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Research article

Integrated urban climate resilience planning in a Hungarian mid-sized city: A scenario-based framework for Kecskemét 2035

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Abstract: Medium-sized cities are increasingly exposed to climate risks that cannot be addressed through isolated sectoral interventions. Thus, a scenario-based urban climate resilience framework was developed for Kecskemét, a Hungarian mid-sized city located in the Duna-Tisza Interfluve and the Homokhátság region, one of Hungary's most climate-sensitive lowland areas. We combined case-based document analysis, scenario-based policy design, SMART indicator structuring, and governance-oriented risk assessment with a structured review of peer-reviewed research on compact development, functional urban-area planning, proximity services, multimodal mobility, blue-green stormwater management, district decarbonization, and socially safeguarded regeneration. The proposed scenario included indicative 2035 targets: A 40% reduction in urban greenhouse gas emissions compared with the 2019 baseline, green space provision of 22 m^2 per capita, a public transport modal split of 28%, and annual stormwater retention of 86,000 m^3 through blue-green infrastructure. The results showed that climate resilience in mid-sized, climate-sensitive cities requires institutional integration across built-environment planning, mobility policy, energy transition, hydrological adaptation, and public participation. Comparative journal evidence indicated that transfer depends on catchment-scale modelling, commuting-area governance, maintenance capacity, auditable greenhouse gas accounting, and affordability safeguards. The Kecskemét case offers a transferable framework for Central European mid-sized cities facing simultaneous pressures of industrial growth, suburban expansion, water stress, and climate adaptation.

Keywords: urban climate resilience; scenario-based planning; blue-green infrastructure; sustainable mobility; SMART indicators; Kecskemét; Central Europe

Abbreviations: CO_2: Carbon dioxide; ESCO: Energy service company; GHG: Greenhouse gas; ISO: International Organization for Standardization; KPI: Key performance indicator; MaaS: Mobility as a service; NBS: Nature-based solutions; PV: Photovoltaic; SMART: Specific, measurable, achievable, relevant and time-bound; SUMP: Sustainable urban mobility plan

1. Introduction

Urban climate resilience is often discussed through the experience of large metropolitan regions; yet, medium-sized cities are increasingly becoming decisive sites of climate adaptation and mitigation. They concentrate population, infrastructure, employment, public services, and industrial activity, while frequently operating with more limited administrative capacity and financial flexibility than capital cities or large metropolitan regions. In Central and Eastern Europe, this challenge is particularly acute. Many mid-sized cities must simultaneously manage economic growth, suburbanisation, ageing infrastructure, increasing car dependency, rising energy demand, and accelerating climate impacts.

Kecskemét, located in central Hungary in the Duna–Tisza Interfluve, offers a particularly relevant case. It is one of Hungary's significant mid-sized urban centers, the county seat of Bács-Kiskun County and the center of a wider functional urban area. Furthermore, it is in Homokhátság, a sandy lowland region exposed to drying, falling groundwater levels, soil deflation, heat waves, and increasingly uneven precipitation. These environmental risks are intensified by the city's spatial structure. Kecskemét is characterized by a relatively large administrative territory, dispersed residential patterns, extensive peripheral and suburban areas, and growing commuting flows from surrounding settlements [1].

Local scholarship has shown that Kecskemét's climate-conscious urban policy relies on the combined use of regulatory and operational urban development tools. The city's policy directions include transport infrastructure transformation, development of urban sub-centers, utilization of brownfield areas, and the strengthening of green and blue infrastructure. These elements support the compact city model and contribute to reducing the city's climate footprint [1]. However, the next analytical step is to translate these policy directions into an integrated resilience framework that can connect mitigation, adaptation, land use, mobility, energy, water retention, governance, and monitoring within a single scenario-based model.

In this study, we develop such a framework. We ask the following research question: How can a climate-sensitive Hungarian mid-sized city integrate built environment planning, water retention, mobility transition, energy transformation, and participatory governance into a coherent urban resilience strategy by 2035? The answer is developed through a case-based, scenario-oriented policy design for Kecskemét. We do not claim that all proposed measures are formally adopted municipal decisions. Instead, we treat them as an integrated planning scenario derived from policy directions, local vulnerabilities, and internationally recognized urban resilience instruments.

The core argument is that Kecskemét's resilience challenge cannot be solved by a single sectoral intervention. Zero-emission public transport, brownfield regeneration, new green areas, water-retention measures, and participatory governance each contribute to resilience, but their effects remain limited if they are implemented separately. The city therefore requires a governance architecture that connects regulatory planning, operational development, investment sequencing, community participation, and measurable climate performance.

The study contributes to the literature in three ways. First, we shift attention from metropolitan climate governance to the specific resilience challenges of mid-sized Central European cities. Second, we integrate compact urban development, blue-green infrastructure, energy transition, and participatory governance into one analytical framework. Third, we develop a scenario-based policy design that can be adapted to other Hungarian and Central European cities facing similar pressures of suburbanization, industrial energy demand, water stress, and urban heat.

1.1. Literature and policy background

Urban resilience refers to the capacity of urban systems to anticipate, absorb, adapt to, and recover from disturbances while maintaining essential functions and improving long-term sustainability. In climate policy, resilience requires more than protection against extreme events. It also requires transformation of the physical, ecological, social, economic, and institutional conditions that produce vulnerability. For cities, this means that climate resilience cannot be separated from land use, housing, mobility, energy systems, water management, public health, and governance.

The compact city model is one of the central planning responses to climate-sensitive urbanization. Compact urban development aims to reduce land consumption, shorten travel distances, increase service accessibility, support public transport, enable active mobility, and reduce infrastructure costs. In climate terms, compactness may contribute to lower transport emissions and more efficient energy use [2]. However, compactness alone is not sufficient. If densification is not combined with green and blue infrastructure, it may intensify heat stress, reduce permeability and worsen the urban heat island effect. A climate-conscious compact city must therefore combine density with ecological performance.

Peer-reviewed brownfield research gives the compact-city concept an operational meaning. Brownfield and underused sites can accommodate new functions while limiting greenfield expansion, and their regeneration can also restore ecosystem services when soil remediation, green infrastructure, accessibility, and long-term management are integrated from the outset [3]. For Kecskemét, densification should therefore be measured not only as additional floor area, but also as avoided land take, remediated land, service mix, accessibility, ecological performance, and retained affordability.

