البحوث الثمانية المقدمة للفحص

البحث الثامن

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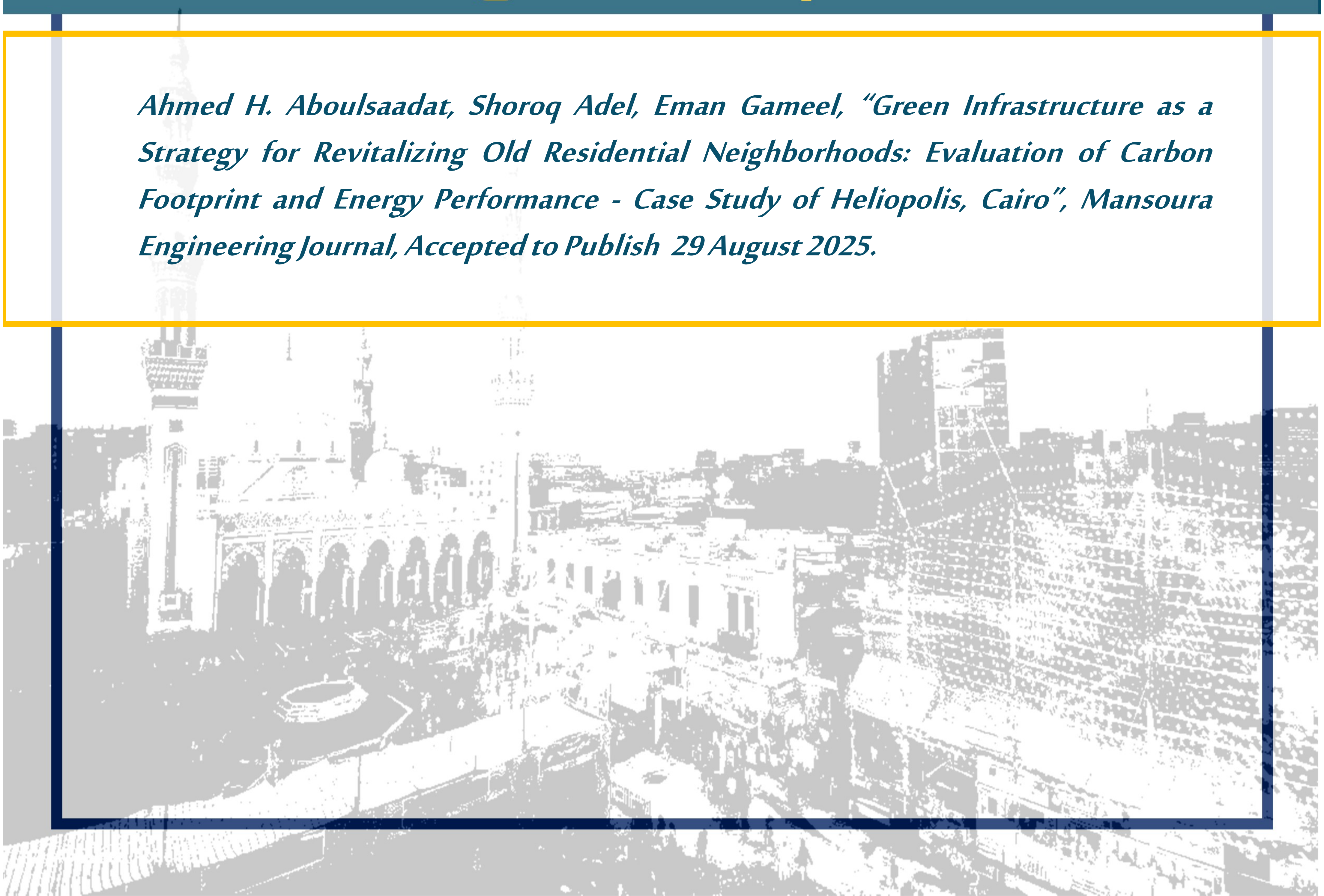

ORIGINAL STUDY

Green Infrastructure as a Strategy for Revitalizing Old Residential Neighborhoods: Evaluation of Carbon Footprint and Energy Performance: Case Study of Heliopolis, Cairo

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Abstract

This study aims to address the challenge of reducing energy consumption and greenhouse gas emissions in urban areas, particularly in aging residential neighborhoods. Despite the benefits of Urban Green Infrastructure and residential retrofitting, current research often examines these strategies separately, leaving a gap in understanding their combined impact at the district-scale. The research proposes a methodology that integrates Geographic Information System -based spatial analysis, Urban Building Energy Modeling, and Life Cycle Assessment to evaluate the effects of UGI (e.g. green roofs, urban trees) and retrofitting strategies on energy use, CO_2 reduction, and urban microclimates. The study will provide a comprehensive analysis of various intervention scenarios up to 2050, incorporating both operational and embodied energy, to offer a holistic approach to sustainable urban regeneration and guide policymakers in achieving climate goals. The research will analyze multiple scenarios for UGI implementation alongside building retrofitting measures, incorporating both operational and embodied energy to provide a holistic view of their environmental benefits.

Keywords: Energy efficiency, Greenhouse gas (GHG) emissions, Life cycle assessment (LCA), Residential retrofitting, Urban building energy modeling (UBEM), Urban green infrastructure (UGI)

1. Literature review

The 2015 Paris Agreement (COP21) set a pivotal global target to limit the rise in average global temperature to 1.5 °C above pre-industrial levels. Achieving this goal requires urgent action, including reducing greenhouse gas (GHG) emissions by 55 % by 2030 (relative to 1990 levels) and achieving net-zero emissions by 2050 (European Commission, 2023). This target acknowledges the substantial benefits of mitigating the adverse impacts of climate change. Faced with this global challenge, as well as with Global Goal 11, sustainable cities and communities of the UN 2030 Agenda, sustainable urban regeneration of obsolete residential neighborhoods is a key aspect (García-López, 2024a).

Urban areas are significant contributors to global GHG emissions, with the building sector accounting for ~40 % of global energy use and 33 % of related CO_2 emissions (Masson-Delmotte et al., 2021). The urgency of addressing these emissions has led to a surge in research on sustainable architectural solutions, particularly within the last 3–5 years.

Given the focus on Cairo, studies in hot and arid climates are particularly pertinent. Research in similar climatic conditions has explored various strategies for reducing energy consumption in buildings, including passive cooling techniques,

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optimized shading devices, and the use of high-albedo materials (Al-Saadi et al., 2023; Kazemi and Mahdavinejad, 2021). These studies often highlight the unique challenges and opportunities associated with designing and retrofitting buildings in such environments, including intense solar radiation, high ambient temperatures, and limited water resources.

2. Related research

Existing studies often focus on either retrofitting or urban green infrastructure (UGI) in isolation, creating a knowledge gap in understanding their combined impacts on district-scale energy performance and carbon emissions (Habibi and Kahe, 2024). The integration of Geographic Information System (GIS), Urban Building Energy Modeling (UBEM), and LCA in sustainable urban regeneration studies is increasingly recognized as essential for a holistic assessment of proposed interventions (Liu et al., 2024). This study aims to bridge this gap by examining the synergistic effects of retrofitting and GI on energy consumption and carbon emissions in a comprehensive manner, utilizing advanced modeling and analytical tools, and drawing lessons from recent research in comparable climates.

2.1. *Green infrastructure in zero-carbon cities*

The development of green spaces, such as parks and urban tree canopies, plays a crucial role in carbon sequestration and reducing energy needs for cooling in urban areas. Green infrastructure naturally removes and stores carbon dioxide, shades and cools surrounding areas, and offers cost-effective methods for carbon sequestration, contributing to the goals of zero-carbon cities (Seto et al., 2021). While the initial installation costs of GI can be high, the long-term benefits, such as reduced energy consumption and improved environmental quality, make GI a cost-effective strategy for sustainable urban development (Santamouris, 2014; Zhang and Ramírez, 2019).

