

Climate mitigation and adaptation strategies tailored for different types of European cities: A typology and associated systematic review

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Climate mitigation and adaptation strategies tailored for different types of European cities: A typology and associated systematic review

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Abstract

Amidst escalating climate impacts and continued emissions, numerous case studies have examined how cities can mitigate and adapt to climate change. Yet, systematic cross-sectoral and cross-impact assessments that identify which climate actions are relevant to which types of cities remain limited. This study addresses this gap for Europe through a data-driven analysis of European cities, categorizing them into four distinct city types (Shrinking cities, Growing cities, Old stagnating cities, Metropolises and economic centers), quantitatively analyzing their need and capacity to act on climate change, and providing a systematic overview of effective climate action strategies for each of these clusters. Based on harmonized data for all 1263 cities in Europe, we identify sectoral and climate impact hotspots requiring concerted climate action across the four city types. Drawing on the existing case study literature comprising 1613 climate action assessments, we provide recommendations for climate mitigation and adaptation actions addressing greenhouse gas emissions from buildings and mobility in metropolises and old stagnating towns, as well as responses to heat and drought in growing Southern European cities, and flooding risks in shrinking Eastern European cities. These insights can inform cross-city learning and targeted policy and investment prioritization across urban planning, public services, technology deployment or governance capacity in line with local contexts.

Keywords

climate change impacts, governance capacity, funding feasibility, local built environment, climate action implementation

1. Introduction

Amidst escalating climate impacts and continued emissions, numerous case studies have examined how diverse cities mitigate and adapt to climate change (Lamb *et al.*, 2019; Sethi *et al.*, 2020; *World Cities Report 2024: Cities and Climate Action*, 2025). Those case studies repeatedly reveal how climate actions play out differently across various local contexts. Yet, systematic cross-sectoral and cross-impact assessments that identify which climate actions are relevant to which types of cities remain limited (Creutzig *et al.*, 2025; Montfort *et al.*, 2025). Scaled, locally differentiated assessment of climate action could facilitate cross-city learning, inform realistic climate change mitigation and adaptation potentials, and guide targeted policy and investment prioritization across urban planning, public services, technology deployment or governance capacity in line with local contexts (Montfort *et al.*, 2026).

This study addresses this research gap for Europe through a data-driven analysis of European cities, categorizing them into four distinct city types, quantitatively analyzing their need and capacity to act on climate change, and providing a systematic overview of climate action strategies for each cluster. This study responds to the call by Creutzig *et al.* (Creutzig *et al.*, 2020) for more systematic comparative analysis of urban climate change mitigation and adaptation by establishing city types using available big data and machine learning. Previous work either typologized cities according to objective characteristics (Baiocchi *et al.*, 2015; Creutzig *et al.*, 2015; Montfort *et al.*, 2026), organized case studies bibliometrically (Lamb *et al.*, 2019; Montfort *et al.*, 2025) or focused on climate mitigation and reviewed effect sizes irrespective of local context (Sethi *et al.*, 2020). Until now, quantitative typologies of cities have not been connected to systematic reviews of the emerging types of cities. Hence, our paper makes an important contribution by connecting a quantitative analysis of different European city types with an existing bibliometric database (Montfort *et al.*, 2025, 2026) and a systematic review, studying effectiveness, feasibility, co-benefits and trade-offs of urban climate action, comprising both mitigation and adaptation.

While the approach is meant to be replicable across world regions, we focus on Europe which has a particularly rich but scattered body of case study literature on urban climate change mitigation and adaptation. European cities are very diverse – from cold, shrinking towns to hot and buzzing metropolises – warranting an attuned assessment of potentials and implementation strategies. At the core of this work lies the proposition that there would be a difference in need and capacity for climate action as well as recorded effect sizes, co-benefits, and barriers of climate action strategies between types of European cities. We build on previous efforts at differentiating and characterizing cities within Europe with regards to climate action (Solecki *et al.*, 2015; Fujii, Iwata and Managi, 2017) by including all European cities, expanding on the set of indicators and linking such a typology to the case study literature.

Together, these insights are meant to facilitate an understanding of the relevance, conditions and potential of climate mitigation and adaptation for different city types.

Such a systematic understanding is particularly valuable ahead of the upcoming IPCC Special Report on Climate Change and Cities, which seeks to provide targeted recommendations for diverse cities based on the most recent literature. We discuss the results in light of the climate change contribution and affectedness of different types of cities. Finally, we discuss what cities of similar kinds can learn from each other, and to what extent reported climate actions already fit the specific capacity and needs of each type.

2. Data and Methods

Based on harmonized data for all European cities, we identify sectoral and climate impact hotspots requiring concerted climate action across different city types. We complement this quantitative analysis with a qualitative understanding of differences in climate action by city type, drawing on existing case study literature.

2.1. City clustering

2.1.1. Database and scope

The 1263 cities classified here comprise all human settlements on the continent of Europe (including Russia to the Ural, Cyprus, and Türkiye in line with the IPCC regional definition¹) that qualify as urban centers according to the Degree of Urbanisation (UN Statistical Commission, 2021). We classify cities into different types based on 12 characteristics sourced from the Global Human Settlement Layer Urban Centre Database (GHS-UCDB, Melchiorri *et al.*, 2024) including the local climate (heating and cooling degree days); the available critical infrastructure; the resident population (size, age, density); and the socio-economic situation and trend (human development index, female development index, gross domestic product per capita). The city types, hence, describe core differences in the environment, layout, size, and development of cities, which we assume are relevant to their capacity and need to act on climate change.

2.1.2. Clustering algorithm

To establish the city typology, we use deep embedded clustering (DEC), which outperforms simpler techniques such as k-means or hierarchical clustering in terms of within-cluster cohesion and between-cluster separation. By learning the embeddings from all cities globally, we align this typology with a global typology of cities (Montfort *et al.*, 2026) making the assessment replicable for other world regions. DEC works by projecting the data into the latent space. This latent representation is often more meaningful to group similar observations as it compresses less relevant indicators. The cluster centroids are then initialized with k-means and refined iteratively for 500 steps (for details, see Xie, Girshick and Farhadi, 2015). We use an ensemble of 50 DEC runs and aggregate over the runs, since embeddings in the latent space can vary depending on their random initialization. This produces robust results. To keep our European

¹ <https://github.com/SantanderMetGroup/ATLAS>

typology consistent with the Global context cities and Evidence assessments in the IPCC, we use the embeddings derived from all cities globally. This also has the advantage that we can use all 11,000 cities from the GHSL-UCDB for more stable projections into the latent space. For details on the implementation of the algorithm, see Montfort *et al.* (2026).

2.2. Quantitative characterization of city types

For each city type, we quantitatively differentiate the need and capacity to act on climate change. This quantitative analysis is constrained by data availability for the cities sourcing from three harmonized databases: the GHS-UCDB (Melchiorri *et al.*, 2024), the CORDEX-CORE climate projections (Nogherotto *et al.*, 2026) and the Divisions of Powers portal (European Committee of the Regions, 2021). For a detailed list of indicators, units and data sources, see Supplementary Information A.