This is particularly important in cities exposed to water scarcity and extreme precipitation. Nature-based solutions, including rain gardens, bioswales, urban forests, green roofs, permeable surfaces, restored water corridors, and multifunctional public spaces, can contribute simultaneously to stormwater retention, cooling, biodiversity, recreation, and public health [4]. The sponge-city logic is especially relevant for lowland cities where sealed surfaces reduce infiltration while extreme rainfall produces localized flooding. In such contexts, stormwater should be retained, slowed, reused, and integrated into the urban landscape rather than treated solely as a drainage problem [5].

Peer-reviewed European evidence also shows why blue-green infrastructure should be planned as a connected hydraulic and public-space system. Combined green, blue, and grey measures can reduce flood risk while providing environmental and social co-benefits [6]. Nature-based interventions become more durable when hydrological performance is linked to co-creation, spatial quality, and clear maintenance responsibility [7]. The Gdańsk rain-garden case further demonstrates the value of standardized soil profiles, planting, inlet design, and post-installation monitoring [8].

Sustainable mobility is the second major pillar of urban climate resilience. Transport systems shape emissions, air quality, accessibility, spatial justice, and everyday quality of life. In dispersed mid-sized cities, however, mobility transition is more complex than simply replacing cars with bicycles

or public transport. Long commuting distances, industrial work patterns, peripheral housing, school logistics, aging populations, and incomplete public transport networks may create structural car dependency. Therefore, the mobility transition must be linked to spatial reorganization: Urban sub-centers, intermodal nodes, public transport priority, cycling infrastructure, parking policy, and digital mobility services must work together [9].

For dispersed cities, the relevant planning geography extends beyond the municipal boundary. Research on Central European functional urban areas shows that commuting and other everyday flows reveal urban relationships that administrative borders alone do not capture [10]. This functional approach should guide Kecskemét's corridor planning, service catchments, and emissions inventory. Sustainable mobility planning likewise requires the coordinated treatment of rail, regional and local buses, active travel, interchange, digital information, and last-mile access rather than the isolated development of individual modes [9].

Energy transition is equally central. Cities with strong industrial functions face a dual challenge: Reducing municipal and residential energy demand while addressing industrial energy intensity. Building retrofits, rooftop photovoltaic systems, heat pumps, district heating modernization, waste heat utilization, storage capacity, and smart-grid solutions may reduce emissions and improve energy security. Yet, energy transition must also be governed spatially. Renewable energy installations, especially solar developments, may compete with agricultural land, landscape values, and ecological functions if not coordinated through planning regulation.

Peer-reviewed research on positive energy districts indicates that measurable urban GHG reduction is most credible when building envelopes, heat supply, renewable generation, storage, mobility, and user behavior are assembled into geographically defined portfolios rather than isolated projects [11]. For Kecskemét, this supports a portfolio that establishes a transparent boundary and baseline, reports operational and embodied emissions, protects energy-poor households, and distinguishes municipal influence from wider industrial emissions.

Finally, climate governance provides the institutional frame for implementation. Urban resilience cannot be delivered by isolated projects. It requires a portfolio approach, cross-sectoral coordination, transparent indicators, participatory processes, financial planning, and adaptive management. Standardized greenhouse gas inventories provide a basis for comparable monitoring [12], while European evidence on local climate plans shows the importance of linking targets, measures, responsibilities, and review mechanisms [13].

The same evidence clarifies the relationship between mixed-use regeneration and affordable housing. Environmental improvement can increase land and housing values and thereby create displacement pressure unless social safeguards are incorporated into planning and implementation [14]. Consequently, Kecskemét's proposed brownfield bonus should be conditional on a defined share and duration of affordable housing, daily services, public space, and sustainable-mobility access, with anti-displacement monitoring built into project approval.

2. Methods and data sources

2.1. Study area overview and climate vulnerability

Kecskemét is a mid-sized Hungarian city in the Duna–Tisza Interfluve. It functions as the administrative and economic center of Bács-Kiskun County and has a population of approximately 108,000

inhabitants. Its administrative area is relatively large compared with its population, which contributes to a dispersed settlement structure [1].



Figure 1. Location and internal urban structure of Kecskemét. Source: Author's compilation. Panel (a) is adapted from NordNordWest, Hungary location map (2008), https://commons.wikimedia.org/wiki/File:Hungary_location_map.svg; panel (b) is adapted from Milei.vencel, Kecskemét térképe (2023), https://commons.wikimedia.org/wiki/File:Kecskem%C3%A9t_t%C3%A9rk%C3%A9pe.png. Both source images are distributed under CC BY-SA 4.0.

The city's spatial structure is one of the core elements of its climate challenge. Kecskemét is a sprawling settlement with strong links between its urban core, outer residential areas, peripheral settlements, and former agricultural areas. In recent decades, internal and external suburbanizations have increased the population of surrounding and peripheral settlements. Lower property prices, lifestyle preferences and the economic attractiveness of the city have contributed to increasing commuting flows. The separation of residential, industrial, service, and institutional functions has intensified road traffic and reinforced car dependency [1].

The transport system reflects this spatial structure. Car use has become dominant, while road capacity has struggled to keep pace with economic and suburban growth. Centralized service provision further increases pressure on the inner city. The concentration of employment and public functions in and around the city center generates daily traffic flows that contribute to congestion, emissions, and declining livability in central areas. Although cycling has an important role, especially for shorter trips and industrial commuting corridors, Kecskemét's dispersed structure limits its potential as a universal substitute for car travel. A realistic mobility transition must therefore combine public transport improvement, intermodal development, cycling infrastructure, road hierarchy rationalization, and spatial decentralization.

Kecskemét's climate vulnerability is equally significant. As a Homokhátság city, it is exposed to drying processes, falling groundwater levels, soil deflation, water scarcity, and increasing temperature extremes. Uneven precipitation patterns create a dual hydrological problem: Water scarcity and flash flooding occur within the same urban system. Excessive surface sealing reduces infiltration, while intense rainfall events are rapidly drained away instead of being retained locally. This worsens the urban water balance and undermines the sustainability of green areas [1].