2.2. *Nearly zero-energy buildings (NZEB)*

In the assessment of Nearly Zero-Energy Buildings, operational energy is typically included, whereas embodied energy is often overlooked (Giordano et al., 2017). For residential buildings, embodied energy constitutes ~25 % of the operational energy over a 50-year lifespan (Pacheco-Torgal et al., 2013). Additionally, advancements in energy-efficient technologies that lower operational energy consumption have led to a growing significance of embodied energy relative to operational energy in modern residential construction (Koezjakov et al., 2018).

Seyedabadi (U.S. Department of Energy (DOE), 2021) highlights the necessity for Life Cycle Assessment (LCA) studies at the neighborhood scale. Neglecting embodied carbon emissions during the renovation of aging residential areas can result in overestimating emissions reductions (Almeida et al., 2018). Therefore, it is imperative to account for both embodied energy and carbon emissions to accurately evaluate the cost-effectiveness and environmental benefits of building renovation.

A related study combines BIM, LCA, and GIS tools to develop an Eco-Efficiency Matrix for evaluating the sustainable performance of high-rise building districts in Quito, Ecuador (Cáceres et al., 2023). This approach is validated through a cradle-to-site LCA methodology, which considers material production, transportation to the construction site, and installation processes. However, the validation of UBEM outcomes often relies on reference models, lacking the incorporation of actual energy consumption data at the neighborhood scale, which is essential for model calibration and accuracy.

2.3. *Urban building energy modelling (UBEM)*

UBEM is a relatively recent discipline that has developed methods and tools for district-scale energy simulation in densely inhabited areas within the past ten years. Many elements, including the urban fabric, building morphology, boundary conditions, typological diversity, building design, and climate, can be taken into account by conducting an accurate and comprehensive examination of the energy consumption of buildings during their use phase (Energy Build, 2018) (Hong et al., 2020). Research on reducing emissions from the residential stock and examining potential climate change scenarios is required for the development of energy strategies and policies. The application of Urban Modelling Interface (UMI) tools in Cambridge highlights the effectiveness of UBEM in evaluating urban-scale energy retrofitting and renewable energy deployment.

The European Commission's report on the Renovation Wave Strategy outlines the need to double the rate of building renovation by 2030 to achieve the EU Green Deal targets. Reinhart and Cerezo-Dávila provide a comprehensive review of advancements in the field, highlighting key actions necessary for developing energy models tailored to urban environments (Reinhart and Cerezo-Dávila, 2016). In recent years, research on UBEM has experienced notable growth in both scope and sophistication, creating a robust and innovative framework for urban energy studies (Yoon, 2023). Prominent case studies include the application of UMI integrated with GIS tools for neighborhood energy modeling in cities.

Furthermore, the role of validation methods and model simplifications is emphasized as essential for understanding the foundational aspects of various UBEM methodologies. A significant advancement in this domain is the International Building Performance Simulation Association's initiative to develop a district-scale energy modeling framework, known as DESTEST (Johra et al., 2022).

2.4. Shortcomings in previous research

Previous research on UGI and energy efficiency has several shortcomings, including the lack of integrated approaches that combine UGI and residential retrofitting at a district-scale. Many studies focus on operational energy savings but neglect embodied energy, leading to overestimated carbon reductions. Long-term impacts, real-world validation of UBEM, and economic feasibility assessments are often insufficient. Additionally, most research is centered on European and North American contexts, with limited studies on hot arid climates like Egypt. This study addresses these gaps by integrating GIS, UBEM, and LCA, incorporating long-term projections, empirical validation, and policy-oriented recommendations tailored to New Cairo's urban challenges.

2.5. Research proposal

By combining GIS-based spatial analysis, UBEM, and LCA, the research quantifies the impacts of UGI on energy consumption, GHG emissions, and urban microclimate improvements. The study will analyze various scenarios for the implementation of UGI, such as green roofs, facades, and urban tree networks, alongside building retrofitting interventions, to predict their combined impact on energy savings and CO_2 reduction up to 2050.

2.6. Study relevance and innovation

This study is highly relevant as it addresses the urgent need to reduce energy consumption and GHG emissions in urban areas, particularly in aging residential neighborhoods. It innovatively combines UGI with residential retrofitting strategies to assess their combined impact on energy efficiency, CO_2 reduction, and microclimate improvement. The study uses GIS-based spatial analysis, UBEM, and LCA to evaluate both operational and embodied energy, offering a holistic approach to sustainable urban regeneration. By integrating these methods, the research provides a comprehensive, cost-effective framework for achieving climate goals and enhancing urban sustainability (Fig. 1).

2.7. Case study approach: New Heliopolis, Cairo (Egypt)

Residential neighborhood built between the 1950s and 1960s in Cairo, Egypt. Obsolete residential neighborhoods in this region exhibit common characteristics, including aging infrastructure, poor energy efficiency, and vulnerability to climate impacts. These traits justify the development of a methodology based on urban vulnerabilities, the integration of green infrastructure, and the repetition of construction systems typical of large-scale urban developments. In particular, the stock of residential buildings in New Heliopolis faces several critical challenges: an aging population, lack of accessibility, poor thermal insulation, and inefficient energy systems.

New Heliopolis, originally designed as a middle-class residential district with significant open

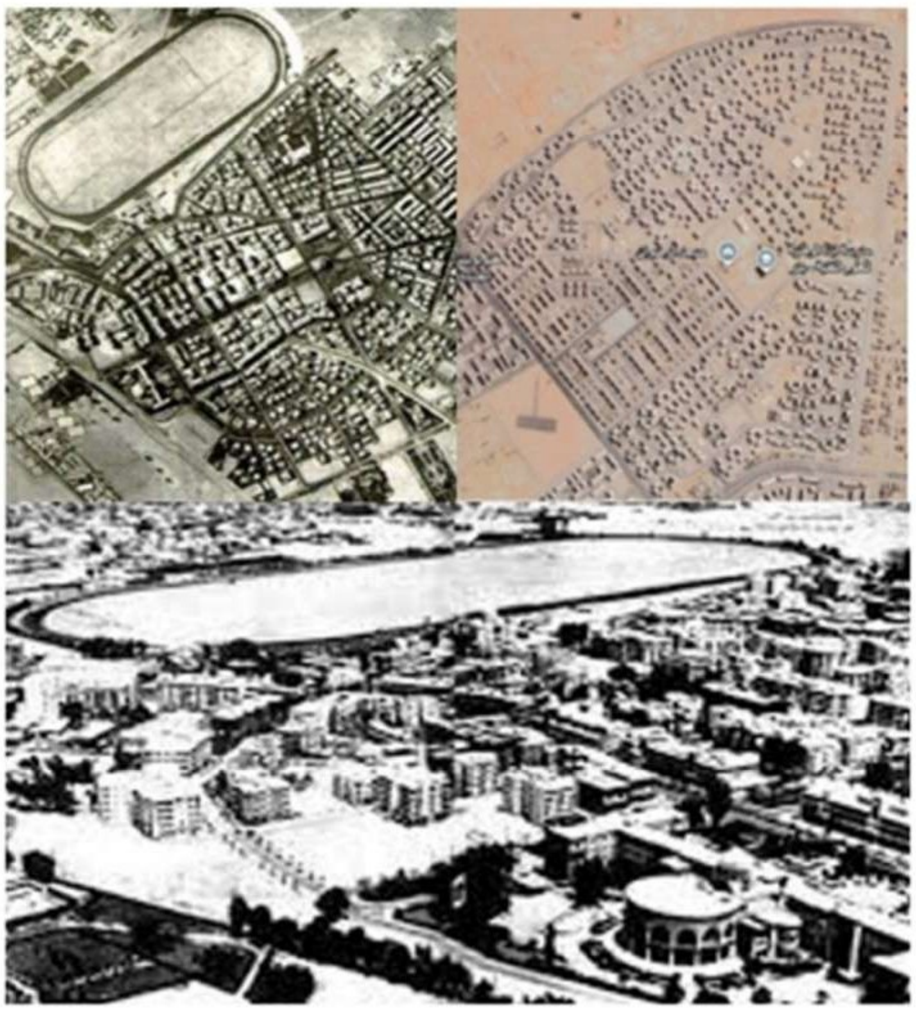

Fig. 1. Comparison of the study area: year 1950 (left) and year 2020 (right). Source: (Ilbert, 1981 (European Journal of Sustainable Development, 2016)).

spaces, includes expansive green areas and wide streets. However, the green infrastructure has faced deterioration over time due to neglect and urban sprawl. Many green spaces, once envisioned as communal parks and recreational areas, have been encroached upon by informal settlements or deteriorated due to the absence of consistent maintenance. Additionally, these green spaces are underutilized for climate mitigation strategies like cooling and stormwater management, leading to increased urban heat island effects (Le Quéré et al., 2016) (Fig. 2).