2.2.1. Data sources addressing the climate action need

The need for climate action is defined relative to the city's location and layout which we assume are least malleable to change substantially. The need for climate mitigation is assessed by total and sectoral territorial greenhouse gas emissions per capita as downscaled by the Emissions Database for Global Atmospheric Research (EDGAR; Crippa *et al.*, 2024) and by proxies for building and mobility energy use which indicate the potential emission burden of two of the largest urban sectors given by the location and layout of the city. These include the road network density, the built-up volume and area per capita and the building age (Melchiorri *et al.*, 2024). The need for climate adaptation is measured as the projected occurrence, intensity and event duration of climate hazards (heat waves, heavy precipitation, coastal flooding, droughts) given by the city's location and layout that are expected to rise at a given global warming level in line with regionalized climate projections based on daily climate variables from the CORDEX-CORE ensemble (cf. Nogherotto *et al.* 2026), as well as by a proxy for climate resilience based on the normalized difference vegetation index (NVDI) for average greenness of a city (Melchiorri *et al.*, 2024).

2.2.2. Data sources addressing the climate action capacity

The capacity for climate action is dependent on a variety of factors, and here we focus on four for which harmonized cross-city data is available: (i) the political, administrative, and fiscal independence of local governments from national governments as provided by the Decentralization Index and available to member states of the European Union (European Committee of Regions, 2021), (ii) the age-dependency ratio indicating the personal capacity for behavioral change and available workforce, (iii) the frequency of non-protest conflicts in the urban area indicating the political stability, and (iv) the local internet latency indicating the digital connectedness of the urban area (Melchiorri *et al.*, 2024).

2.3. Literature review for tailored recommendations

To provide tailored recommendations on effective climate actions, we systematically review case studies for effectiveness, co-benefits and feasibility of 20 core urban climate action strategies targeting different hazards, spanning different urban sectors and changes in behavior, technology and infrastructure (Table 1). By dividing the case study sample by the previously established city types, we aim to understand how the effectiveness and knowledge of these urban climate actions differ between city types, and how knowledge and effectiveness compare to the local needs and capacities to act.

Table 1: Climate actions covered by this review.

Climate Action	Hazard	Sector	Change in
Low-carbon heating technology roll-out	Emissions	Heating & Cooling	Technology, Infrastructure
Insulation and energy retrofits	Emissions	Building	Technology
Building occupancy increase	Emissions	Building, Urban planning	Infrastructure, Behavior
Smart metering and dynamic tariffs	Emissions	Electricity	Behavior
Rooftop photovoltaic and battery systems	Emissions	Electricity	Technology
Electric vehicle roll-out	Emissions	Mobility	Technology
Modal shift towards shared and active mobility	Emissions	Mobility	Infrastructure, Behavior
Compact urban planning	Emissions	Mobility, Urban planning	Infrastructure
Low-carbon use of consumables	Emissions	Consumables	Behavior
Waste management	Emissions	Consumables	Technology, Behavior
Carbon dioxide removal	Emissions	Urban planning	Infrastructure, Technology
Air conditioning roll-out	Heat waves	Heating & Cooling	Technology
Urban design for cooling	Heat waves	Urban planning	Infrastructure
Sponge city roll-out	Floods	Urban planning	Infrastructure
Flood-, subsidence- and fire-sensitive zoning	Floods/Subsidence/Fire	Urban planning	Infrastructure
Resistant building materials and structures	Various	Building	Technology
Water source diversification and access	Droughts	Water management	Infrastructure
Water demand management	Droughts	Building	Technology, Behavior
Early warning systems	Various	Governance	Technology, Behavior
Distributed electricity microgrids	Various	Electricity	Technology

2.3.1. Sampling of relevant literature

The body of case study literature considered for this review is an update and extension of Montfort et al. (2025) who queried the OpenAlex database for articles on climate change and human settlements and matched the identified records with city names. This updated database contains articles in any language published until March 2025. We consider records of cited case study articles that analyze cities in Europe and have been published between January 2000 and March 2025. The abstracts of those 7411 cited European urban climate change case studies have been automatically screened and classified using gpt-5-mini and following a structured questionnaire (cf. Supplementary Information B) for quantitatively or qualitatively assessing either of the iteratively defined urban climate action strategies listed in Table 1. Studies that do not quantitatively nor qualitatively assess the effect of one of these climate actions are excluded, resulting in a total of 2361 suitable case studies. From our initial set of climate actions, we excluded ‘Building occupancy increases’ since only two records were assigned, insufficient to understand differences between city types.

2.3.2. Coding and structure of the review process

Each study with available open-access full text, comprising 1613 selected studies, is systematically analyzed for effect sizes, factors affecting effectiveness, feasibility, co-benefits and trade-offs, alongside a critical appraisal of the methodology with regards to key limitations, sample sizes, real world validation and scope of the evaluated action. To enable the systematic coding of the case studies, an automated procedure is employed using the large language model gpt-5 to classify and summarize information based on a structured questionnaire (cf. Supplementary Information B) for each open-access case study full text. The automated extraction of information from a paper using gpt-5 comes along with limited replicability compared to a self-trained model as gpt-5 is continuously further developed. Nevertheless, we chose gpt-5 over a simpler self-trained model due to its high reasoning and summarizing capabilities which exceed those of publicly available local models (Cao *et al.*, 2025; Joos, Keim and Fischer, 2026). The reliability of this automated approach is comparable to human inter-coder agreement as we validate with a sample of double manually coded case studies (Supplementary Information B).

Each of the coded case studies is matched with city types based on the cities covered in the case study allowing for multiple assignments. The resulting information from the set of classified and coded case studies is subsequently manually interpreted for each climate action extracting the key differences between city types following a set of guiding questions (cf. Supplementary Information C).