Urban heat is another key concern. Built-up and sealed surfaces heat up much more than vegetated areas, producing significant surface temperature differences during summer periods. Heat waves affect public health, energy demand, labor productivity, urban vegetation, and the usability of public spaces. In this context, green and blue infrastructure is not an aesthetic addition to urban planning. It is a core adaptation infrastructure.

Energy demand adds a further layer to the problem. Kecskemét's economic growth and industrial development have increased electricity consumption, particularly in industrial, commercial, service, and institutional sectors. Residential building stock also represents a major retrofit challenge. New buildings may meet higher energy standards, but older public and residential buildings continue to consume substantial amounts of energy. The energy transition must therefore address industrial demand, public building retrofits, residential renovation, renewable energy deployment, waste heat use, and grid flexibility.

Kecskemét's urban policy directions recognize several of these challenges. The city's planning principles include limiting the expansion of new buildable land, reusing brownfield and underutilized areas, creating urban sub-centers, designating renewable energy production areas, developing continuous green corridors along watercourses and water surfaces, providing areas for water retention and stormwater collection, protecting landscape values, and designating climate-protection afforestation areas [1]. These principles form the local policy foundation on which the present scenario-based framework builds.

Table 1. Local climate vulnerability and urban-structural drivers in Kecskemét [1,4].

Driver	Manifestation in Kecskemét	Climate relevance	Main response direction
Dispersed urban structure	Large administrative territory, peripheral residential areas, extended commuting patterns	Higher transport demand, higher infrastructure costs, service-access inequality	Compact city, sub-centers, brownfield reuse
Suburbanization	Growth of surrounding settlements and peripheral areas	Increased car dependency and land consumption	Functional urban area planning, multimodal corridors
Centralized service structure	Public and private services concentrated in the city center	Inner-city congestion, emissions, access burdens	15-minute sub-centers
Road dependency	Strong commuting and industrial labor-market flows	Transport emissions, congestion, air pollution	SUMP, intermodal node, zero-emission buses, cycling corridors
Water scarcity	Homokhátság drying, falling groundwater, limited infiltration	Urban vegetation stress, heat island intensification	Sponge-city design, stormwater retention, blue-green corridors
Extreme rainfall	Flash flooding in lower urban areas	Infrastructure damage, drainage overload	Rain gardens, bioswales, permeable surfaces, retention basins
Energy-intensive economy	Industrial and institutional energy demand	High greenhouse gas footprint	Public retrofit, PV, waste heat, smart grid
Underused brownfields	Valuable inner urban sites with redevelopment potential	Opportunity to reduce greenfield expansion	Mixed-use regeneration, affordable housing, green public spaces

Table 1 summarizes the main urban-structural and climate-vulnerability drivers identified for the Kecskemét case and links them to the corresponding response directions.

2.2. Data sources and a scenario-based analytical method

A scenario-based policy design methodology is applied. Our aim is not to evaluate an already implemented strategy, but to construct a coherent 2035 resilience framework for Kecskemét by integrating existing policy directions, documented local vulnerabilities, internationally recognized urban climate-planning principles, and implemented European precedents. The method combines local case analysis with a targeted comparative evidence review and translates the resulting intervention logic into measurable scenario parameters.

The methodology has five components:

First, we use case-based document analysis. The empirical starting point is Kecskemét's documented climate-conscious urban policy, including its regulatory and operational urban development approach, compact city orientation, transport policy, brownfield regeneration, urban sub-centers, and green-blue infrastructure [1]. On this basis, the study constructs an author-developed Kecskemét 2035 scenario that integrates indicative targets, intervention packages, governance arrangements, and monitoring tools. The scenario is an analytical design rather than an adopted municipal plan.

Second, we translate local problems into an integrated intervention logic. The identified problem fields are dispersed urban structure, suburbanization, car dependency, insufficient sub-center structure, brownfield underutilization, increasing energy demand, water scarcity, excessive surface sealing, heat island effects, and limited capacity for integrated implementation. These are then matched with policy instruments: Compact urban development, brownfield reuse, 15-minute sub-centers, sustainable mobility, energy retrofit, renewable energy, water retention, nature-based solutions, participatory governance, and indicator-based monitoring.

Third, we use SMART indicators to structure the scenario. The proposed 2035 targets include a 40% reduction in urban greenhouse gas emissions compared with the 2019 baseline, an increase in urban density, a public transport modal split of 28%, green space provision of 22 m^2 per capita, annual water retention of 86,000 m^3, and measurable reduction of daytime heat island intensity. These values are treated as indicative scenario targets, not as legally binding adopted commitments. This distinction is important for analytical clarity. The framework is designed as a policy model that can be tested, revised, and adapted.

Fourth, we incorporate governance and risk assessment. The proposed implementation model includes a local Climate Office, a stakeholder coalition, citizen participation instruments, open data reporting, ISO-style greenhouse gas monitoring, a KPI matrix and a 5 × 5 risk matrix covering financial, physical climate, technological, social, and legal risks. This governance layer is essential because urban resilience depends not only on the quality of individual projects, but also on the city's capacity to coordinate, finance, monitor, and revise them.

Fifth, a targeted comparative review is conducted across the seven implementation themes raised by the framework: Compact development and brownfield reuse; functional urban areas and multimodal corridors; proximity-based sub-centers; sponge-city and blue-green systems; rain gardens and permeable surfaces; GHG-footprint reduction; and mixed-use regeneration with affordable housing. Evidence is drawn exclusively from peer-reviewed journal articles that report empirical cases,

comparative assessments, or operational frameworks relevant to these themes [3–18]. The review is structured and purposive rather than systematic; it is used to test design plausibility and transfer conditions, not to estimate pooled intervention effects.

Several numerical targets in the framework are indicative and scenario-based. They should not be read as observed outcomes or adopted municipal commitments. Their function is analytical: They translate broad climate-policy objectives into measurable planning assumptions that can be tested through greenhouse gas accounting, hydrological modeling, transport modeling, cost-benefit analysis, and participatory review. This approach enables the framework to remain policy-relevant while avoiding the overstatement of empirical certainty.

