sustainability.

In summary, the combined integration of solar panels, green walls, and Advanced insulation material systems offers a multi-layered future strategy for sustainable development in Batıkent. Each intervention addresses different aspects of environmental performance—energy generation, thermal regulation, acoustic comfort, fire safety, and water management—while remaining adaptable to the distinct morphological conditions of the four cooperative sites. Together, these solutions form a coherent, scalable framework for climate-responsive urban regeneration that can be implemented incrementally and strategically across Batıkent.

3.3. Visual Simulation of Future Scenarios: Before–After Comparisons

Visual simulation constitutes a critical component of performance-based urban design, as it enables the translation of numerical and analytical results into spatially comprehensible representations. In the context of Batıkent's sustainable redevelopment, before–after visual simulations were employed to illustrate the potential impacts of proposed environmental interventions on the four cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular. These simulations complement the quantitative findings presented in previous sections by providing a clear visual narrative of how spatial form, building orientation, and material integration can transform environmental performance and urban quality.

For each site, the visual analysis follows a consistent structure. The "before" condition represents the current or baseline situation (status quo), reflecting existing building layouts, orientations, and envelope characteristics. The "after" condition illustrates a future-oriented scenario incorporating the proposed strategies discussed in Section 4.2, including adjusted building orientation, the integration of solar panels, green walls, and the application of Advanced insulation material. This standardized visual framework ensures comparability across the four sites and supports a coherent evaluation of design interventions under different morphological conditions.

In Ortadoğulular, the before–after visuals highlight how the integration of renewable energy systems and envelope improvements can mitigate the environmental limitations of mixed-height development. The existing condition shows a combination of duplex units and mid-rise blocks with limited rooftop utilization and conventional façade materials. In the future scenario, rooftop solar panels are added to both low-rise and mid-rise structures, while Advanced insulation material is applied to building envelopes to enhance thermal and fire performance. The visual outcome demonstrates a more coherent environmental identity, with improved energy-generation capacity and a visibly enhanced building envelope without altering the fundamental urban morphology.

Figure 7: Site 1 ORTADOGULULAR

Figure 8: Site 1 ORTADOGULULAR

In the case of Harp-İş, the before–after comparison plays a particularly important analytical role. The existing visuals reveal the limitations of uniform mid-rise blocks, including repetitive façades and limited environmental differentiation. The future scenario illustrates how targeted interventions—such as rooftop solar panel installation, façade-based green walls, and improved insulation through Advanced insulation material —can significantly enhance environmental quality without requiring structural reconstruction. The visual contrast clearly demonstrates that even morphologically constrained settlements can achieve substantial sustainability gains through strategic retrofitting.

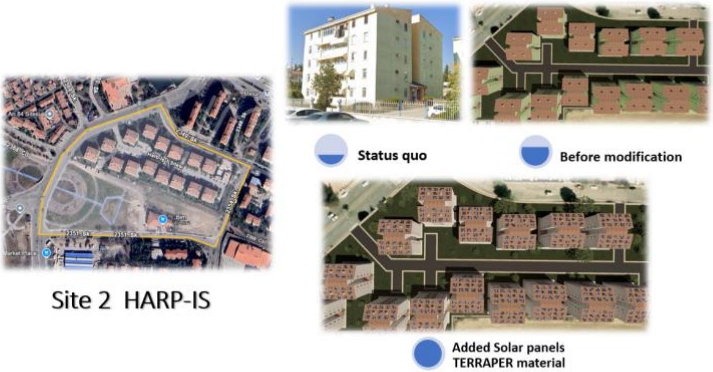

Figure 9: Site 2 HARP-IS

Figure 10: Site 2 HARP-IS

For Akademilier, the visual simulations emphasize the advantages of low-rise, open layouts when combined with renewable and nature-based solutions. The existing condition already exhibits strong spatial permeability and generous open spaces. The future scenario reinforces these qualities through the addition of solar panels on duplex roofs, green wall applications along selected façades, and permeable outdoor surfaces. Visually, the intervention maintains the human-scale character of the site while clearly communicating an upgrade in environmental performance and sustainability.