3. Results

3.1. European cities by type

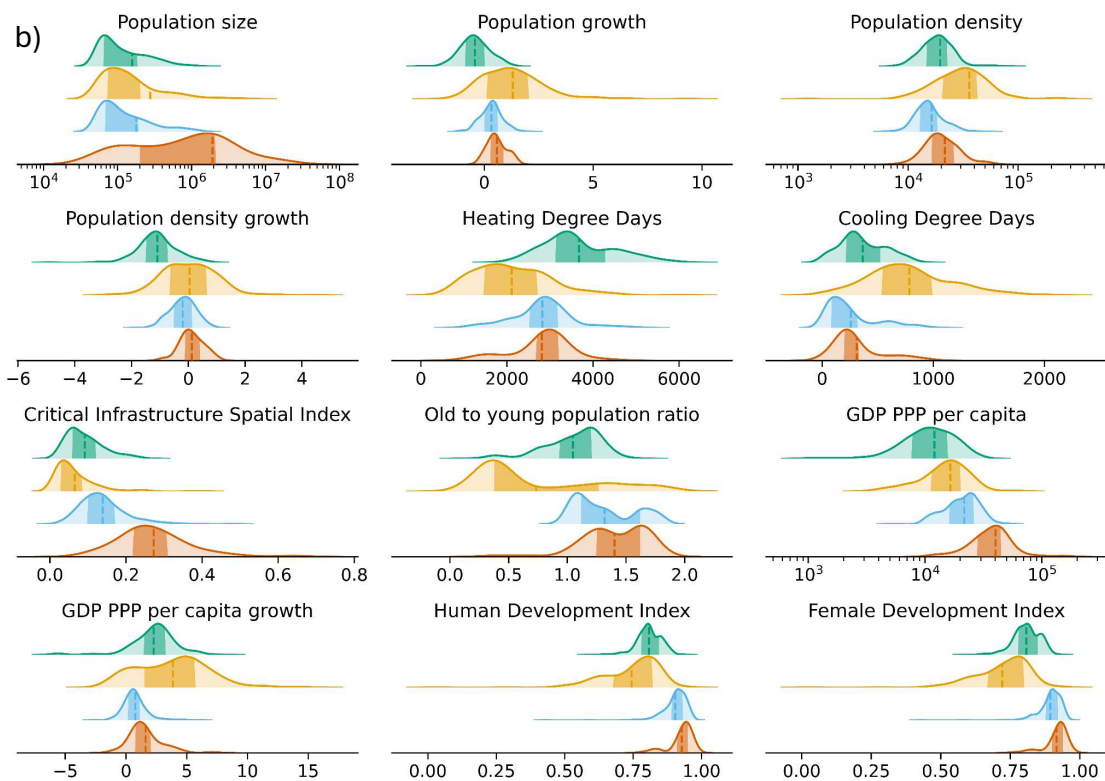
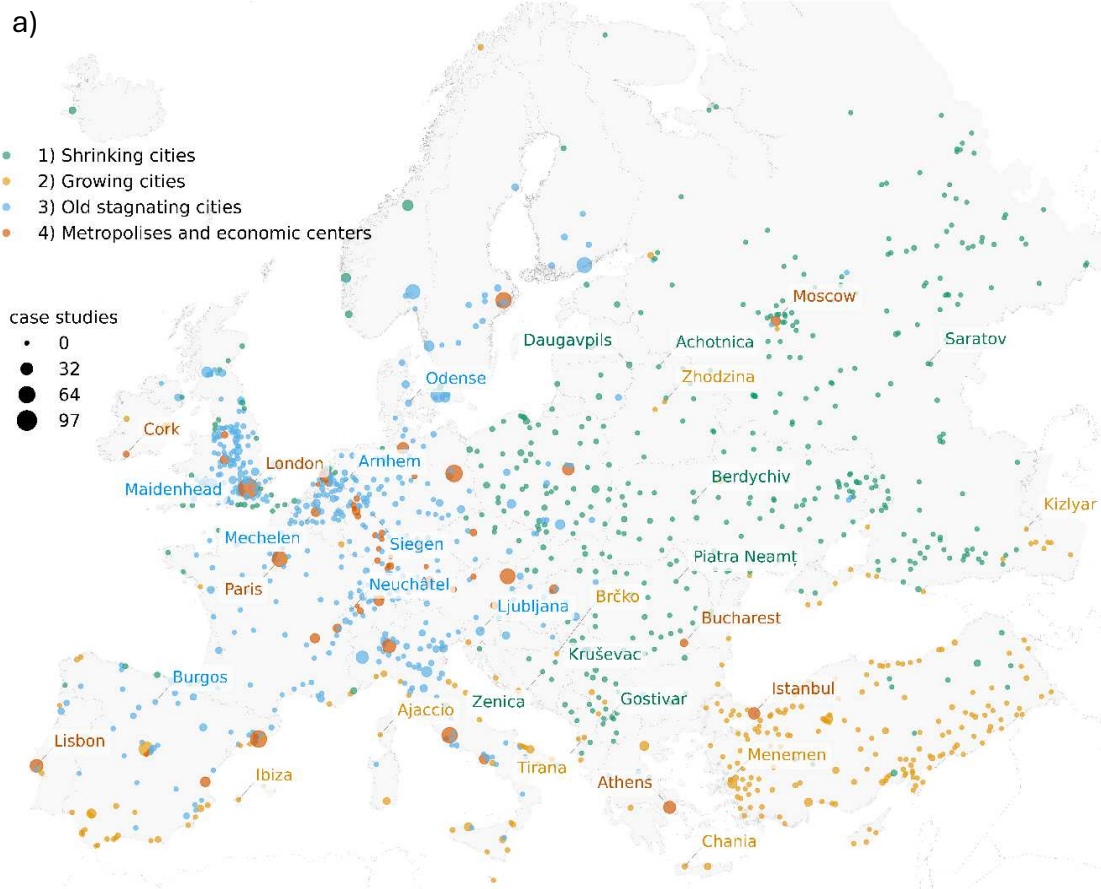


Figure 1: European cities by city type. a) Each city is colored by the city type that most aligns with the city's unique characteristics. City names are displayed for cities which most align with each type from a diversity of countries. The size of the point indicates the number of case studies included in this review which cover the city. b) Distribution of the city characteristics used for clustering by city type. The solid line describes the kernel density estimate based on the number of cities. The dashed vertical lines describe the arithmetic mean for each type. The shaded area displays the interquartile range for each type.

We find four different types of cities in Europe that share common climate, infrastructure, population, and socio-economic characteristics (Figure 1): 1) **shrinking cities** that tend to face declining populations and thereby a sprawling population density trend in combination with a lower but rising economic activity tend to be located in colder climates in Eastern Europe and along the Atlantic coast; 2) **growing cities** that are already densely populated with a younger resident population, a lower human and female development index (comprising years of schooling, life expectancy and incomes), less available critical infrastructure and that experience population and economic growth tend to be located in warmer climates in Southern Europe along the Mediterranean and the Black Sea; 3) **older stagnating cities** that tend to be of smaller population size, face slower population and economic growth, have an older and more sprawled resident population with a high human and female development index as well as gross domestic product are spread across Central and Western Europe; 4) large **metropolises and economic centers** with high economic activity, a high human and female development index and abundant critical infrastructure are spread across Europe.

3.2. Climate-relevant discrepancies and commonalities of city types

3.2.1. *Need for climate action: emission sources and climate hazard exposure*

The different types of cities experience a diverging need to mitigate and adapt to climate change (Figure 2). **Metropolises and economic centers** tend to have higher territorial GHG emissions per capita related to the presence of energy and industrial facilities and transport infrastructure within the urban area but also reflecting higher residential building emissions. Together with **Old stagnating cities**, Metropolises and economic centers tend to have older building stocks which are associated with higher space heating demand. Old stagnating cities additionally have larger and more sprawled building stocks per capita which pose a challenge in reducing building- and transport-related GHG emissions. Also some **Shrinking cities** show higher GHG emissions per capita related to industrial facilities onsite and waste management practices.

Growing cities which have lower emissions on average, on the other hand, tend to be more exposed to climate hazards. Already now, Growing cities which are mostly located in Southern Europe more frequently experience heat waves and are expected to experience the strongest rise in heat waves and droughts under +2°C global warming,

while having less urban green available to mitigate heat stress. Similarly, **Shrinking cities** already experience flooding relatively frequently and are expected to see a stronger rise in heavy precipitation and coastal flooding. Overall, heatwaves, droughts, and floods are expected to increase in intensity and frequency in all types of cities.