2.3. Derivation and evidentiary status of the quantitative targets

The quantitative values are not generated by a single forecasting model. They are author-developed scenario parameters derived from documented local conditions and planning directions [1], then tested for methodological plausibility against peer-reviewed research on urban GHG accounting, European climate planning, and Hungarian local climate strategies [12,13,16]. Their role is to convert qualitative ambitions into testable planning hypotheses. Comparative evidence is used as a plausibility check rather than as a direct numerical transfer because baseline years, territorial boundaries, inventory methods, and institutional capacities differ between cities.

Accordingly, the 40% urban GHG reduction target is treated as a policy-aspiration benchmark rather than an adopted commitment. Its baseline and pathway must be validated through a sectoral greenhouse gas inventory and periodic monitoring [12,13]. The 28% public transport share represents a deliberate doubling of the 14% scenario baseline and requires transport-demand modelling and an updated travel survey. The 22 m^2 per capita green-space target represents an increase of approximately 29% from the 17 m^2 scenario baseline and should be validated through GIS-based quantity and accessibility mapping rather than interpreted as a universal European standard. The 86,000 m^3/year stormwater-retention figure and the public-building retrofit target are author-defined scenario capacities requiring, respectively, catchment-scale hydrological modelling and a building-asset audit. This staged logic is consistent with peer-reviewed assessments that emphasize baseline inventories, locally specified measures, implementation capacity, and iterative monitoring in European and Hungarian climate planning [13,16].

3. Results

The proposed Kecskemét 2035 framework is organized around five mutually reinforcing intervention fields: Compact urban structure and brownfield regeneration; sustainable mobility; energy transition and building retrofit; water-retentive blue-green infrastructure; and participatory governance with indicator-based monitoring. The central assumption is that none of these fields can deliver resilience alone. Their combined effect depends on integration.

3.1. Compact urban development and brownfield regeneration

The first pillar aims to reduce spatial dispersion and strengthen the compact city model. For Kecskemét, this is not a purely urban design preference. It is a climate strategy. Sprawl increases

infrastructure costs, travel distances, car dependency, energy demand, and land consumption. A compact urban structure can reduce these pressures if it is combined with accessible services, green space, and affordable housing.

Brownfield and underutilized sites are therefore strategic assets. Their reuse can accommodate new housing, employment, services, cultural functions, and green spaces without further expanding the urban footprint. The proposed scenario identifies brownfield regeneration as one of the main tools for limiting greenfield development. The Rudolf Barracks area and the Homokbanya Eco-Innovation Hub are treated as potential flagship areas in the scenario. Their role is not merely real estate development, but urban restructuring: They can support mixed-use development, green employment, public space renewal, and reduced commuting pressure.

A compact city strategy must also address affordability. If regenerated areas become socially exclusive, they may displace rather than reduce mobility and housing pressure. For this reason, the scenario links brownfield bonuses to sustainability criteria and affordable housing requirements. The objective is to ensure that compactness functions as a climate and social-accessibility instrument.

Implementation should therefore proceed through a brownfield-first sequence: Site inventory and ownership mapping; contamination and infrastructure assessment; temporary-use strategy; land-value and financing model; mixed-use master planning; and enforceable affordability and green-space conditions. Peer-reviewed brownfield research supports the integration of remediation, ecosystem services, and long-term management [3], while evidence on green gentrification demonstrates the need for anti-displacement safeguards [14]. Applied to Rudolf Barracks and Homokbánya, this sequence would turn the brownfield bonus from a discretionary incentive into a performance contract linked to avoided land take, remediation, affordable units, service provision, and mobility access.

3.2. Fifteen-minute sub-centers

The second structural intervention is the development of decentralized urban sub-centers. Kecskemét's centralized service structure contributes to inner-city traffic pressure and unequal accessibility. A network of sub-centers can reduce unnecessary trips, improve everyday access to services and support low-carbon mobility.

The scenario proposes six sub-centers: Helvécia-kapu, Katonatelep, Hetényegyháza, Széchenyiváros-North, Máriaváros-Southwest, and Vacsi-köz. Each sub-center would combine basic public and private services, such as kindergarten, medical practice, local market, coworking space, e-mobility points, and green public areas. The objective is that most residents should be able to access everyday services within approximately 500 meters or a short active/public transport trip.

The sub-center approach also supports climate justice. In dispersed cities, peripheral residents often face higher mobility costs and weaker service access. Decentralized services reduce this burden. They also make climate policy more socially acceptable, because the transition is experienced not only as restriction, but as improved everyday access.

The '15-minute' label should be treated as an accessibility standard rather than a uniform geometric radius. Moreno et al. organized proximity around six urban functions: Living, working, supplying, caring, learning, and enjoying; they emphasized density, diversity, proximity, and digitalization [15]. In Kecskemét, GIS testing should therefore measure door-to-service travel time separately for walking, cycling, and public transport, and should report results by age, disability, income, and peripheral location. The six proposed nodes may justifiably have different catchments and

service bundles, provided that the network reduces aggregate travel demand and closes identified accessibility gaps.

3.3. Sustainable mobility and intermodal transition

The third intervention field is sustainable mobility. In Kecskemét, mobility transition cannot be reduced to a simple modal shift target. The city's dispersed spatial structure, industrial employment patterns, suburban commuting, centralized services, and high level of car dependency create a structural transport problem. A realistic climate strategy must therefore combine network rationalization, public transport improvement, intermodal development, cycling infrastructure, micromobility, and spatial decentralization.

The proposed framework treats the road network as a system that must be reorganized rather than simply expanded. Ring-road completion and hierarchy-based traffic management may reduce unnecessary through-traffic in the inner city and help relieve overloaded radial roads. However, road infrastructure must not reproduce car dependency. It must be linked to public transport priority, intermodal nodes, park-and-ride and bike-and-ride facilities, and urban design measures that make central areas more livable.

The Noszlopy Park intermodal node is a central element in this logic. By integrating rail, regional buses, local buses, park-and-ride, bike-and-ride, and digital mobility services, it can reduce the emission burden of the present central bus terminal structure and support a more efficient distribution of mobility flows. The proposed MaaS platform, referred to in the scenario as MoviKKT, would further integrate ticketing, real-time information, tariff management, and individual carbon feedback. This digital layer can support behavioral change if it makes sustainable mobility easier, cheaper, more predictable, and more visible.