2.8. Research scope and structure

This study aims to develop an integrated methodology to assess the combined impact of UGI and residential retrofitting on energy efficiency and carbon footprint reduction at the district-scale, aligning with Net-Zero 2050 goals. It evaluates both operational and embodied energy to provide a comprehensive framework for sustainable urban regeneration.

After the introduction (Section 1), the methodology (Section 2) details the integration of GIS, UBEM, and LCA. Section 3 applies this to a New Heliopolis, Cairo case study, analyzing intervention scenarios up to 2050. Section 4 discusses findings, policy implications, and replication potential, while Section 5 concludes with key insights and recommendations for sustainable urban planning.

2.9. Methodological approach

The study's methodology involves an integrated approach starting with GIS-based spatial analysis to identify urban fabric characteristics and energy consumption patterns. This is followed by an energy modeling phase using UBEM to simulate various renovation and green infrastructure scenarios. Finally, LCA is applied to determine long-term environmental benefits, considering both operational and embodied energy. Fig. 3 visually represents this integration.

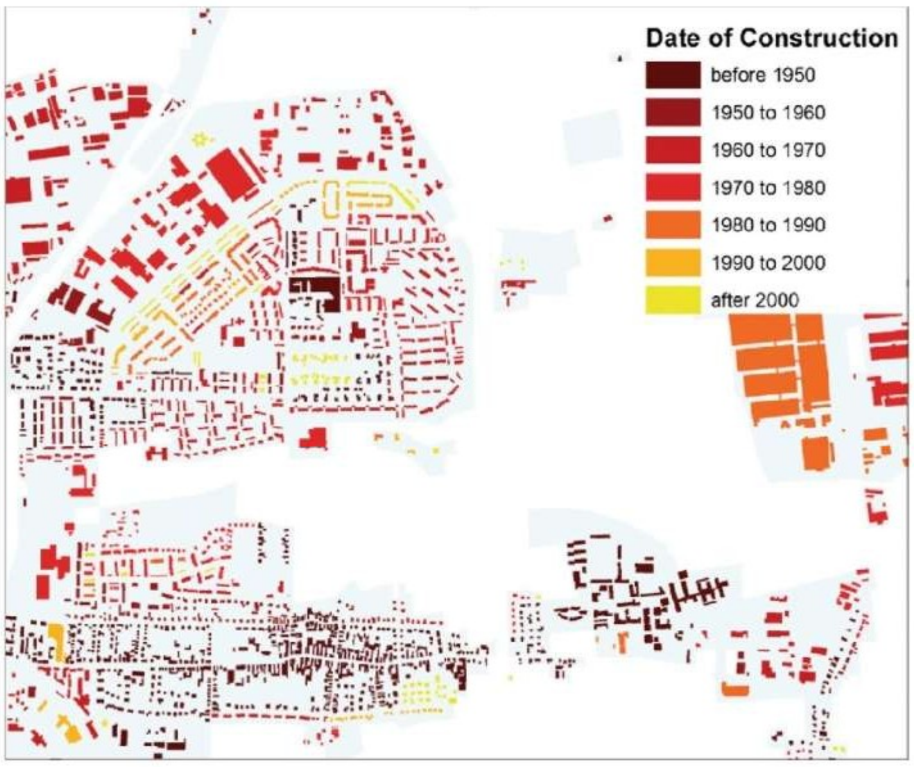

Fig. 2. Investigated area building age.

3. Case study selection and characterization

The case study area was selected based on the following Variables: Urban Vulnerability-Energy Inefficiency-Lack of Accessibility-Degraded Green Infrastructure-Building Age and Obsolescence-Typological Homogeneity.

3.1. Phase 1: case study selection and characterization

This phase focuses on selecting and characterizing a case study area that meets the criteria for applying the proposed methodology. The selected neighborhood must exhibit characteristics of an obsolete residential area, evaluated through urban vulnerability indicators, building age, and typological homogeneity. The characterization process involves GIS-based spatial analysis and open data sources to establish key parameters defining the neighborhood's physical and environmental conditions. The selection process considers the following criteria:

(a) Urban vulnerability: significant portion of the residents are elderly, living in dwellings that are not suited to their needs, with limited access to modern amenities and public services (Ali, 2017).
(b) Energy inefficiency: Like many old housing developments, the buildings in New Heliopolis suffer from poor thermal insulation, single-glazed windows, and outdated HVAC systems. The building stock primarily consists of linear blocks with simple concrete structures and facades that lack insulation or advanced energy-efficient features (Shafik et al., 2021).
(c) Lack of accessibility: Many of the residential blocks in New Heliopolis were built with limited accessibility for people with mobility issues, and the neighborhood's infrastructure does not fully accommodate modern demands for inclusivity.
(d) Green infrastructure deterioration: The once abundant green spaces in New Heliopolis are underdeveloped and poorly maintained,