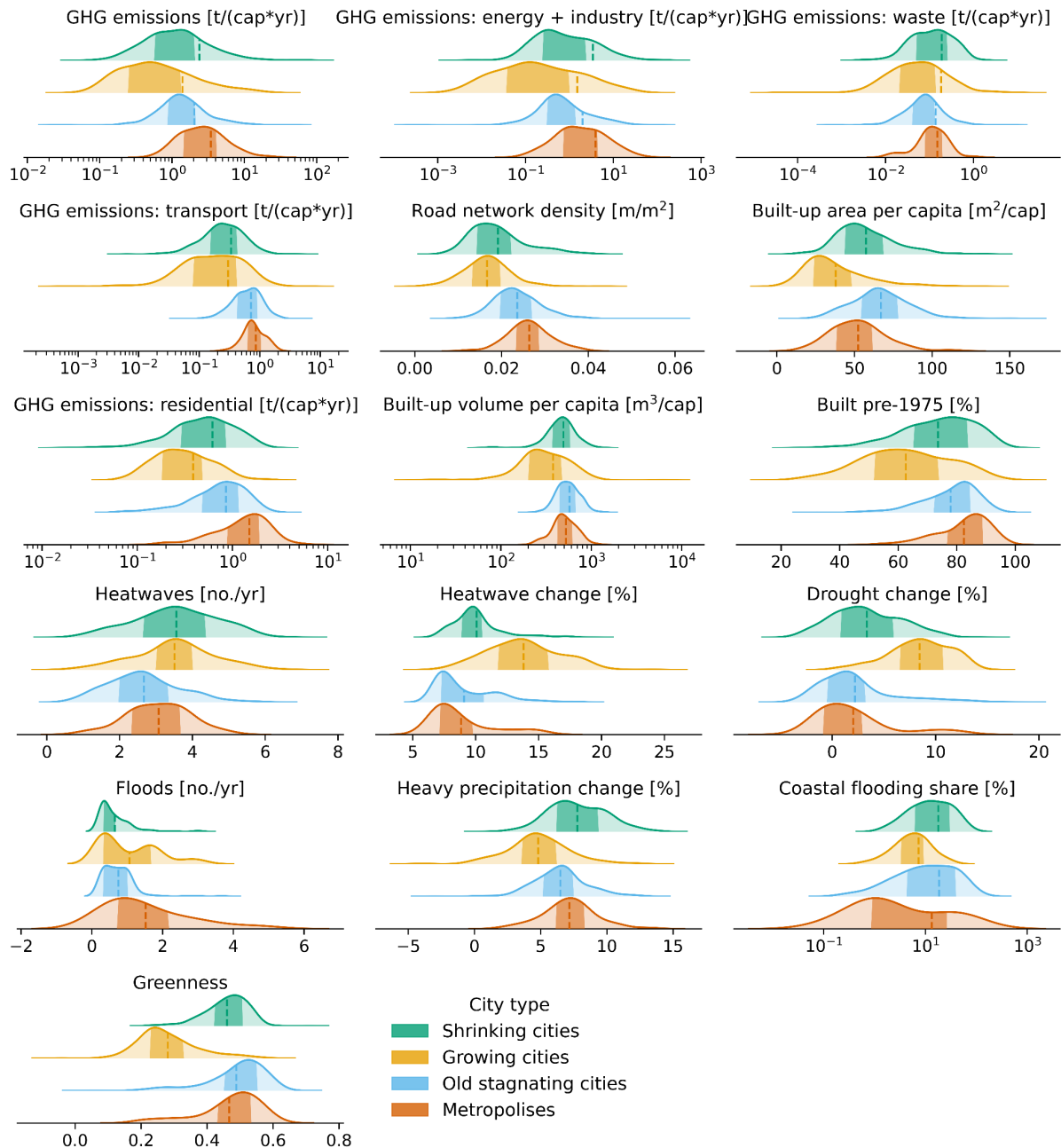


Figure 2: Distribution of city types across indicators for need to mitigate and adapt to climate change including GHG emissions, built environment and climate hazards. Change in heatwaves, droughts and heavy precipitation refers to a +2°C global warming level above pre-industrial conditions compared to event occurrence and intensity between 1980-2010; coastal flooding share refers to the percentage of urban area flooded in 2050 under RCP8.5. The solid line describes the kernel density estimate based on the number of cities. The dashed vertical lines describe the arithmetic mean for each type. The shaded area displays the interquartile range for each type.

3.2.2. Capacity for climate action: economic, demographic and political power

To mitigate and adapt to climate change, cities require power and capacity for change. Low-carbon technologies and climate resilient infrastructures require investment capacity and a skilled workforce for implementation (Lim, Aklin and Frank, 2023), behavioral change is dependent on stable political and administrative power to establish new norms and enforce regulation (Sohail *et al.*, 2022; Behera, Behera and Sethi, 2024), or on residents which are willing to change and technologies which are able to spread social norms (Bastida *et al.*, 2019; Nielsen *et al.*, 2026). Attempts to quantify this capacity for change are always incomplete, yet they can provide a first indication of the challenges at hand.

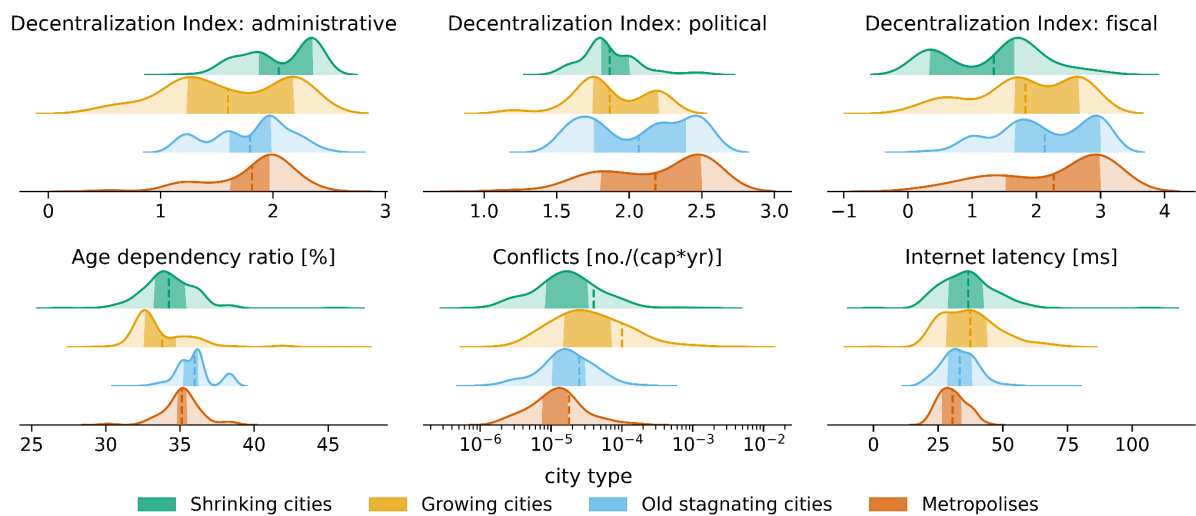


Figure 3: Distribution of city types across indicators for capacity to mitigate and adapt to climate change including municipal decision-making power represented by the decentralization index, workforce availability, conflict events (including riots, battles, violence against civilians, explosions and remote violence) and internet connectivity. The decentralization index only represents cities that are part of the European Union member states. The solid line describes the kernel density estimate based on the number of cities. The dashed vertical lines describe the arithmetic mean for each type. The shaded area displays the interquartile range for each type.

Growing cities and Shrinking cities have limited capacity to act on climate change. These cities tend to have a lower per-capita GDP (Figure 1), while also having less fiscal and political independence from national governments –at least for those cities that are part of the European Union– (Figure 3) which is complicating investments and regulation. Internet speed tends to be slower in these cities which may complicate digital climate actions such as smart energy demand flexibility or early warning systems. Growing cities additionally tend to have lower administrative independence from national governments and face more frequent conflicts such as riots, battles and violence against civilians which may diminish political stability. Shrinking cities in contrast have relatively independent well-staffed local administrations and less conflict events. Both Growing and Shrinking cities, however, also have faster growing economies and a larger working

age share of the population which can support investments and implementation of climate actions.