Figure 11: Site 3 Akademilier

Figure 12. Site 3 Akademilier

For Tez-Koop, the visual simulations focus on the vertical dimension of sustainability. The baseline condition highlights the dominance of high-rise blocks and their extensive façade surfaces. In the future scenario, these surfaces are reimagined as active environmental elements through the integration of photovoltaic systems and advanced insulation materials. The visual outcome underscores the potential of high-rise typologies to function as energy-producing structures, transforming perceived environmental challenges associated with height into long-term advantages.

Figure 13: Site 4 Tez-Koop

Figure 14: Site 4 Tez-Koop

Across all four sites, the before–after visual simulations serve three primary purposes. First, they validate the feasibility of the proposed interventions by demonstrating their spatial compatibility with existing urban forms. Second, they support comparative analysis, allowing differences in response between low-rise, mid-rise, high-rise, and mixed typologies to be visually assessed. Third, they enhance communication, making complex environmental strategies accessible to planners, decision-makers, and non-technical stakeholders.

In summary, the visual simulation of future scenarios provides a critical bridge between analytical results and design-oriented interpretation. By presenting clear before–after comparisons for each cooperative area, this section reinforces the argument that Batıkent's sustainable transformation can be achieved through incremental, site-specific interventions that respect existing morphology while significantly improving environmental performance. These visuals not only illustrate possible futures for Batıkent but also function as decision-support tools for guiding sustainable urban redevelopment strategies.

3.4. Strategic Synthesis of Future Scenarios

The future-oriented scenarios developed in this study provide a comprehensive framework for guiding the sustainable transformation of Batıkent through performance-based, context-sensitive strategies. By synthesizing the findings from terrain-based simulations, renewable energy integration, nature-based solutions, and visual before–after comparisons, this section consolidates the key strategic insights that can inform both short-term interventions and long-term urban redevelopment policies for the four cooperative areas—3D Dubleks, Harp-İş, Tez-Koop, and Ortadoğulular.

A central outcome of the future scenarios is the recognition that morphological diversity requires differentiated strategies rather than uniform solutions. The comparison between flat and sloped terrain conditions demonstrates that topography significantly influences solar radiation performance, particularly in mid-rise and high-rise settlements. Sloped terrain scenarios consistently produced more balanced and stable solar exposure by reducing mutual shading and introducing vertical differentiation. This finding suggests that future planning in Batıkent should avoid excessive land leveling and instead adopt terrain-responsive massing, stepped building profiles, and slope-aligned orientations. Treating topography as an environmental asset rather than a constraint enables more efficient use of solar potential without increasing density or building height.

The integration of renewable energy systems, particularly solar panels, emerges as a second strategic pillar. Simulation results and visual scenarios confirm that all four sites possess varying but meaningful potential for decentralized solar energy production. High-rise façades and rooftops in Tez-Koop offer large, uninterrupted surfaces for photovoltaic systems, while the low-rise roofs of 3D Dubleks provide ideal conditions for efficient rooftop installations. Mixed-typology areas such as Ortadoğulular can benefit from hybrid deployment strategies, and even lower-performing sites like Harp-İş can achieve significant gains through selective rooftop and orientation-based applications. Strategically, this indicates that Batıkent can transition toward a distributed energy model, reducing reliance on centralized systems while enhancing neighborhood-level energy resilience.

Nature-based solutions, particularly green walls and permeable outdoor surfaces, constitute a third strategic dimension. These interventions address not only thermal performance but also microclimatic comfort, acoustic quality, and visual enhancement. The future scenarios demonstrate that green walls are especially valuable for dense mid-rise and high-rise blocks where ground-level green space is limited. Permeable flooring systems further contribute to sustainable stormwater management and urban heat mitigation, reinforcing Batıkent's adaptive capacity under climate-change pressures. Together, these solutions support a shift toward multifunctional urban surfaces that perform ecological, climatic, and social roles simultaneously.

The application of Advanced insulation material represents a critical enabling strategy that bridges environmental performance and practical feasibility. Its thermal, acoustic, and fire-resistant properties—combined with ease of application—make it particularly suitable for retrofitting existing cooperative housing stock. From a strategic standpoint, Advanced insulation material allows Batıkent to improve building-envelope performance without structural alteration, making sustainability upgrades achievable within legal, financial, and organizational constraints typical of cooperative developments. When combined with renewable energy systems, Advanced insulation material contributes to a holistic envelope strategy that enhances both energy efficiency and safety.