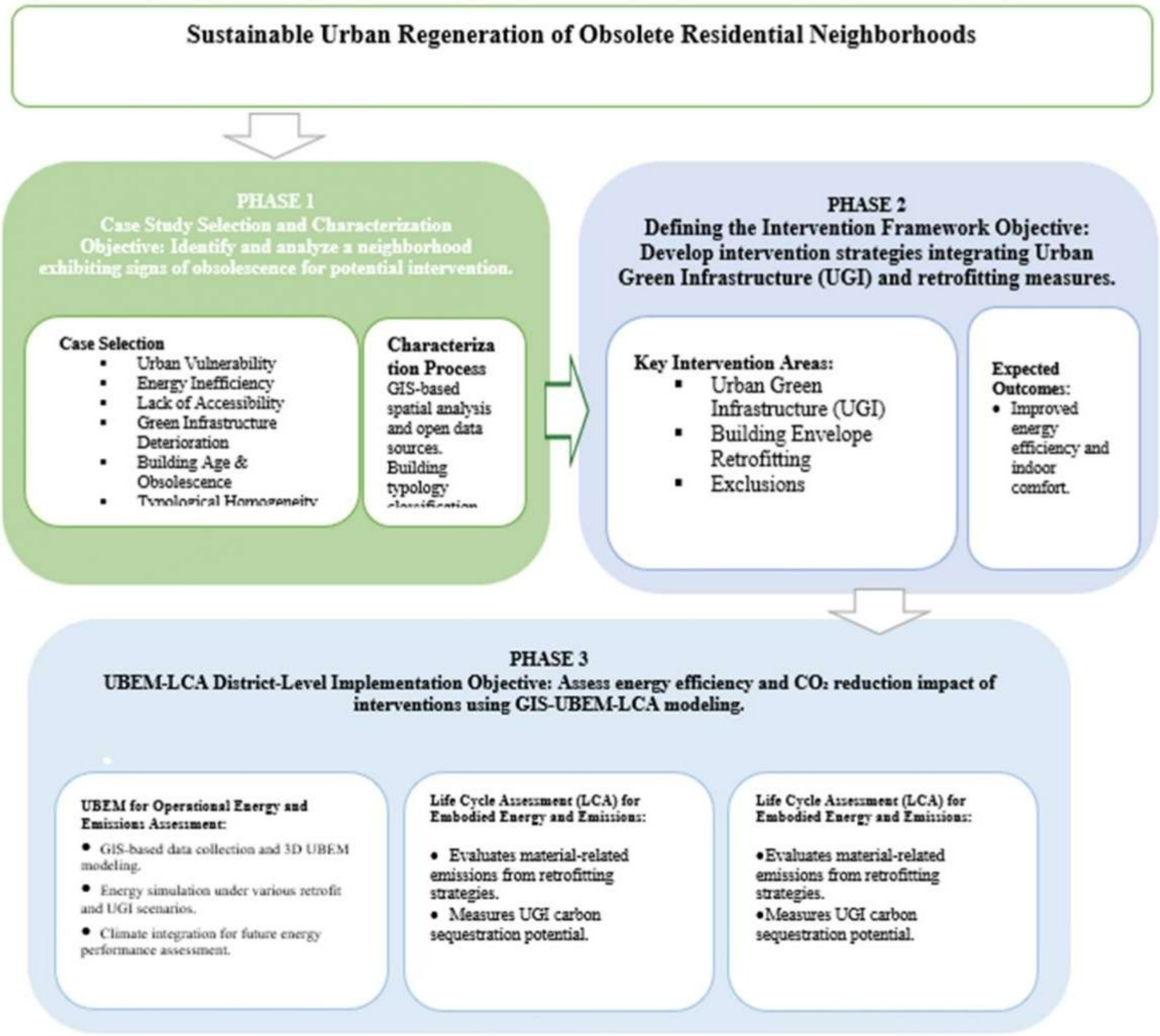

Fig. 3. Phased methodological framework for the sustainable urban regeneration of obsolete residential neighborhoods.

leading to reduced environmental benefits such as air quality improvement and urban cooling. The green infrastructure is fragmented and poorly connected, affecting social cohesion and the quality of life for residents

(e) Building age and obsolescence: residential buildings over 50 years old are prioritized due to outdated construction techniques, poor insulation, and inefficient energy systems, which contribute to high operational energy consumption.

(f) Typological homogeneity: The neighborhood consists of repetitive architectural and construction patterns, including linear blocks, reinforced concrete structures, flat roofs, and single-glazed windows. This homogeneity allows for scalable and standardized retrofitting solutions across the district.

The typological classification of representative buildings is conducted using GIS tools and open databases, mapping parameters such as building height, number of dwellings, façade and roof surface areas, and construction typology. A bottom-up methodology is applied for detailed construction characterization, involving on-site surveys and data validation for calibration in energy performance simulations. This ensures an accurate and representative model for assessing the impact of UGI and retrofitting interventions.

3.2. Phase 2: defining the intervention framework

Phase 2 defines the intervention hypothesis by integrating UGI and building envelope retrofitting at the district-level to maximize energy efficiency and carbon footprint reduction. UGI measures, such as green roofs, facades, and urban trees, contribute to carbon sequestration, cooling, and air quality improvement, while building envelope retrofitting focuses on thermal insulation, advanced glazing, and passive cooling to enhance energy efficiency and indoor comfort. The study excludes individual interior renovations to maintain scalability across neighborhoods. By combining UGI and retrofitting, the approach aims to optimize energy savings, mitigate urban heat island effects, and support long-term sustainability goals.

3.3. Phase 3: UBEM-LCA district-level implementation for urban green infrastructure and residential retrofitting

In this phase, the integrated GIS-UBEM-LCA methodology is applied to assess the combined impact of UGI and residential retrofitting on energy efficiency and CO_2 emissions reduction at the district-scale. The study utilizes UBEM to simulate various intervention scenarios, evaluating both operational energy and embodied energy up to 2050.

The methodology follows a bottom-up engineering approach, incorporating urban morphology, building typologies, and climate data to analyze the energy and carbon footprint of different retrofit and UGI strategies. The results contribute to evaluating the temporal evolution of decarburizations scenarios, aligning with global Net-Zero 2050 targets (Fig. 4).

3.4. UBEM for operational energy and emissions assessment

The process begins with GIS-based data collection from cadastral records, remote sensing, and municipal databases Building classification: Categorizing structures based on typology, age, and construction characteristics. Three-dimensional UBEM modeling: Converting GIS data into three-dimensional energy models using UBEM. IO and UMI tools. Energy simulation: Using Energy Plus and UMI v3.0 to evaluate the operational energy demand of buildings under different UGI and retrofitting scenarios. Weather and climate integration: Climate files in EPW format are incorporated to simulate energy performance under future climate conditions.

Once the baseline model is established, results are validated by comparing UBEM energy outputs with reference buildings from the Energy Plus database. Model adjustments are performed using confidence bands derived from BESTEST methodologies.

3.5. Life cycle assessment (LCA)

For Embodied Energy and CO_2 Emissions the following UBEM validation, LCA calculations assess the embodied energy and CO_2 emissions embedded in construction materials and renovation activities. The LCA module within UMI tools is employed to:

(a) Estimate material-related emissions for various retrofitting strategies (e.g., insulation, facade improvements, energy-efficient windows).

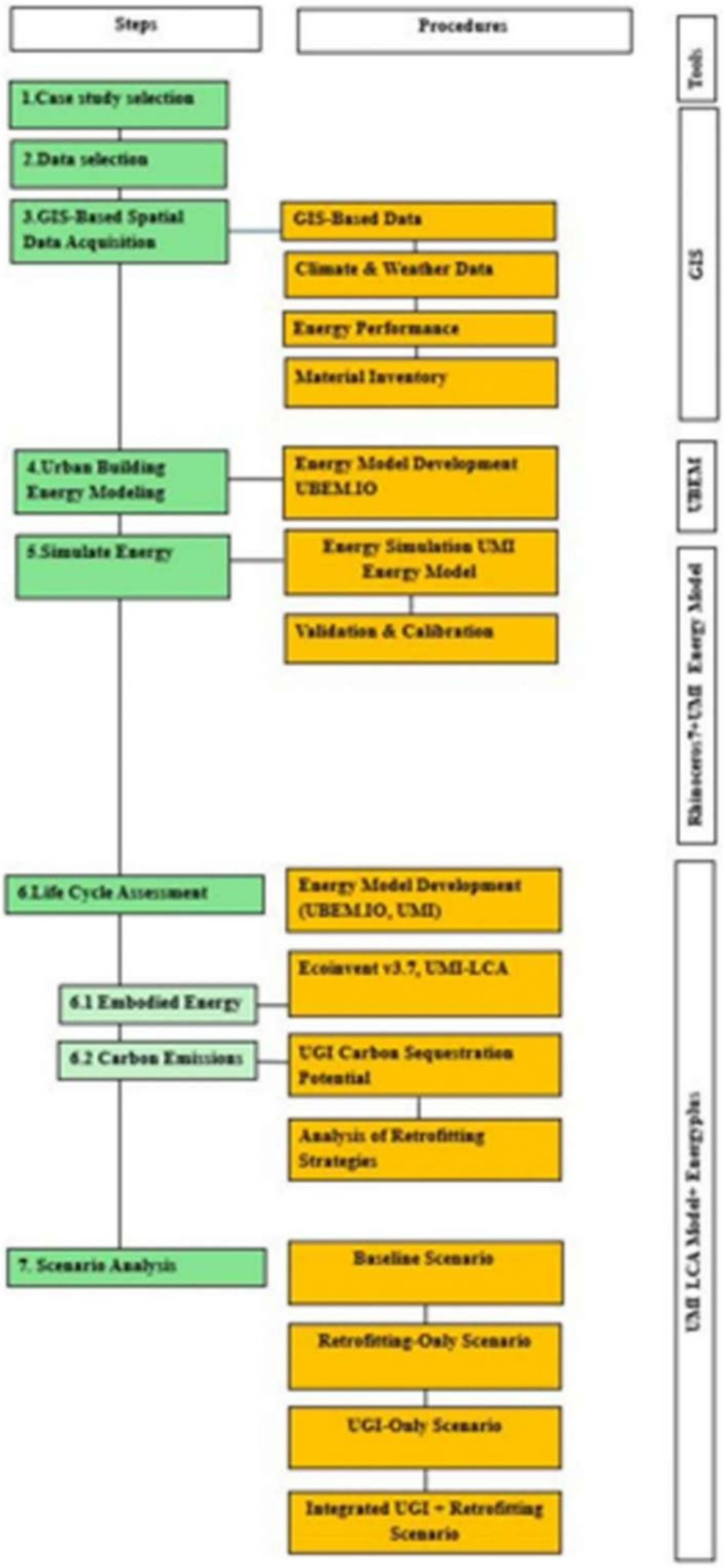

Fig. 4. Shows phase 3 workflow.