Old stagnating cities tend to have more political and fiscal independence from national governments as well as less conflicts and a higher per capita GDP which could support local investments and regulation for climate action. However, the ageing population in these cities means that a lower share of the population is of working age and potentially a lower share of the population willing to change their behavior (Heckhausen, Wrosch and Schulz, 2010).

Metropolises and economic centers tend to have the highest political and fiscal independence, the highest internet speeds and the highest per-capita GDP in combination with a low incidence of conflicts which is supporting investments, regulation and digital climate actions.

3.3. Knowledge on climate actions by city type

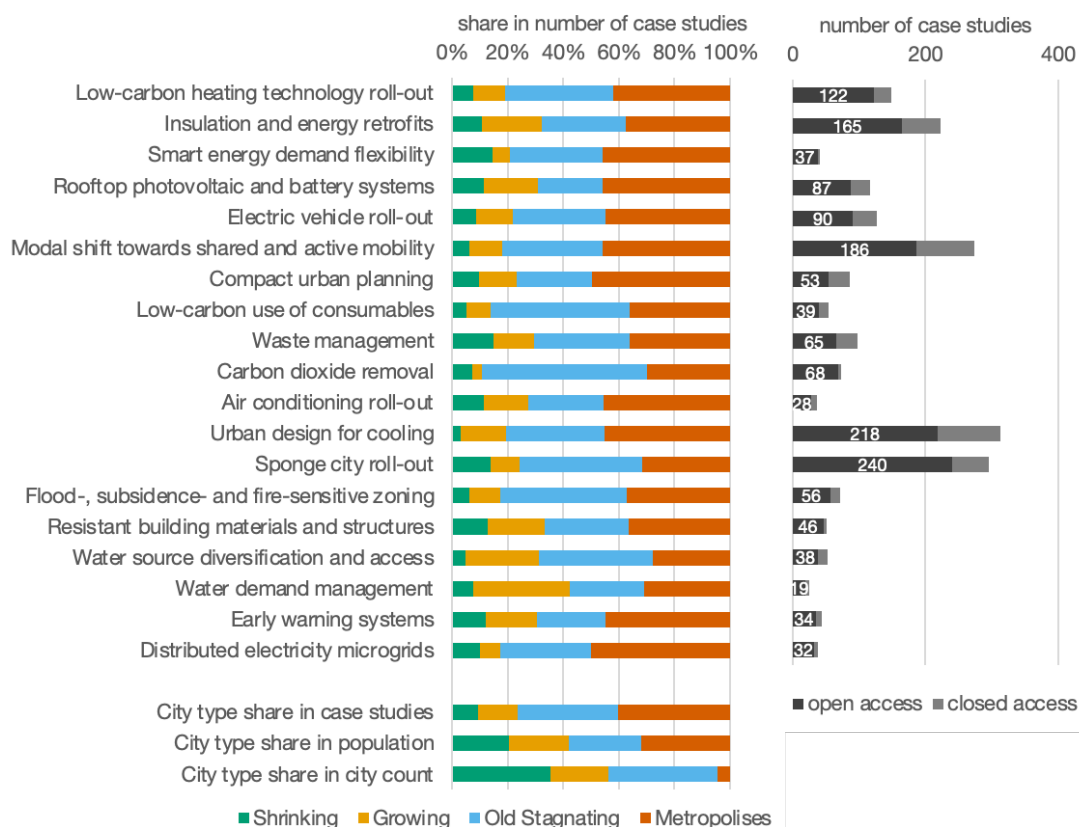


Figure 4: Number of case studies per climate action and distribution across city types.

Literature on urban climate actions is unevenly spread across city types. Case studies cover Metropolises and economic centers and Old stagnating cities considerably more than the share of these city types in population and city count (Figure 4). In contrast, very few studies assess climate actions in Shrinking cities. Additionally, case study coverage varies by climate action. Only for some climate actions, there is sufficient literature to

make qualified statements on differences in climate action effectiveness and implementation. For most climate actions assessed, the differences in effectiveness due to diverging technological alternatives or modelling assumptions between studies are greater than differences between city types. Therefore, we focus on factors affecting effectiveness rather than quantitative differences in effectiveness. Table 2 summarizes the differences in climate action implementation and factors affecting effectiveness between city types as reported in the case study literature.

3.3.1. Type 1: Shrinking cities

We find only comparably few studies covering climate actions in cities that fall into the Shrinking cities cluster. While Shrinking cities comprise 20% of the European population, only 10% of the identified studies cover these cities (Figure 4). In particular, there is limited coverage of behavioral climate actions such as low-carbon consumption and modal shift and of water management and urban cooling strategies in these cities. In contrast, studies on flood protection, waste management, resistant building practices and smart energy demand flexibility are comparably often situated in Shrinking cities.

Climate actions such as building insulation, waste and water management in Shrinking cities tend to be driven by top-down national or EU regulation which prescribe standards for energy efficiency (Nooraei, Littlewood and Evans, 2013; Beihmanis and Rosa, 2016; Zawada and Starostka-Patyk, 2016; Grynning, Gaarder and Lohne, 2017; Loli, Bertolin and Kleiven, 2019; Burmaka *et al.*, 2020; Jekabsone, Kamenders and Rosa, 2020; Kutty, Barakat and Khoukhi, 2023; Çakıcı and Takva, 2023), fuel standards (Todoruț, Cordoș and Iclodean, 2020; Bartłomiejczyk and Połom, 2021; Połom and Wiśniewski, 2021), early warning (Chen *et al.*, 2018; Pfeifer *et al.*, 2020), waste management (Trombin *et al.*, 2017; Boer *et al.*, 2021; Milovanovic *et al.*, 2021), and water treatment (Dura *et al.*, 2010; Ertugay and Bulut, 2022). The implementation of climate actions is often pursued by public utilities which control centralized systems such as district heating (Rušeljuk *et al.*, 2020; Garrido-Marijuan *et al.*, 2021; Melsted, 2021; Mészáros, 2021), landfills (Trombin *et al.*, 2017; Boer *et al.*, 2021; Milovanovic *et al.*, 2021; Vaskina *et al.*, 2024) and public transport (Iclodean, Cordoș and Todoruț, 2019; Todoruț, Cordoș and Iclodean, 2020; Bartłomiejczyk and Połom, 2021; Cepeliauskaite *et al.*, 2021; Lie *et al.*, 2021; Čorejová *et al.*, 2021; Ün, 2023; King, Tråsavik and Sareen, 2024; Tokmylenko, Chernyshova and Chyzhyk, 2024). For instance, studies report that water saving in these cities is implemented through operational efficiency (Kristvik, Muthanna and Alfredsen, 2019; Ertugay and Bulut, 2022); electric vehicle roll-out through public transport electrification (Iclodean, Cordoș and Todoruț, 2019; Todoruț, Cordoș and Iclodean, 2020; Bartłomiejczyk and Połom, 2021; Lie *et al.*, 2021; Połom and Wiśniewski, 2021; Ün, 2023; Tokmylenko, Chernyshova and Chyzhyk, 2024); modal shift through public transport service expansion (Cepeliauskaite *et al.*, 2021; King, Tråsavik and Sareen, 2024); air conditioning in public transport (BiLgiLi *et al.*, 2019); and low-carbon waste management through landfill or waste processing plant upgrades (Trombin *et al.*, 2017; Milovanovic *et al.*, 2021; Vaskina *et al.*, 2024). With public implementation