Fleet replacement alone is insufficient if the underlying network structure remains congested and unreliable. The climate impact of zero-emission public transport depends on route redesign, priority measures, service frequency, intermodal connections, and user trust. For this reason, the proposed framework treats zero-emission buses as part of a broader mobility transition rather than as an isolated technological solution.

Cycling and micromobility have a complementary role. Kecskemét's flat terrain offers potential, but its dispersed structure, long commuting distances, weather extremes, industrial shift patterns, and family logistics limit cycling as a universal substitute for car travel. The framework therefore proposes cycle superhighways and suburban cycling corridors where they can realistically serve commuting and local trips while avoiding the assumption that cycling can solve all mobility challenges in a sprawling mid-sized city. In climate-sensitive planning, active mobility must be treated as part of a broader accessibility system, not as a symbolic substitute for structural transport reform.

At the regional scale, the corridor network should be based on functional relationships identified through commuting and other origin-destination flows rather than the administrative border alone [10]. Each radial corridor should be assessed as a multimodal chain: Feeder access from surrounding settlements; interchange with rail or regional bus; local public transport priority; safe cycling and walking links; and last-mile access to industrial, educational, and service destinations. This is consistent with sustainable urban mobility planning, which treats land use, accessibility, modes, institutions, and implementation as one coordinated process [9].

3.4. Energy transition and building retrofit

The fourth intervention field is energy transition. Kecskemét's economic development and industrial structure create high energy demand, while older public and residential buildings remain significant sources of energy inefficiency. A credible urban climate framework must therefore address energy supply and energy demand.

The proposed Kecskemét 2035 scenario combines public building retrofit, residential renovation, photovoltaic deployment, agro-photovoltaic development, battery storage, heat pump-based district heating, and industrial waste heat utilization. The objective is not only to reduce greenhouse gas emissions, but also to improve energy security, reduce operating costs and create a more flexible local energy system.

Public buildings are a strategic starting point. Municipal and state-owned buildings are visible, measurable, and institutionally controllable. A Public-ESCO program can reduce final energy demand in schools, offices, cultural institutions, social facilities, and other public buildings while avoiding excessive upfront municipal expenditure. Such programs also have a demonstration effect: They show that the public sector does not merely demand climate action from residents and businesses, but begins with its own infrastructure.

Residential retrofit is more complex. Multi-apartment buildings and older housing stock require financing models that combine public support, private contribution, long-term savings, and social safeguards. Without such safeguards, retrofit policy may become socially regressive: Those with capital benefit first, while lower-income households remain trapped in high-energy, low-comfort buildings. A climate resilience framework must therefore connect energy efficiency with affordability, health, and social vulnerability.

Renewable energy deployment must also be spatially governed. Rooftop photovoltaic systems reduce pressure on agricultural land, while agro-photovoltaic systems may offer combined energy and water-retention benefits in selected areas. However, uncoordinated solar development can generate land-use conflicts, especially in a region where agricultural land, landscape structure, water scarcity, and ecological functions are under pressure. The scenario therefore treats renewable energy not simply as installed capacity, but as a planning issue.

Waste heat utilization and heat pump-based district heating represent a further opportunity. In industrial cities, climate mitigation should not ignore the thermal by-products of production. If industrial waste heat can be captured and integrated into district heating, it may reduce fossil energy demand and improve system efficiency. Such solutions require complex institutional coordination between industrial actors, utilities, and municipal authorities, including contractual arrangements, technical integration, and long-term governance commitments [11].

A project-level carbon test should accompany this portfolio. Research on positive energy districts recommends an auditable geographic boundary, a common energy and emissions baseline, coordinated demand reduction and renewable supply, and monitoring that distinguishes design estimates from measured performance [11]. City-scale greenhouse gas accounting further requires consistent sectoral boundaries and transparent reporting [12]. For Kecskemét, annual reporting should therefore separate municipal operations, residential and service buildings, transport, and major industrial sources while also recording embodied carbon for large regeneration and infrastructure projects. Affordability and resident-retention safeguards should be monitored alongside carbon performance [14].

3.5. Water-retentive blue-green infrastructure

The fifth intervention field is water-retentive blue-green infrastructure. This is the most locally specific part of the Kecskemét framework. In a Homokhátság city, water is not merely an environmental issue. It is the foundation of urban liveability, vegetation survival, cooling capacity, public health, soil stability, and long-term climate adaptation.

Kecskemét faces a dual water challenge. On the one hand, the region is exposed to drying, falling groundwater levels and increasing water scarcity. On the other hand, intense precipitation events can produce flash flooding in lower urban areas. Conventional drainage logic, which removes stormwater as quickly as possible, is therefore maladaptive. It worsens the local water balance by exporting a resource that the city increasingly needs. The framework consequently shifts from drainage-oriented thinking to retention-oriented urban hydrology.

The proposed blue-green infrastructure package includes rain gardens, bioswales, artificial ponds, permeable surfaces, green corridors, urban forests, green roofs, and a central Blue Belt-Green Belt stormwater corridor. These measures are designed to slow runoff, increase infiltration, reduce heat stress, support biodiversity, and improve public space quality. Their value lies not only in individual performance, but in networked interaction. A connected water-retentive landscape can combine ecological, hydraulic, and public-space functions more effectively than isolated projects [4–8].

The scenario proposes an indicative annual water retention target of 86,000 m^3. This figure should be treated as a planning target requiring hydrological validation, not as a verified outcome. Its analytical function is to make adaptation measurable. Without quantified targets and monitoring, blue-green infrastructure may remain symbolic rather than transformative. Measurable adaptation indicators are therefore required to assess whether interventions produce meaningful hydrological and thermal benefits.

Urban forests and shading policies are particularly important in relation to the heat island effect. The scenario proposes a 200-hectare climate forest program, a minimum shading requirement for new public spaces and a green-roof standard for larger new public and commercial buildings. These measures connect adaptation with everyday public space quality. Shade, cooling, walkability, and resting opportunities determine whether public space remains usable during heat waves, especially for older people, children, outdoor workers and people with chronic health conditions.