(b) Assess UGI interventions (e.g., green roofs, tree canopies) in terms of carbon sequestration potential.

(c) Compare low-carbon retrofitting solutions by analyzing life cycle environmental impacts.

3.6. Temporal analysis of decarburization scenarios

The final step involves projecting carbon reduction trajectories and evaluating different decarbonization strategies:

(a) Business-as-usual scenario: No intervention, highlighting expected energy use and emissions trends.
(b) Retrofitting-only scenario: Evaluating the impact of energy-efficient building upgrades.
(c) UGI-only scenario: Analyzing CO_2 sequestration and urban cooling effects.
(d) Integrated UGI + Retrofitting scenario: Assessing the combined impact on energy savings and carbon neutrality.

By integrating GIS, UBEM, and LCA, this phase provides a holistic evaluation of urban regeneration strategies, offering data-driven insights to guide policymakers toward achieving Net-Zero 2050 targets.

3.7. Selected area for the case study

For the purposes of this case study, the neighborhoods located in the central and southern parts of New Heliopolis, particularly those built in the 1950s–1960s, will be analyzed. These areas contain approximately 3000–4000 dwellings, primarily housing middle-income families. The residential blocks are low-rise (4–5 stories) with repetitive construction techniques, including:

(a) Reinforced concrete: The use of concrete skeletons with infill brick walls and poorly insulated facades.
(b) Thermal insulation deficiencies: Single-glazed metal windows and walls with air cavities but no insulation, leading to poor energy performance (Al).
(c) Flat roofs: Most roofs are flat, contributing to poor thermal comfort, and higher energy demands.

4. Results

4.1. Description of the case study proposal

Heliopolis is a planned residential district in Cairo, Egypt, originally developed between the 1950s and 1960s as part of Egypt's urban expansion efforts. The neighborhood consists of low-to mid-rise residential buildings, many of which have aged without significant retrofitting, leading to high energy consumption and environmental inefficiencies. The district was planned with green spaces and wide streets, but over time, urban sprawl and lack of maintenance have led to the deterioration of its green infrastructure and energy performance.

The study area includes approximately 4000 dwellings across multiple residential blocks, following a repetitive architectural pattern. The construction primarily consists of reinforced concrete structures, uninsulated brick facades, and single-glazed windows, making the buildings highly susceptible to heat gain and excessive cooling demands. The methodology developed in the previous sections is applied to this district to assess the impact of UGI and residential retrofitting on energy efficiency and carbon footprint reduction.

4.2. Urban and building characteristics

The study area consists of low-rise residential blocks (4–5 stories) with repetitive construction patterns. The majority of buildings feature reinforced concrete frames, uninsulated brick facades, and single-glazed windows, leading to high operational energy consumption and poor thermal comfort (European Commission, 2020).

Key observations include:

(a) Obsolete building stock: 80 % of the buildings are over 50 years old, with minimal energy-efficient features.
(b) Green infrastructure decline: Many originally planned green spaces are underutilized or have been replaced by informal structures.
(c) Energy performance gaps: Lack of insulation, outdated HVAC systems, and poor ventilation contribute to excessive cooling demands.

4.3. Typological classification of buildings

To validate the building characterization across the district, data was gathered from a representative sample building. The selected sample is a 5-story linear block with 10 dwellings, located at 30.0256°N, 31.3624°E. This structure was analyzed for calibration of the GIS-UBEM-LCA models, ensuring accuracy in energy performance simulations and urban regeneration assessments.

The constructive characteristics of the sample building include:

(a) Façade: Double brick walls with no thermal insulation.
(b) Windows: Metal frames with single-glazed glass.
(c) Roof: Flat, uninsulated concrete slab.
(d) Cooling and Heating: Mostly individual air conditioning units, leading to inefficient energy use.

Since all buildings in New Heliopolis share similar construction typologies, a set of four standardized templates was created for use in GIS-UBEM-LCA simulations. These templates account for façade openings, thermal properties, and energy performance metrics, allowing for an accurate district-wide evaluation of retrofit and UGI interventions (García-López et al., 2024b) (Fig. 5, Table 1).

4.4. *Characterization of proposed interventions*

Based on the analysis of New Heliopolis, Cairo, a set of intervention strategies has been designed, integrating UGI and residential retrofitting to enhance energy efficiency and reduce carbon footprint. The interventions exclude internal modifications to ensure scalability across the neighborhood. Five intervention hypotheses (H1, H2, H3, H4, and H5) have been developed, four of which focus on low-impact, extensive retrofit strategies, while the fifth scenario considers new construction (International Energy Agency (IEA), 2021).

4.4.1. *Constructive definition of intervention hypotheses: H1, H2, H3, H4, and H5*

For this study, technical specifications for materials and energy systems were sourced from government building datasets, environmental product declarations (EPDs), and industry-certified records. These datasets ensure accuracy in assessing embodied energy, global warming potential (GWP), and material life cycle emissions in the LCA and UBEM models (Fig. 6).

Intervention Scenarios: H1: Insulation Injection in Façade Air Chambers (1A) Retrofitting external walls with mineral wool insulation, injected into existing uninsulated air chambers.

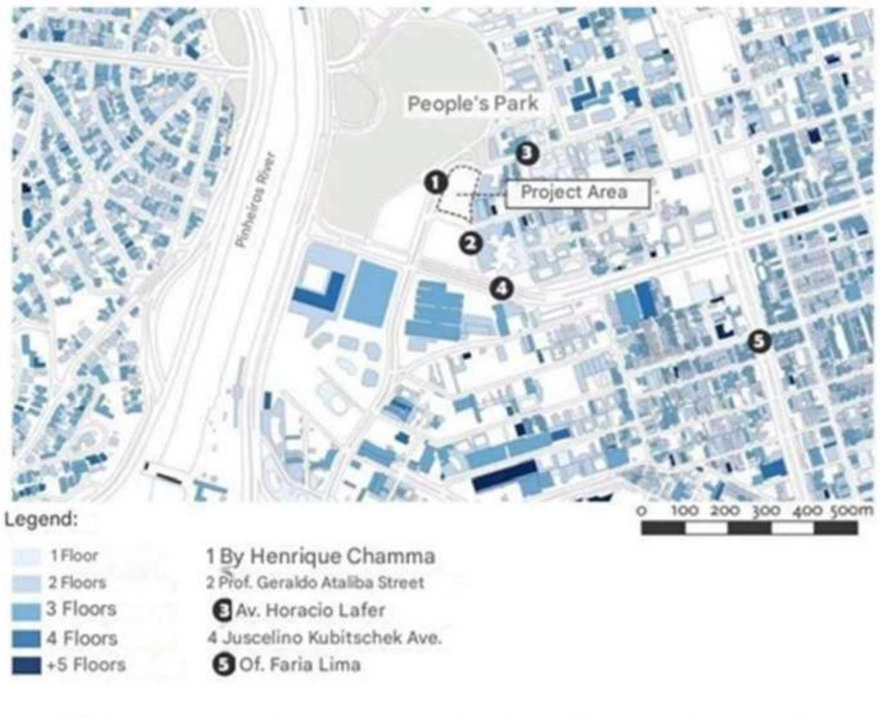

Fig. 5. This scenario does not consider demolition emissions but evaluates a fully optimized neighborhood model.

Requires minimal disruption to residents and no external scaffolding.

H2: Replacement of Exterior Windows and Frames (2A).

Upgrading single-glazed metal windows to high-performance PVC windows with triple glazing.

Involves removal, transportation, and recycling of old window materials.