of these climate actions, the focus also tends to be on enhancing provision in underserved neighbourhoods (Yatskiv (Jackiva) and Budilovich, 2017; Бытаков and Червочков, 2018; Sareen *et al.*, 2021; Ljubojević *et al.*, 2022; Trojanowska, 2022; Wójcik-Madej and Sowińska-Świerkosz, 2022; King, Tråsavik and Sareen, 2024; Koster, Van Sark and Ricker, 2024; Soczówka *et al.*, 2024). Stakeholder acceptance is reported as critical for uptake of photovoltaics (Bazan-Krzywoszańska *et al.*, 2018; Gradziuk and Gradziuk, 2020; Kairisa *et al.*, 2022; Mrówczyńska *et al.*, 2022; Oliveira, Sousa and Kotoviča, 2022), electric vehicles (Bartłomiejczyk and Połom, 2021; Ün, 2023; Soczówka *et al.*, 2024) and modal shifts (Haarstad, 2016; Yatskiv (Jackiva) and Budilovich, 2017; Øksenholt and Tennøy, 2020; Sareen *et al.*, 2021), and some urban planning interventions (Trojanowska, 2022; Oleynikov, Arslan and Pertsev, 2023; Senior *et al.*, 2023) with limited examples of successful stakeholder engagement formats (Haarstad, 2016; Gradziuk and Gradziuk, 2020; Oliveira, Sousa and Kotoviča, 2022; Trojanowska, 2022). This centralized approach together with limited availability of private funds means that public funding or international loans are required for investments in low-carbon heating technologies (Stritih, Zavrl and Paksoy, 2019; Rušeljuk *et al.*, 2020; Melsted, 2021; Wrana *et al.*, 2022), photovoltaics (Gradziuk and Gradziuk, 2020; Mrówczyńska *et al.*, 2022; Koster, Van Sark and Ricker, 2024), smart energy management systems (Mészáros, 2021; Čorejová *et al.*, 2021), electric vehicles (Iclodean, Cordoş and Todoruţ, 2019; Todoruţ, Cordoş and Iclodean, 2020; Bartłomiejczyk and Połom, 2021; Połom and Wiśniewski, 2021), waste management (Trombin *et al.*, 2017; Vaskina *et al.*, 2024) and flood protection (Thodesen, Time and Kvande, 2022; Musz-Pomorska, Widomski and Gołębiowska, 2024).

In line with this, costs are reported as key mediators of co-benefits and trade-offs with high capital cost often hindering implementation but operational cost savings or real estate value upgrades motivating adoption (Kändler *et al.*, 2018; Jekabsone, Kamenders and Rosa, 2020; Čorejová *et al.*, 2021; Mrówczyńska *et al.*, 2022; Kutty, Barakat and Khoukhi, 2023; Musz-Pomorska, Widomski and Gołębiowska, 2024). Next to costs, studies on Shrinking cities frequently mention reduced air, water and soil pollution as co-benefits of climate actions such as low-carbon heating (Kazjonovs *et al.*, 2014; Hast *et al.*, 2018; Melsted, 2021; Wrana *et al.*, 2022), building insulation (Zawada and Starostka-Patyk, 2016; Mrówczyńska *et al.*, 2020; Jaradat *et al.*, 2023), photovoltaics (Bektaş Ekiçi, 2016; Bazan-Krzywoszańska *et al.*, 2018; Gradziuk and Gradziuk, 2020; Mrówczyńska *et al.*, 2022; Koster, Van Sark and Ricker, 2024), electric vehicles (Iclodean, Cordoş and Todoruţ, 2019; Bartłomiejczyk and Połom, 2021; Ün, 2023; Soczówka *et al.*, 2024; Tokmylenko, Chernyshova and Chyzhyk, 2024), waste management (Hung and Solli, 2012; Trombin *et al.*, 2017; Boer *et al.*, 2021; Milovanovic *et al.*, 2021; Vaskina *et al.*, 2024) and water management (Ertugay and Bulut, 2022), as well as green space expansion as part of flood-protection (Kristvik, Muthanna and Alfredsen, 2019; Opania and Marques, 2021; Ljubojević *et al.*, 2022), carbon dioxide removal (Karamova *et al.*, 2023) or urban cooling initiatives (Костюков and Зеленяк, 2019; Maksymenko *et al.*, 2022; Güller and Toy, 2024).

3.3.2. Type 2: Growing cities

In line with the rising water scarcity in Growing cities in Southern Europe, literature on these cities contains comparably many studies on water management, wildfire and drought forecasting. Further, building-related climate mitigation including rooftop PV, insulation, green roofs and heat-resistant materials is comparably more covered with case studies on Growing cities. Specific themes that are unique to this group of cities include desalination as an option for increasing water security and the cooling co-benefits of insulation. There is less literature on flood protection measures such as sponge-city roll out or zoning as well as low-carbon technologies including EVs, low-carbon heating and smart metering.

Similar to Shrinking cities, implementation of insulation (Loukaidou, Michopoulos and Zachariadis, 2017; Cirrincione *et al.*, 2019; Finamore, 2019; Ruiz-Pérez *et al.*, 2019; Buckley, Mills and Fealy, 2020; Jiménez Mejía, Barbero-Barrera and Rodríguez Pérez, 2020; Mercader-Moyano, Esquivias and Muntean, 2020; Soutullo *et al.*, 2020), waste management (Cirrincione *et al.*, 2022; Dağlıoğlu *et al.*, 2024), water source diversification (Expósito, 2019; Jodar-Abellan, Fernández-Aracil and Melgarejo-Moreno, 2019; Hernández-Hernández, Olcina and Morote, 2020; Cauteruccio and Lanza, 2023; Kilinc *et al.*, 2023; Muhammetoglu *et al.*, 2023) and early warning systems (Gil Cuesta *et al.*, 2017; Hunt *et al.*, 2017; Santos *et al.*, 2020; Cervigón *et al.*, 2024) in these Growing cities tends to be driven by national or EU regulation and standards, and high capital investments for water management (Berardi and Giustolisi, 2016; Yoon, Sauri and Rico Amorós, 2018; Jodar-Abellan, Fernández-Aracil and Melgarejo-Moreno, 2019), heat pumps (Abokersh *et al.*, 2021; Testasecca *et al.*, 2023; Yu *et al.*, 2023), and EVs (Karapidakis *et al.*, 2021; Charly *et al.*, 2024) present a challenge often relying on national or EU funds. Also lower-cost urban planning options such as compact mixed-use development (Shoina *et al.*, 2024), urban agriculture (Puigdueta *et al.*, 2021; Basso, Biagi and Crupi, 2022) and green spaces (Jorge, 2021; Katsavounidou, 2021; Sturiale, Scuderi and Timpanaro, 2023; Bagiouk, Sotiriadis and Katsifarakis, 2024) face financial constraints relying on EU and international funding for pilots. The case study literature on low-carbon technologies (heating, EVs, smart energy management) in these cities tends to be dominated by studies that explore technological options rather than investigating coordinated roll-out and upscaling. Even for photovoltaics with ample case study coverage and cost-efficiency due to the higher amount of sunshine in Growing cities, studies report a lack of finance models for upscaling (Chatzigeorgiou and Martinopoulos, 2023; Coşgun *et al.*, 2024). The warmer climate in these cities makes heating-related climate mitigation such as insulation and heat pumps less cost-effective and also limits the GHG emission reducing effectiveness compared to other city types (Delmastro *et al.*, 2017; Valdiserri and Biserni, 2018; Stritih, Zavrl and Paksoy, 2019). Investments in infrastructures in these cities tend to expand service provisioning as for instance in the case of unmanaged waste (Dağlıoğlu *et al.*, 2024; Pence *et al.*, 2024), limited water systems (Yoon, Sauri and Rico Amorós, 2018; Expósito, 2019; Hernández-