The water-retentive city also has a social dimension. Climate adaptation must not be limited to prestigious central spaces. Peripheral residential areas, suburban zones, socially vulnerable neighborhoods and heat-exposed public service locations must be included. If blue-green infrastructure is concentrated only where urban image benefits are highest, adaptation may reproduce spatial inequality and displacement pressure. A resilience framework must therefore use vulnerability mapping and service-accessibility analysis to determine where interventions are most urgent [14,18].

The peer-reviewed evidence implies a three-scale design rule for Kecskemét. At parcel scale, green roofs, cisterns, and permeable surfaces reduce runoff at source; at street and neighborhood scales, rain gardens, bioswales, and multifunctional public spaces slow and temporarily store flows; at catchment scale, connected blue-green corridors route excess water safely and support reuse [5–8]. Combined green, blue, and grey measures are required where urban form constrains surface retention [6], while the Gdańsk case underlines the need for replicable technical details and post-installation monitoring [8]. The 86,000 m^3 target should therefore be disaggregated by catchment and intervention type and verified against design storms, infiltration capacity, groundwater protection, and maintenance resources.

Table 2 presents the integrated intervention framework by linking proposed measures to their expected resilience functions and governance requirements.

Table 3 lists the indicative 2035 scenario targets used to structure the proposed resilience model.

Table 2. Integrated Kecskemét 2035 intervention framework. Source: Author's scenario-based framework grounded in the documented Kecskemét case [1].

Intervention field	Proposed measures	Expected resilience function	Main governance requirement
Compact city and brownfields	Rudolf Barracks regeneration, Homokbanya Eco-Innovation Hub, brownfield bonus	Reduces land consumption and supports mixed-use density	Planning regulation, investment sequencing, affordability safeguards
Fifteen-minute sub-centers	Six decentralized service nodes	Reduces centralized mobility pressure and improves local access	Service planning, GIS-based accessibility monitoring
Sustainable mobility	Intermodal node, zero-emission buses, MaaS platform, cycling corridors	Reduces transport emissions and improves multimodal access	SUMP alignment, public transport priority, open mobility data
Energy transition	Public ESCO retrofit, residential renovation, rooftop PV, agro-PV, battery storage, waste heat	Reduces emissions and increases energy security	Climate finance unit, utility coordination, industrial partnerships
Blue-green infrastructure	Rain gardens, bioswales, artificial ponds, urban forest, green roofs, Blue Belt-Green Belt	Retains water, reduces heat, supports biodiversity and public space quality	Maintenance capacity, hydrological monitoring, vulnerability targeting
Participatory governance	Climate Office, stakeholder coalition, citizens' assembly, participatory budgeting	Builds legitimacy, coordination and adaptive learning	Open data, regular reporting, feedback loops
Monitoring and risk management	KPI matrix, ISO-style reporting, 5 × 5 risk matrix, quick-turn mechanism	Makes implementation measurable and revisable	Annual climate report, external audit, corrective action protocol

Table 3. Indicative 2035 scenario targets and validation requirements. Source: Indicative scenario targets developed by the author from the documented Kecskemét case [1] and tested for methodological plausibility against peer-reviewed research on European and Hungarian local climate planning [13,16].

Indicator	Baseline	Proposed 2035 target	Scenario basis and validation
Total urban GHG emissions	2019 = 100%	−40%	Policy-aspiration benchmark; validate through a sectoral GHG inventory and emissions pathway.
Public transport modal split	14%	28%	Normative doubling from the local baseline; validate through travel survey and transport-demand modelling.
Green space per capita	17 m^2/person	22 m^2/person	Approximately 29% increase from the local baseline; validate through GIS-based quantity and accessibility mapping.

Continued on next page

Indicator	Baseline	Proposed 2035 target	Scenario basis and validation
Water retention	Current drainage-dominant system	86,000 m^3/year retained	Author-defined scenario capacity; catchment-scale hydrological modelling required.
Urban density	1,870 persons/km^2	≥2,200 persons/km^2	Compact-city aspiration; test through demographic and land-use scenarios.
Zero-emission bus fleet	Initial pilot stage	40–50% by 2030–2034 scenario	Fleet-transition milestone; test procurement, charging, energy and financing feasibility.
Public building retrofit	Existing public building stock	52 public buildings renovated	Author-defined project-count scenario; confirm through a public-building asset audit and investment sequencing.
Heat island reduction	Current heat exposure	−1.0 °C average daytime inner-zone reduction	Thermal-performance aspiration; establish a baseline and validate through remote sensing and microclimate monitoring.

3.6. Governance, financing, and monitoring

The proposed framework requires institutional capacity. Integrated climate resilience cannot be implemented through fragmented departmental responsibility. Land-use planning, transport, energy, water management, public space design, finance, public procurement, citizen participation, and data governance must be coordinated. For this reason, the scenario proposes the establishment of a Kecskemét Climate Office.

The Climate Office would function as a project portfolio and monitoring unit. Its tasks would include greenhouse gas accounting, project sequencing, external funding applications, KPI management, open data publication, stakeholder coordination, and periodic reporting to the municipal assembly. This does not mean creating another administrative island. It means creating an integration point. Without such an institutional node, climate policy risks becoming a fragmented portfolio of unrelated projects rather than an integrated transformation pathway.

Stakeholder governance is the second pillar. The framework proposes a stakeholder coalition involving industry, civil society, academic institutions, peripheral settlements, youth representatives, and business actors. This is essential because Kecskemét's climate challenges cross administrative and sectoral boundaries. Commuting, industrial energy demand, suburbanization, water retention, and green infrastructure cannot be governed by the municipality alone. They require cooperation across the functional urban area.

Citizen participation is also necessary, but it must be designed carefully. The proposed Climate Citizens' Assembly and participatory climate budgeting can support legitimacy and public learning if they are connected to real municipal decisions [17]. Participation should not be limited to consultation after core decisions have been made. Effective participation must therefore be connected to project prioritization, neighborhood-level adaptation, public space design, and monitoring.

Financing is the third pillar. The proposed framework uses a mixed financing model, combining EU cohesion and infrastructure funds, recovery and resilience resources, national co-financing, municipal green bonds, private-public partnerships, and ESCO mechanisms. Such a mix reflects the scale of the intervention package. No single funding source can deliver compact urban redevelopment, transport infrastructure, building retrofit, renewable energy, water retention, and governance capacity by 2035.