Finally, the visual simulation of before–after scenarios plays a key strategic role in translating analytical findings into actionable design guidance. These visuals demonstrate that meaningful environmental improvements can be achieved through incremental interventions rather than radical urban restructuring. They also provide a powerful communication tool for stakeholders, supporting informed decision-making and increasing the likelihood of implementation.

In synthesis, the future scenarios collectively indicate that Batıkent's sustainable development should be guided by four core principles: terrain-sensitive planning, distributed renewable energy integration, nature-based and material-based envelope enhancement, and incremental, site-specific transformation. By aligning these principles with the district's existing morphological structure, Batıkent can evolve into a resilient, energy-efficient, and climate-responsive urban environment while preserving its original cooperative planning identity. This strategic synthesis provides a transferable model for sustainable redevelopment in similar mass-housing contexts in Ankara and beyond.

4. Discussion

The findings of this study demonstrate that future-oriented, simulation-based strategies can play a decisive role in enhancing the environmental performance of existing cooperative housing districts such as Batıkent. By focusing on forward-looking scenarios rather than static evaluations of current conditions, the research contributes to an emerging body of literature that frames urban sustainability as a dynamic and adaptive process. The results highlight how spatial morphology, terrain configuration, and targeted environmental interventions interact to shape long-term solar performance and energy potential.

One of the most significant outcomes concerns the role of topography in future urban performance. The comparison between flat and sloped terrain scenarios reveals that terrain-sensitive configurations consistently improve or stabilize solar radiation distribution, particularly in mid-rise and high-rise developments. This finding aligns with previous studies demonstrating that elevation differences and stepped massing reduce mutual shading and enhance sky exposure in dense urban environments (Compagnon, 2004; Lobaccaro & Frontini, 2014). The results challenge conventional planning practices that prioritize land leveling and instead support approaches that integrate natural terrain as a design parameter. From a sustainability perspective, this reinforces the argument that topography should be leveraged as an environmental asset rather than treated as a constraint (Toparlar et al., 2017). The site-based comparisons further reveal that urban morphology strongly mediates environmental performance outcomes. Low-rise, permeable configurations such as the 3D Dubleks site show relative stability across terrain scenarios, confirming that horizontal openness and reduced building height inherently mitigate shading effects. In contrast, uniform mid-rise developments such as Harp-İş exhibit greater sensitivity to both terrain and orientation, resulting in lower baseline solar performance. High-rise typologies, represented by Tez-Koop, benefit from increased exposure at upper levels but require careful spatial coordination to avoid excessive shading at lower interfaces. These patterns are consistent with earlier research linking building height diversity and spatial articulation to improved solar access at the neighborhood scale (Ratti et al., 2005; Steemers, 2003).

The integration of renewable energy systems, particularly solar panels, emerges as a viable and scalable strategy across all four sites, albeit with varying degrees of effectiveness depending on morphology. The simulations indicate that both rooftop and façade-based photovoltaic installations can significantly enhance energy potential when aligned with building height and orientation. This finding supports existing literature emphasizing the importance of integrating solar energy considerations into early design and retrofit stages rather than treating renewable systems as add-on technologies (Kämpf et al., 2010; Mainzer et al., 2014). In the context of cooperative housing districts, where structural transformation is often limited, the ability to deploy solar systems incrementally is particularly valuable.

Nature-based solutions, including green walls, contribute an additional layer of environmental performance by addressing thermal regulation and microclimatic comfort. While green walls do not directly increase solar energy production, their capacity to reduce façade surface temperatures and mitigate heat accumulation enhances overall energy efficiency, especially in dense mid-rise and high-rise settings. This aligns with empirical studies demonstrating the cooling and insulating effects of vertical greening systems in urban environments (Perini et al., 2011; Ng et al., 2012). In Batıkent, green walls are shown to be most effective as complementary interventions that enhance envelope performance rather than as standalone solutions.

The application of advanced insulation materials, such as Advanced insulation material, further strengthens the feasibility of future-oriented sustainability strategies. Material-based interventions play a critical role in bridging the gap between analytical potential and practical implementation. High-performance insulation has been widely recognized as one of the most cost-effective means of reducing energy demand in existing buildings (Santamouris, 2014). In this study, Advanced insulation material's suitability for retrofitting without structural modification positions it as a strategic enabler for cooperative housing contexts, where legal, financial, and organizational constraints often limit large-scale redevelopment.