H3: Roof Insulation Upgrade (3A+3B).

Installation of 50 mm extruded polystyrene insulation tiles combined with 35 mm precast concrete tiles.

Improves thermal performance and passive cooling on flat, uninsulated roofs.

H4: Photovoltaic (PV) Solar Panel System Installation (4A+4B).

Mounting PV panels on elevated support structures (3 m above the roof), maintaining roof usability while generating energy.

Uses high-efficiency 430 W peak panels, covering 1.82 m^2 per unit, with a 25-year lifespan.

H5: New Construction with Modern Energy Standards.

A full replacement of obsolete buildings with new, energy-efficient structures, incorporating advanced insulation, HVAC systems, and renewable energy sources.

4.4.2. *Constructive characterization of intervention hypotheses*

Each hypothesis includes specific thermal transmittance (U-values), material density, and thickness. These parameters are integrated into UBEM-UMI templates for energy and carbon footprint simulations. The material performance complies with Egyptian thermal regulations and global standards for energy-efficient retrofitting (Reinhart and Cerezo-Dávila, 2016) (Table 2).

4.4.3. *CO_2 emissions and energy use across life cycle stages*

For each intervention, data from EPDs was extracted and integrated into LCA calculations within UMI tools. The emissions and energy use were categorized into the following life cycle stages:

(a) A1−A3: Raw material supply, transportation, and product manufacturing (Embodied Carbon and Embodied Energy).
(b) A4: Transport to construction site (Transportation Carbon and Energy).
(c) A5: Installation and construction-phase (Assembly Carbon and Energy).

Table 1. Detailed classification of buildings based on typology and construction features.

Category	Blocks	Floors	Dwellings	WWR (% Windows-to-Wall Ratio)	Built area (m^2)	Roof type	Construction type
Type A1	50	5	500	25	90/200	Flat, uninsulated	Reinforced concrete, brick façade
Type A2	45	5	450	30	85/190	Flat, uninsulated	Reinforced concrete, brick façade
Type B1	60	4	600	20	75/150	Flat, partially insulated	Concrete, single-glazed windows
Type B2	55	4	550	22	80/160	Flat, partially insulated	Concrete, brick façade
Type C1	40	4	400	18	60/120	Flat, insulated	Concrete, upgraded windows
Social housing	150	5	1500	15	50/100	Flat, uninsulated	Simple brick, single-glazed
Total residential	400	4–5	4000	Varies	50–200	Mixed	Standardized typologies
Non-residential	80	1–3	N/A	N/A	Varies	Flat	Concrete, commercial buildings
Total buildings	480	Varies	N/A	N/A	N/A	N/A	Mixed typologies

Fig. 6. This scenario does not consider demolition emissions but evaluates a fully optimized neighborhood model.

(d) C1–C4: End-of-life phase, including material disposal and recycling potential.

Table 3 is as shown below.

4.5. Results of energy consumption and CO_2 emissions in the renovation phase

For the new construction scenario (H5), an estimated emission factor of 400 kg CO_2/m^2 was used, based on comparative studies of buildings with similar typologies in Cairo and other hot arid climate (International Energy Agency (IEA), 2021).

For this study, the baseline scenario (H0) represents the current state of the buildings, where operational energy and embodied emissions from initial construction are not included in the assessment (Seyedabadi, 2023). Instead, the focus is on future emissions and energy consumption resulting from the different intervention scenarios (H1, H2, H3, H4, and H5). The calculations were conducted using the UMI LCA module, and the results have been processed to evaluate GWP in CO_2-equivalent emissions and primary energy use.

For this study, the baseline scenario (H0) represents the current state of the buildings, where operational energy and embodied emissions from initial construction are not included in the assessment (Seyedabadi, 2023). Instead, the focus is on future emissions and energy consumption resulting from the different intervention scenarios (H1, H2, H3, H4, and H5). The calculations were conducted using the UMI LCA module, and the results have been processed to evaluate GWP in CO_2-equivalent emissions and primary energy use.

4.5.1. Renovation carbon footprint

The EPD database was used to assess the LCA impact of material manufacturing, transport, and installation (Reinhart and Cerezo-Dávila, 2016). The

Table 2. Thermal characteristics of building retrofit interventions.

Intervention	Material	Density (kg/m^3)	Thermal conductivity (W/mK)	U-value ($W/m^2 \cdot K$)
H1	Mineral wool insulation	50	0.035	0.25
H2	PVC triple-glazed windows	–	–	0.73
H3	XPS roof insulation	32	0.034	0.18
H4	PV panel + Metal frame	20	–	N/A

Table 3. CO_2 and energy consumption data for each scenario.

Hypothesis	Embodied carbon (kg CO_2-eq/m^2)	Nonrenewable Energy (MJ/m^2)	Transport carbon (kg CO_2-eq)	Assembly carbon (kg CO_2-eq)
H1	2.19	41.8	0.14	0.22
H2	183	1930	1.27	1.89
H3	16.6	200	0.67	7.3
H4	107	1300	7.12	0.097

described methodology allows for the aggregated calculation of embodied energy and GWP CO_2-equivalent emissions for all proposed interventions. Although results are aggregated at district-scale, calculations were performed for each individual building in the New Heliopolis neighborhood using the LCA module of UMI v3.0 (Fig. 7).

From the intervention scenarios, the results indicate the following:

(a) H1 (Façade Insulation) exhibits the highest embodied carbon emissions among renovation strategies due to the large surface area covered and the high energy intensity of insulation materials.
(b) H2 (Window Replacement) and H3 (Roof Insulation) show moderate embodied carbon impacts but provide significant operational energy savings.
(c) H4 (PV Solar Installation) presents a higher initial carbon footprint, primarily due to manufacturing emissions of photovoltaic panels, but achieves long-term energy savings and carbon offsetting over its lifetime.
(d) H5 (New Construction) has an impact 100 times higher than façade renovation (H1) and 27 times higher than a complete renovation scenario with PV integration (H4). This highlights the environmental advantage of deep retrofitting over new construction in achieving carbon reduction goals.

These findings reinforce the importance of prioritizing renovation strategies over complete rebuilding, as they provide significant emissions savings with lower embodied energy costs (United Nations (UN-Habitat), 2016). The next phase of the study will focus on quantifying operational energy reductions across intervention scenarios and assessing their alignment with Net-Zero 2050 targets (Fig. 8).

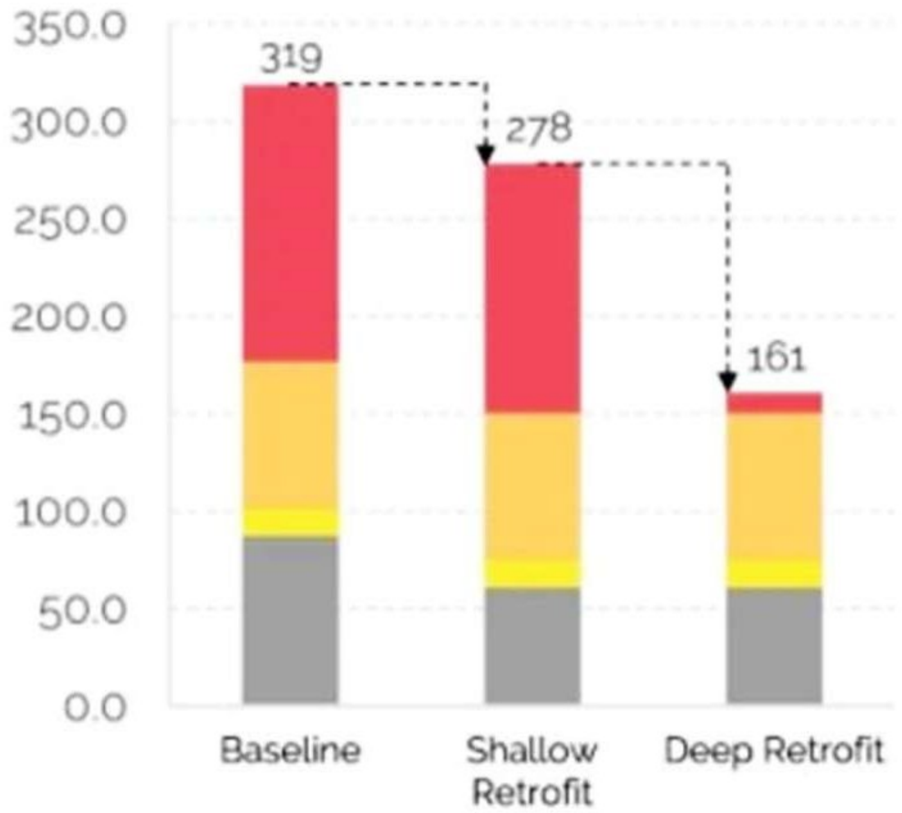

Fig. 7. CO_2 and energy consumption data for each scenario.