However, mixed financing creates coordination risk. Different funds have different timelines, eligibility rules, audit requirements, procurement procedures, and political vulnerabilities. The Climate Office should therefore include a climate finance unit capable of sequencing projects, managing cash-flow risks, aligning funding windows, and preparing fallback options. Financing resilience is a resilience problem.

Monitoring is the fourth pillar. The framework proposes a KPI matrix aligned with greenhouse gas accounting, urban sustainability indicators, mobility data, green space mapping, water retention metrics, and heat island monitoring. Indicators include total greenhouse gas emissions, energy-sector emissions, transport emissions, population density, modal split, green space per capita, green roof area, retained stormwater volume, and heat island reduction. Comparable inventories and published review cycles are necessary if these indicators are to support accountability and corrective action [12,13].

The value of monitoring does not lie in data visualization alone, but in adaptive management, public accountability and timely corrective action. The framework proposes a three-year strategic review cycle and a trigger mechanism: If key indicators deviate significantly from expected trajectories for two consecutive years, a corrective action plan should be required. Climate policy must be revisable because climate risks, technology costs, funding conditions, and social behavior all change. A rigid strategy is poorly suited to climate governance, where risks, technologies, funding conditions, and social behavior may change over time.

Risk management completes the governance architecture. The proposed 5 × 5 risk matrix covers financial delays, extreme rainfall, battery storage safety, social resistance to redevelopment, and regulatory changes. Each risk is assessed by probability and impact, with mitigation strategies attached. This approach is important because urban resilience projects often fail not because their objectives are wrong, but because implementation risks are underestimated. Climate planning must therefore include not only desired futures, but failure pathways.

4. Discussion

The Kecskemét 2035 framework illustrates that climate resilience in mid-sized cities requires integration across four layers: Spatial structure, infrastructure systems, ecological adaptation, and institutional governance. None of these layers can be treated as secondary.

The first lesson concerns the built environment. Urban form is a climate variable. Dispersed settlement patterns increase travel demand, infrastructure costs, energy use, and service-delivery burdens. Compact development and brownfield regeneration can reduce these pressures, but only if they are combined with accessibility, affordability, public space quality, and green-blue infrastructure. Density without cooling and permeability may deepen climate vulnerability.

The second lesson concerns mobility. In dispersed cities, sustainable mobility requires realism. Public transport, cycling, micromobility, and intermodal nodes must be strengthened, but car dependency cannot be reduced by behavioral messaging alone. It is produced by spatial structure, employment geography, service distribution, and household logistics. The transition must therefore combine land-use reform with transport reform.

The third lesson concerns water. In dry lowland cities, climate adaptation must move beyond drainage. Stormwater should be treated as a resource to be retained and reused wherever possible. Blue-green infrastructure provides a bridge between adaptation, livability, biodiversity, and public health. Its success depends on network design, maintenance capacity, and social targeting.

The fourth lesson concerns governance. Integrated climate planning needs institutional integration. A Climate Office, stakeholder coalition, open data dashboard, participatory mechanisms, KPI matrix, financing unit, and adaptive review cycle are not additional administrative burdens. They are part of the operating structure of the strategy. Without them, urban climate policy may remain a list of projects instead of becoming a transformation pathway.

The fifth lesson concerns climate justice. The benefits and burdens of urban climate policy are not automatically distributed fairly. Retrofit programs, green infrastructure, mobility transition, parking reform, brownfield redevelopment, and energy investments can produce uneven effects across social groups and neighborhoods. If affordability, accessibility, peripheral residents, older people, low-income households, and heat-exposed groups are not explicitly considered, resilience may become socially selective and may reproduce existing socio-spatial inequalities [14,18].

The transferability of the Kecskemét framework lies in its structure rather than in each individual measure. Other Central European mid-sized cities may not share Kecskemét's exact hydrological, economic or spatial conditions, but many face similar combinations of industrial growth, suburbanization, aging infrastructure, increasing heat stress, mobility pressure, and limited governance capacity. The framework can therefore be adapted as a modular model: Diagnose structural vulnerabilities, define integrated intervention fields, set measurable scenario targets, create governance capacity, and build adaptive monitoring.

4.1. Comparative Central European perspective

Peer-reviewed Central European and EU-wide research supports transferability at the level of planning architecture. The assessment of Hungarian local climate strategies shows that mitigation and adaptation measures are often constrained by uneven municipal capacity, financing, and coordination [16]. A wider assessment of 885 EU cities likewise demonstrates the importance of explicit baselines, linked mitigation and adaptation measures, and monitorable implementation arrangements [13]. Research on Czech functional urban areas adds a spatial lesson: Commuting relations and everyday flows should inform planning boundaries when municipal borders do not reflect the area in which mobility and service systems operate [10].

These findings are not numerical templates for Kecskemét. Baseline years, territorial boundaries, climate hazards, and fiscal capacities differ. What is transferable is the planning sequence: Establish an auditable baseline, connect mitigation and adaptation objectives to sectoral measures, assign responsibilities, couple investment with measurable indicators, and review performance periodically. Kecskemét's added specificity lies in joining this governance sequence to Homokhátság water stress, dispersed settlement patterns, and industrial growth. Transferability is therefore modular rather than replicative.

The wider comparison moves the analysis from target plausibility to implementation design. Across the peer-reviewed evidence base, successful transfer depends on a functional planning boundary, a measurable baseline, cross-sectoral project packaging, dedicated delivery capacity, long-term maintenance, and explicit social safeguards [3–18]. Table 4 summarizes how the seven action families can be translated into Kecskemét-specific mechanisms without assuming that metropolitan-scale resources are available locally.

Table 4. Peer-reviewed implementation evidence and transfer conditions for Kecskemét. Source: Author's comparative synthesis of peer-reviewed journal evidence [3–18].