A key methodological contribution of this study lies in the use of before–after visual simulations to support the interpretation of numerical results. Visual representations translate abstract performance metrics into spatially intelligible scenarios, facilitating communication between researchers, planners, and decision-makers. Previous studies have emphasized that visualization enhances stakeholder engagement and improves the uptake of sustainability-driven design strategies (Robinson et al., 2009; Sheppard, 2012). In the Batıkent case, the visual simulations confirm that meaningful environmental improvements can be achieved through incremental, site-specific interventions rather than radical urban restructuring.

From a broader perspective, the results reinforce the argument that there is no universally optimal urban form for sustainability. Instead, environmental performance emerges from the interaction between morphology, terrain, climate, and technological intervention. This finding supports adaptive planning frameworks that prioritize context-sensitive solutions over standardized design models (Sharifi & Murayama, 2013). For Batıkent, this implies that future development strategies should be differentiated across cooperative areas while guided by shared sustainability principles.

Despite its contributions, the study has limitations that should be acknowledged. The analysis focuses primarily on solar radiation as a key environmental indicator, while other factors such as wind comfort, indoor thermal performance, and user behavior are addressed conceptually rather than through full simulation. Future research could extend the framework by integrating multi-variable environmental modeling and socio-economic considerations to further refine strategic recommendations.

Overall, the discussion underscores that simulation-based, future-oriented strategies provide a robust foundation for sustainable redevelopment in cooperative housing districts. By combining terrain-sensitive planning, renewable energy integration, material-based interventions, and visual simulation, the study offers a transferable model for enhancing environmental performance in established urban contexts under increasing climatic and energy-related pressures.

5. Conclusion

This study has examined future-oriented, simulation-based strategies for the sustainable development of Batıkent, Ankara, with a particular focus on how existing cooperative housing areas can be environmentally enhanced through scenario-driven planning rather than large-scale reconstruction. By employing parametric simulation tools and visual scenario modeling, the research moves beyond conventional performance evaluation and demonstrates how alternative future configurations can inform sustainable urban transformation in established residential districts.

The findings confirm that urban morphology and terrain configuration play a decisive role in shaping environmental performance. The comparison between flat and sloped terrain scenarios clearly shows that terrain-sensitive planning improves the stability and distribution of solar radiation, particularly in mid-rise and high-rise settlements. Rather than treating topography as a constraint to be neutralized, the results support planning approaches that integrate natural elevation differences into massing and orientation strategies. This insight is especially relevant for districts such as Batıkent, where gentle slopes are present and can be leveraged to enhance solar access without increasing building height or density.

The study also demonstrates that renewable energy integration and nature-based solutions can significantly improve environmental performance when applied in a typology-sensitive manner. Solar panels, green walls, and advanced insulation materials such as Advanced insulation material were shown to be adaptable across low-rise, mid-rise, high-rise, and mixed-use configurations. Importantly, these interventions can be implemented through incremental retrofitting, making them feasible within the institutional and financial constraints typical of cooperative housing environments. The results underline that sustainability gains do not require radical urban restructuring but can be achieved through targeted, evidence-based interventions aligned with existing spatial conditions.

A key contribution of this research lies in the combined use of numerical simulation and visual before–after scenarios. While quantitative results provide objective performance indicators, visual simulations translate these outcomes into spatially intelligible representations that support communication and decision-making. This dual approach strengthens the applicability of simulation-based strategies by bridging the gap between technical analysis and design-oriented planning practice.

From a broader perspective, the study reinforces the understanding that there is no single optimal urban form for sustainability. Environmental performance emerges from the interaction between spatial configuration, terrain, climate, and technological intervention. Consequently, sustainable redevelopment strategies should prioritize flexibility, context sensitivity, and adaptability rather than uniform design prescriptions. In the case of Batıkent, this implies differentiated strategies for each cooperative area, guided by shared sustainability principles but tailored to local morphological characteristics.

In conclusion, the research demonstrates that future-oriented, simulation-based planning offers a robust framework for guiding sustainable development in existing cooperative housing districts. The strategies proposed for Batıkent provide transferable insights for similar urban contexts seeking to enhance energy efficiency, environmental resilience, and long-term sustainability through incremental, data-driven, and context-aware interventions.

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