Hernández, Olcina and Morote, 2020; Kilinc *et al.*, 2023) (Yoon 2018, Expósito 2019, Kılınç 2023, Hernández 2020) or heating (Buckley, Mills and Fealy, 2020; Mercader-Moyano, Esquivias and Muntean, 2020; Soutullo *et al.*, 2020) rather than replace inefficient technology.

Tourism acts as an important motivator for climate adaptation in these cities. For instance, water reuse is motivated by increasing supply for tourism (Yoon, Sauri and Rico Amorós, 2018; Kilinc *et al.*, 2023), and nature-based solutions for flood protection and cooling are promised to increase attractiveness for tourism (Velibeyoğlu, Yazdani and Baba, 2018; Calia *et al.*, 2021; Sánchez-Almodóvar *et al.*, 2023). In line with this, the maintenance of place identity in building-related interventions such as insulation and resilient building materials is a central concern (Olğün and Karatosun, 2019; Şatiroğlu, DiNçer and Korgavuş, 2023; Sipahi and Sipahi, 2024). Reduced water pollution for instance of bathing waters (Hernández-Hernández, Olcina and Morote, 2020) is valued as a co-benefit of water management, sponge-city roll-out and waste management, while modal shifts (Hynes *et al.*, 2018; Migliore, D’Orso and Caminiti, 2020; López-Lambas, Sánchez and Alonso, 2021; Tarriño-Ortiz *et al.*, 2021; Gonzalez, Gomez and Vassallo, 2022; Arias-Molinares *et al.*, 2023; Mylonakou *et al.*, 2023; Royo *et al.*, 2023; Tercan, 2023; Campisi *et al.*, 2024; Morillas *et al.*, 2024; Moslem, 2024) and electric vehicles (Brady and O’Mahony, 2011; Efthymiou *et al.*, 2017; Marino *et al.*, 2020; Karapidakis *et al.*, 2021; Konstantinidis, Karapidakis and Paspatis, 2022; Sennefelder, Martín-Clemente and González-Carvajal, 2023; Charly *et al.*, 2024) are recognized to reduce local air and noise pollution. Still, local air pollution trade-offs are also mentioned in a few studies for instance related to rerouted traffic related to pedestrianization (Sanchez-Flack *et al.*, 2019), congestion in compact urban development (Tsirigoti and Tsikaloudaki, 2018) or reduced ventilation from street trees (Sylliris, Papagiannakis and Vartholomaos, 2023).

3.3.3. Type 3: Old stagnating cities

There is abundant case study literature on climate actions in Old stagnating cities. While these cities comprise 26% of the European population, 35% of the identified studies cover Old stagnating cities (Figure 4) suggesting considerable potential for cross-city learning. In particular, case studies on carbon dioxide removal, flood protection, low-carbon consumption, modal shifts and low-carbon technologies such as heat pumps and smart energy demand flexibility feature more prominently with this city type. In contrast, compact urban planning, air conditioning, rooftop PV and early warning systems feature more prominently with other city types. In contrast, compact urban planning, air conditioning, rooftop PV and early warning systems feature more prominently with other city types.

Literature on climate action implementation in Old stagnating cities is particularly rich in mentions of participation and resident awareness as pre-conditions for climate action implementation since climate actions are often connected to individual household decisions. For instance, low-carbon heating (Baborska-Narozny *et al.*, 2020;

Rossknecht and Airaksinen, 2020; Yang *et al.*, 2022; Salite *et al.*, 2024), insulation (Broto, 2015; Zavrl and Stegnar, 2017; Verellen and Allacker, 2022; Kalmár *et al.*, 2024), heat-stress mitigation (Osborne and Alvares-Sanches, 2019; Lavtižar, Fikfak and Fink, 2023; López-Maciel *et al.*, 2023; Wang, Scott and Dallimer, 2023) and photovoltaics roll-out (Matschoss and Heiskanen, 2017; Caprioli, Bottero and De Angelis, 2020; Massano *et al.*, 2023)(Caprioli 2020, Matschoss 2017, Massano 2022) is related to individual homeowners changing technologies, issuing building retrofits and installing green roofs; consumers are expected to decide for private electric vehicles (Aasness and Odeck, 2015; Cellina *et al.*, 2016; Milligan *et al.*, 2019; Bienias, Kowalska-Pyzalska and Ramsey, 2020; Wangsness, Proost and Rødseth, 2020), switch modes using mobility management apps (Pratelli *et al.*, 2020; Namoun *et al.*, 2021; Ruiz-Varona, Blasco-Cubas and Iglesias-Soria, 2023), and adopt new consumption habits guided by environmental behavioural campaigns (Cuomo, Lambiase and Castagna, 2021; Pitkänen *et al.*, 2022; Brock, Williams and Kemp, 2023; Lange *et al.*, 2024); low-carbon waste management practices focus on source separation in households (Kuusiola, Wierink and Heiskanen, 2012; Thomsen *et al.*, 2018; Eaton *et al.*, 2022; Vanhuyse *et al.*, 2022); and household-scale rainwater harvesting (Styś and Stec, 2015; Csete, Kolcsár and Gulyás, 2021; Carpio-Vallejo *et al.*, 2024) and water saving measures (Topi, Esposto and Marini Govigli, 2016; Bryan *et al.*, 2019) are evaluated. In line with this, many studies evaluate and test co-creation schemes of climate actions that also address vulnerable groups, and highlight the corresponding social co-benefits (Matschoss and Heiskanen, 2017; Pardo-Bosch, Cervera and Ysa, 2019; Cuomo, Lambiase and Castagna, 2021; Krzeptowska-Moszkowicz, Moszkowicz and Porada, 2022; Medina-García *et al.*, 2022; Schaefer, 2022; Onencan, Ou and De Koning, 2024; Salite *et al.*, 2024). For climate actions with strong co-benefits such as modal shifts (Saidla, 2018; Karjalainen, 2024)(Karjalainen 2024, Saidla 2016), urban agriculture (Jakobsen, 2011) and urban green space expansion (Kristiánová, Gécová and Putrová, 2016; Trovato, 2021; Willems *et al.*, 2021; Beaumont *et al.*, 2022) citizen initiatives are reported to have initiated the implementation. At the same time, reduced access to services for low-income households or tenants as a consequence of tariff schemes such as Low Emission Zones (Santos *et al.*, 2020; Allan, Waite and Roy, 2023), environmental behavioural campaigns (Medina-García *et al.*, 2022; Pitkänen *et al.*, 2022; Lange *et al.*, 2024), green gentrification (Tubridy, 2020; Hunter *et al.*, 2022; Pacetti *et al.*, 2022; Palliwoda *et al.*, 2022; Tate *et al.*, 2023; Zhou, Galway and Megarry, 2023; Neidig *et al.*, 2024) and heating technology investments (Himpe, Janssens and Rebollar, 2015; Baborska-Narozny *et al.*, 2020; Onencan, Ou and De Koning, 2024; Salite *et al.*, 2024) are a key concern. For building insulation, the potential co-benefits in reducing energy poverty are highlighted (Gupta, 2009; Boeri, Gianfrate and Longo, 2016; Pardo-Bosch, Cervera and Ysa, 2019).