Theme	Peer-reviewed evidence	Transfer to Kecskemét	Critical condition
Compact development and brownfields	Brownfield regeneration, ecosystem services, and anti-displacement evidence [3,14]	Prioritize Rudolf Barracks and Homokbánya before peripheral greenfield expansion	Contamination audit, land-value capture, phased delivery
Functional urban area and multimodality	Sustainable mobility planning and Central European functional urban-area evidence [9,10]	Delineate the commuting shed and connect it to Noszlopy Park and radial corridors	Intermunicipal governance and origin-destination data
X-minute services	Proximity planning and six-function accessibility model [15]	Use six sub-centers as service bundles rather than identical-radius circles	Walking, cycling and transit-time accessibility tests
Sponge-city and blue-green corridors	Nature-based solutions and integrated green-blue-grey infrastructure [4–7]	Develop the Blue Belt-Green Belt as a connected retention and cooling system	Catchment modelling, space allocation and long-term maintenance
Rain gardens and permeable surfaces	Gdańsk rain-garden design and implementation evidence [8]	Adopt standard details for streets, car parks, schools and public facilities	Soil and groundwater testing, winter operation, performance monitoring
GHG-footprint reduction	Positive energy districts and city-scale GHG accounting [11,12]	Bundle retrofit, district heat, PV, mobility and consumption-side measures	Auditable baseline, life-cycle carbon and social safeguards
Mixed-use and affordable regeneration	Brownfield regeneration and climate-justice safeguards [3,14,18]	Tie brownfield development bonuses to affordable units, services and green space	Anti-displacement rules, affordability period and transparent allocation

4.2. Implementation challenges and institutional feasibility

Implementation feasibility is the main risk in translating the scenario into policy. Evidence from Hungarian cities indicates that local climate strategies can be constrained by limited financial resources, municipal expertise, local autonomy, and cross-sectoral coordination [16]. For Kecskemét, financial risk arises from dependence on EU and national funding windows and from the long payback periods of major infrastructure; institutional risk arises from coordination across municipal departments, utilities, state bodies, and neighboring settlements; stakeholder conflict may emerge around parking and road-space reallocation, brownfield redevelopment, housing affordability, and land-use change; and political risk arises from electoral cycles that can alter priorities or disrupt investment sequencing. Climate impacts, energy prices, and technology costs may also shift the relative urgency or feasibility of individual projects.

These constraints do not invalidate the scenario, but they change the governance requirements. The Climate Office should be understood as a minimum coordinating capacity rather than as an additional administrative layer. It should maintain a rolling project pipeline, publish annual KPI data, operate the proposed three-year strategic review cycle, and trigger corrective planning after two consecutive years of material deviation. Major projects should pass a common screening protocol covering lifecycle cost, GHG effect, adaptation benefit, distributional impact, legal competence, operational staffing, and funding robustness. Where the municipality lacks direct competence, the stakeholder coalition should provide a formal coordination mechanism with utilities, state agencies,

industry, and neighboring settlements. In this way, implementation uncertainty becomes an explicit component of adaptive governance rather than an unacknowledged weakness of the plan.

The implementation safeguards above do not remove the framework's analytical limitations. First, the numerical targets require empirical validation through hydrological, transport, energy, land-use, and greenhouse gas modeling. Second, the comparative benchmarks demonstrate plausibility and methodological transferability, not causal equivalence between cities. Third, the study does not provide project-level cost curves, committed financing or primary stakeholder evidence from which social acceptance can be inferred. Fourth, the framework focuses primarily on municipal and urban-development instruments and therefore does not fully address regional water governance, agricultural land-use transformation or industrial decarbonization beyond direct municipal influence. These limitations delimit what the scenario can claim: It is a structured planning framework, not a forecast or an adopted investment program.

Despite these limitations, the integrated approach is valuable because it avoids the fragmentation that often weakens urban climate policy. It shows that resilience is not achieved by adding a green project to an otherwise unchanged urban development model. It requires reordering the relationship between growth, land use, mobility, water, energy, public space, and governance.

5. Conclusions

In this study, we developed a scenario-based urban climate resilience framework for Kecskemét, a Hungarian mid-sized city located in one of the country's most climate-sensitive regions. The case demonstrates that climate resilience in mid-sized cities cannot be addressed through isolated interventions. Kecskemét's vulnerability emerges from the interaction of spatial dispersion, suburbanisation, industrial energy demand, car dependency, water scarcity, sealed surfaces, heat island effects, and governance complexity.

The proposed Kecskemét 2035 framework integrates compact urban development, brownfield regeneration, decentralized sub-centers, sustainable mobility, energy transition, water-retentive blue-green infrastructure, participatory governance, financing coordination, KPI-based monitoring, and adaptive risk management. Its indicative targets include a 40% reduction in greenhouse gas emissions, increased public transport share, expanded green space provision, significant stormwater retention, and measurable heat island reduction by 2035.

The comparative review strengthens this conclusion with peer-reviewed evidence on brownfield regeneration, functional urban areas, proximity-based services, sustainable mobility, blue-green infrastructure, rain gardens, district-scale decarbonization, greenhouse gas accounting, citizen participation, and climate justice [3–18]. Their relevance to Kecskemét is conditional rather than automatic: Each requires local hydrological and transport modelling, an auditable emissions baseline, maintenance financing, cross-municipal cooperation, and safeguards against displacement or unequal access. These conditions convert transferable evidence into a realistic implementation agenda for a mid-sized city.

The central conclusion is that urban climate resilience is not a separate environmental sector. It is a mode of governing the relationship between the built environment, natural systems, infrastructure, social access, economic development, and institutional responsibility. In climate-sensitive mid-sized cities, resilience must be planned as an integrated urban operating system.

Kecskemét's experience and the proposed scenario offer transferable lessons for other Central European cities. Climate policy should not merely respond to extreme weather events after they occur. It should reshape the urban conditions that determine exposure, vulnerability, and adaptive capacity before damage becomes inevitable. In this sense, the resilient city is not simply a city that survives shocks. It is a city that learns how not to manufacture its own fragility.

Use of AI tools declaration

The author used ChatGPT, a generative artificial intelligence tool developed by OpenAI, to support manuscript preparation, including structural organisation, language drafting, stylistic refinement and editorial revision. The tool was not used as an author. The author reviewed, revised and verified the manuscript, including factual statements, source relevance and final interpretation, and accepts full responsibility for the content, integrity and submission of the manuscript.

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Conflict of interest

The author declares no conflicts of interest in this paper.

Data availability statement

This article is based on document analysis and scenario-based policy design. The local empirical background and comparative framework are derived from published peer-reviewed journal articles, while the proposed 2035 framework is presented as an analytical planning scenario. No new primary dataset was generated for this study.

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