4.5.2. Scenario comparison

Table 4 is as shown below.

4.5.3. Results of operational energy consumption and CO_2 emissions

The assessment of energy consumption and carbon emissions during the operational phase begins with the calibration of the UBEM model (Reference (U.S. Department of Energy (DOE), 2021)). As described in the methodology, the sample building energy model was calibrated by comparing the UBEM results with the BEM results. This process ensures accuracy in energy demand predictions for the entire district.

4.5.4. Validation of the UBEM model with BEM

The validation was performed using Energy Plus (BEM tool) and UMI v3.0 (UBEM tool), with admissible confidence margins based on reference validation protocols:

(a) ±15 % deviation allowed for energy demand.
(b) ±12.5 % deviation allowed for heating and cooling consumption.

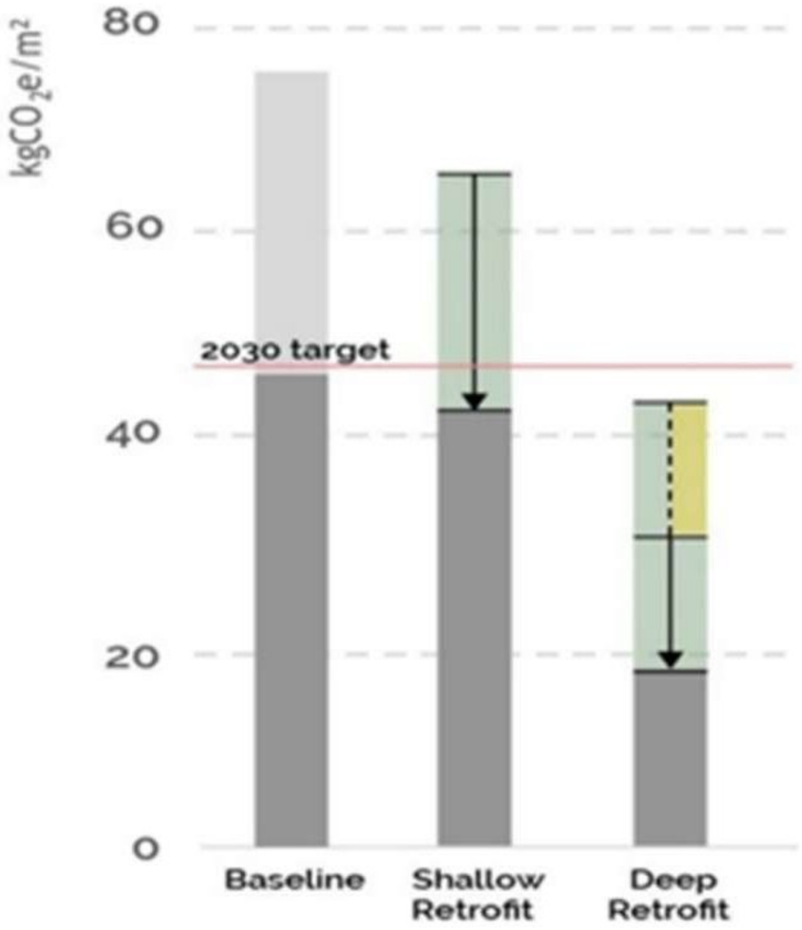

Fig. 8. Annual carbon emissions.

Table 4. Shows scenario comparison.

Scenario	Operational energy savings (%)	Carbon emission reduction (%)	Key benefits
Business-as-Usual (BAU)	0	0	No improvement in energy performance.
Retrofitting-only	25–30	28	Improved insulation and HVAC upgrades.
UGI-only	5–10	12–15	Green roofs and urban trees reduce cooling loads.
Integrated UGI + Retrofitting	35–40	45–50	Maximum efficiency and climate resilience.

4.5.5. Operational energy consumption results of the UBEM models

The UBEM characterization of New Heliopolis was conducted using GIS-based cadastral data and the EPW climate file (PVGIS reference). A series of intervention-specific models (UMI bundles) were generated, incorporating technical and material improvements for each retrofit scenario (H1–H4) and new construction (H5). For each intervention, the final energy consumption was calculated for:

(a) The entire district (4000 dwellings across 357 buildings).
(b) Each individual building in the neighborhood.
(c) Specific energy uses (heating, cooling, lighting, etc.).

4.5.6. Standard operational emissions of the intervention hypotheses

Once validated, the UBEM model was used to estimate the operational energy demand and CO_2 emissions for each intervention scenario under standard operating conditions (HVAC usage, lighting, hot water, and electrical equipment) (Table 5).

H4 (PV Integration) and H3 (Roof Insulation) offer the highest energy savings in retrofit scenarios, reducing operational energy demand by 30–36 %.

(a) H1 (Façade Insulation) and H2 (Window Replacement) provide moderate improvements, with 23–27 % reductions in energy consumption.
(b) H5 (New Construction) achieves the highest efficiency (55 %), but embodied carbon emissions in construction make it less sustainable compared to deep retrofitting.

4.6. Analysis of operational carbon footprint

According to the methodology, the UBEM workflow requires an initial model calculation for calibration and validation. Once the model has been validated the accuracy level is considered acceptable based on the established reference protocol. However, as noted in Reinhart and Cerezo-Dávila (Reinhart and Cerezo-Dávila, 2016), 'an UBEM is not a BEM', meaning that UBEM models prioritize large-scale energy trends rather than detailed individual building accuracy.

For the New Heliopolis case study, the UBEM results were analyzed for each individual building, considering variations in solar exposure, building orientation, and construction typologies. These factors significantly influence energy demand and carbon emissions across the sector.

4.6.1. Gross lifetime energy use and carbon footprint

The operational energy consumption and carbon emissions were analyzed under different intervention scenarios (H1–H5). The results, summarized in Table X, show:

(a) A comprehensive retrofit with PV integration (H1234) can reduce total sector emissions by 50 %.
(b) The new construction scenario (H5) achieves a 69 % reduction in carbon footprint, mainly due to higher construction standards and more efficient energy systems (HVAC, DHW, and solar integration).

Table 5. Shows comparison of energy consumption, CO_2 emissions, and energy savings across different retrofitting interventions.

Intervention	Final energy consumption ($kWh/m^2 \cdot year$)	CO_2 emissions ($kg\ CO_2\text{-}eq/m^2 \cdot year$)	Energy savings (%)
H0 (Baseline)	220	110	0
H1 (Façade insulation)	170	85	23
H2 (Window replacement)	160	80	27
H3 (Roof insulation)	155	75	30
H4 (PV integration)	140	60	36
H5 (New construction)	100	50	55

(c) PV installations (H4) alone contribute to a 32 % reduction in total energy consumption across the sector.

The UBEM energy consumption per household was calibrated using district-level electricity consumption data, obtaining an adjustment coefficient of 0.5220 (see Fig. X). This ensures that modeled energy demand aligns with real recorded consumption patterns in New Heliopolis.

Additionally, fossil fuel consumption (e.g., LPG or natural gas for heating) was not considered due to its minor role in the district's energy mix (Reference (United Nations (UN-Habitat), 2016)). Although this may underestimate total energy demand, it is compensated by higher electricity-related emissions, ensuring a balanced overall carbon assessment.

4.6.2. EPC standard lifetime carbon footprint

The standard operational emissions (EPC framework) were evaluated to meet technical and administrative regulations for potential energy retrofitting incentives. The findings indicate:

(a) H4 (PV installation alone) has a minimal impact (−0.09 %) on direct energy demand, despite its potential for grid decarbonization.
(b) H3 (Roof Insulation) achieves a 4.65 % energy reduction, mainly benefiting upper-floor apartments exposed to direct sunlight.
(c) H1 (Façade Insulation) provides the greatest energy savings (17.88 %), 3–4 times more effective than window (H2) and roof (H3) interventions.
(d) H123 (combined retrofit) achieves a 27.53 % reduction in operational emissions, approaching the 30 % threshold required for Next Generation EU funding eligibility.
(e) H1234 (Comprehensive Retrofit + PV) exceeds this threshold at 31.52 %, highlighting its long-term sustainability benefits.

These results confirm that passive retrofitting measures (insulation, windows, roofs) must be complemented with renewable energy (PV) and HVAC/DHW upgrades for maximum impact (Table 6).

4.7. Lifetime carbon emissions and sector-wide impact

(a) Using the calibrated UBEM model, long-term carbon emissions projections were developed for each scenario until 2100.
(b) Key findings:
(c) H5 (New Construction) initially has the highest emissions due to embodied carbon in materials. However, over time, its higher efficiency results in a lower lifetime footprint.
(d) By 2050, the H5 new-building scenario emits 30.1 % more than the baseline (H0), highlighting the slow payback of embodied emissions.
(e) H1234 (Comprehensive Retrofit + PV) outperforms all scenarios, achieving a 46.97 % reduction in carbon footprint compared to H0.
(f) PV integration (H4) offsets its emissions within 0.98 years, reinforcing the long-term benefits of solar energy adoption.

5. Final discussion

This research applied an integrated GIS-UBEM-LCA methodology to assess the environmental impact of UGI and residential retrofitting in New Heliopolis, Cairo. Our approach evaluated GHG emissions and energy performance at the 2050 horizon, considering both operational emissions from building usage and embodied emissions from construction materials and processes. The analysis of various low-impact retrofitting scenarios demonstrated the effectiveness of strategic interventions in reducing the carbon footprint of aging residential neighborhoods. Additionally, the study compared the sustainability of extensive retrofitting against new construction, providing a long-term perspective on emissions reduction.

The GIS-UBEM-LCA framework proved particularly suitable for analyzing large-scale urban areas

Table 6. Assessment of energy and CO_2 reductions under different retrofit scenarios and eligibility for EPC funding'

Scenario	Energy savings (%)	CO_2 emission reduction (%)	Meets 30 % EPC funding threshold
H1 (Façade insulation)	17.88	20	No
H2 (Windows upgrade)	6.12	7	No
H3 (Roof insulation)	4.65	5	No
H4 (PV installation)	0.09	32	Yes
H123 (Full retrofit)	27.53	29	Close
H1234 (Retrofit + PV)	**31.52**	**50**	**Yes**

characterized by typological repetition and standardized building designs. By utilizing open data sources, the methodology efficiently categorized 357 residential buildings with a limited number of archetype templates, allowing for highly scalable and precise energy modeling. The implementation of UMI v3.0 for the analysis enabled detailed district-scale simulations, incorporating shading effects, solar orientations, and material variations. After calibration with reference validation methods, the energy model provided insights into both operational and embodied energy consumption, offering a comprehensive overview of emissions for each intervention scenario.

Our findings confirm that total emissions (operational + embodied) remain lower for extensive retrofitting compared to new construction at both the 2050 and 2100 horizons. Retrofitting strategies, particularly those incorporating green infrastructure and passive cooling techniques, offer significant reductions in energy demand while maintaining lower embodied carbon footprints. This study strongly supports prioritizing residential retrofitting over demolition and redevelopment, especially for aging housing stock built between 1950 and 1980. Achieving Net-Zero 2050 climate targets will necessitate large-scale, district-level retrofit initiatives, with a strong focus on sustainable renovation, energy efficiency, and UGI integration.

5.1. Conclusion

This study successfully demonstrated the feasibility and effectiveness of integrating GIS, UBEM, and LCA. We used this integrated approach to evaluate the carbon footprint and energy efficiency of UGI and retrofitting strategies in New Heliopolis, Cairo. By leveraging open data sources, our methodology enabled a bottom-up assessment of energy consumption and emissions at the individual building level, which we then scaled up to encompass the entire residential sector. The research meticulously analyzed the long-term environmental impact (2050–2100) of various renovation scenarios, directly comparing them against the construction of new energy-efficient buildings.

Our findings unequivocally highlight that extensive retrofitting strategies offer significant reductions in carbon emissions and energy consumption, proving to be a more sustainable approach than demolition and reconstruction. This research further reinforces the critical importance of district-scale modeling in shaping effective urban regeneration strategies.

5.2. Key findings

- (i) Dual metric approach: We found that energy and carbon emissions should be analyzed using two distinct metrics:
  - (a) Gross energy consumption and emissions for a comprehensive environmental impact perspective.
  - (b) Standard EPC-based emissions for technical and regulatory compliance within renovation incentive programs.
- (ii) Embodied versus operational emissions:
  - (a) The construction-phase energy and emissions in retrofit scenarios are 100 times lower than in the new-building scenario.
  - (b) Over a 70-year lifespan, initial construction energy accounts for 3 % of total operational energy in retrofits, whereas for new buildings, it represents a substantial 116 % of operational energy.
- (iii) Net-Zero EPC Emissions by 2050:
  - (a) Only the new construction scenario (H5) achieves net-zero emissions by 2050.
  - (b) None of the retrofit scenarios fully reach carbon neutrality, indicating the need for additional measures to meet this ambitious target.
- (iv) New Construction versus retrofit strategies:
  - (a) Building new districts now would result in higher cumulative emissions primarily due to the significant impact of construction processes.
  - (b) Emission reduction strategies should consider cumulative emissions over the period leading to 2050, rather than solely focusing on final emission levels in 2050.
- (v) Best-case carbon footprint by 2050:
  - (a) The minimum real carbon footprint expected in the best-case retrofit scenario (H1234) is 220.28 kg CO_2/m^2, achieving a 46.97 % reduction compared to the baseline (H0: 415.41 kg CO_2/m^2).
  - (b) The new construction scenario (H5) has the highest carbon footprint (540.42 kg CO_2/m^2), exceeding the baseline scenario emissions by 30.09 %.
  - (c) Even by 2100, the new construction scenario remains less sustainable than the full retrofit scenario (H1234 with PV integration).
- (vi) On-Grid Photovoltaics (PV) and Urban Regeneration:
  - (a) Massive PV integration at the neighborhood scale provides substantial benefits from the early stages of a project.

(b) PV installations should be a priority in urban regeneration projects to significantly support Net-Zero 2050 decarbonization goals.

5.3. Policy and practical implications

These findings underscore the urgent need for policies supporting comprehensive regeneration of old residential areas, with a strong focus on integrating green infrastructure solutions and energy efficiency retrofits. Governments and municipalities should prioritize investments in district-scale retrofit programs, particularly for buildings dating back to the mid-20th century, to effectively achieve 2050 climate targets. Financial incentives, potentially including EU funding support, could play a crucial role in encouraging such extensive renovation efforts.

5.4. Broad applicability of methodology

The integrated methodology applied in this study, which effectively utilizes open data sources and typological categorization, provides a replicable framework for other urban areas with similar urban fabric and building archetypes, especially those in hot and arid climates. This suggests its potential for broader application in guiding sustainable urban development across diverse geographical contexts.

Credit statement

A.A.: Conceptualization, Methodology, Supervision, Writing—Original Draft, Project Administration. E.G.: Data Curation, Formal Analysis, Visualization, Writing—Review and Editing. S. A.: Investigation, Software (GIS/UBEM/LCA . modeling), Validation, Writing—Review and Editing

Conflict of interest

. There are no conflicts of interest

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