Heritage conservation and old building stocks in these old towns presents a key barrier and challenge for implementation of building-related climate actions such as insulation (Büttner and Rink, 2019; Vandemeulebroucke *et al.*, 2019; Gibb, 2023), green

roofs (Joshi *et al.*, 2020; Marvuglia, Koppelaar and Rugani, 2020; Vojvodíková, Tichá and Starzewska-Sikorska, 2022), flood-resistant designs (Bradecki and Konsek, 2020), air conditioning (Balocco and Marmonti, 2012; Belleri, Avantaggiato and Lollini, 2017), district heating expansion (Büttner and Rink, 2019; Alimonti, Vitali and Scrocca, 2023), and photovoltaics (Roosmalen and Gritzki, 2020). Similarly, the fixed urban structure in combination with some not-in-my-backyard attitude present challenges for optimizing urban layouts for lower transport demand (Bulkeley and Betsill, 2005; Næss, 2014; Kohler *et al.*, 2017; Gillott, Davison and Densley Tingley, 2022) and placing storage infrastructures for flood protection (Pacetti *et al.*, 2022; Masi *et al.*, 2023), waste separation (Buzjak, Vuk and Jakovcic, 2015; Masella *et al.*, 2018; Valero *et al.*, 2021), carbon capture and storage (Kühn *et al.*, 2017; Stephenson *et al.*, 2022) and electric vehicles (Melo, Baptista and Costa, 2014; Aasness and Odeck, 2015; Cellina *et al.*, 2016; Braun and Rid, 2017; Milligan *et al.*, 2019; Bienias, Kowalska-Pyzalska and Ramsey, 2020; Thorne *et al.*, 2021).

3.3.4. Type 4: Metropolises and economic centers

Similar to Old stagnating cities, case study literature evaluating climate actions in Metropolises and economic centers (short: Metropolises) is abundant. In particular, case studies on transport-related climate mitigation such as modal shifts and compact urban development, low-carbon and climate adaptive technologies including electric vehicles, photovoltaics, electricity microgrids, air conditioning and low-carbon heating, as well as digital actions including early warning systems and smart energy demand flexibility are frequently situated in Metropolises. In contrast, there is comparably less coverage of water management, flood protection or carbon dioxide removal in Metropolises.

Metropolises are frequently portrayed as high-ambition environmental performers where climate action is guided by dedicated municipal targets and frameworks (Kokx and Spit, 2012; Pan *et al.*, 2020; Revich *et al.*, 2020; Simperler, Ertl and Matzinger, 2020; Ajanovic, Siebenhofer and Haas, 2021; Badura *et al.*, 2021; Ten Caat *et al.*, 2021; Verheij and Corrêa Nunes, 2021; Bastida-Molina *et al.*, 2022; Busker *et al.*, 2022; López Plazas *et al.*, 2023; Magrinyà, Mercadé-Aloy and Ruiz-Apilánez, 2023; Nóbrega-Carriquiry, March and Sauri, 2023; Schröder *et al.*, 2023), sometimes conflicting with slower evolving national policy (Drummond, 2021). The large administrative jurisdictions of Metropolises mean that single decisions and public procurement can be highly effective in scaling climate actions such as the case with low-emission zones (Crocì, 2016; Drummond, 2021; Attia, Alade and Attia, 2023), transit-oriented development (Bhagwati and Kumar, 2024), sustainable food procurement (Berner *et al.*, 2019; Chiaverina *et al.*, 2023), landscaping and de-sealing initiatives (Giezen and Pellerey, 2021; Reinwald *et al.*, 2021; Addabbo *et al.*, 2023; lungman *et al.*, 2025), environmental modelling for early warning (Carbone *et al.*, 2014; Yi, Peng and Robinson, 2023) and concept-based development tenders for low-carbon or resilient buildings (Hafner, 2017; Hafner, Slabik and Storck, 2020; López Plazas *et al.*, 2023).

However, the high population and building density of Metropolises can also lead to capacity limitations for scaling as in the case of required grid reinforcement for electric vehicle roll-out (Bastida-Molina *et al.*, 2022; Carranza *et al.*, 2022; Straub *et al.*, 2023) or high-density geothermal energy use that can damage soil ecosystems and sub-soil infrastructure (Zhu *et al.*, 2010; Terrington *et al.*, 2019; Korhonen *et al.*, 2023). Compact urban development in these already dense settlements focuses on mixed use and urban infill (Caparros-Midwood, Dawson and Barr, 2019; Vuckovic *et al.*, 2019; Nickayin *et al.*, 2020; Erlwein and Pauleit, 2021; Gaglione *et al.*, 2022; Wilhelmsson, 2023). Limited space is also a key dimension moderating co-benefits and trade-offs with modal shifts being recognised to hold potential for green space expansion and noise reduction (Skayannis, Goudas and Rodakinias, 2017; Werner, Resch and Loidl, 2019; Caravaggi, Imbroglini and Lei, 2022; Gouveia, Dias and Silva, 2023; Hahn, Pakusch and Stevens, 2023; Magrinyà, Mercadé-Aloy and Ruiz-Apilánez, 2023; Mishra *et al.*, 2023; Schröder *et al.*, 2023; Frago and Morcuende, 2024; Sanchez-Sepulveda *et al.*, 2024), photovoltaics being implemented with green roofs (Toboso-Chavero *et al.*, 2021; Fassbender *et al.*, 2022; Slootweg *et al.*, 2023), and green and blue infrastructure recognized to contribute to mitigating the urban heat island effect (Vasilevska and Vasilevska, 2019; Johnson, Exl and Geisendorf, 2021; Gargiulo and Zucaro, 2023; Wild, Fuchs and Davis, 2024) and offer spaces for attention restoration (Mittermüller *et al.*, 2021; Piga *et al.*, 2021; Scharf *et al.*, 2021; Barseghyan *et al.*, 2023; López Plazas *et al.*, 2023; Conte *et al.*, 2024).

As Metropolises are complex systems with large administrations and specialized expertise, multi-actor and cross-departmental coordination is highlighted as a common implementation challenge by studies across climate actions (Csete and Buzasi, 2016; Zach, Kretschmer and Stoeglehner, 2019; Neumann *et al.*, 2021; Rolim and Baptista, 2021; Föllmi *et al.*, 2023; Gouveia, Dias and Silva, 2023; Shah, Jaya and Piludaria, 2023). Metropolises are also characterized by strong civil society organizations demanding fairness (Momm-Schult *et al.*, 2013; Loorbach *et al.*, 2021; Verbeek and Hincks, 2022; Yazar *et al.*, 2023) or piloting climate actions (Murota, 2014; McLeod and Swainson, 2017; Simperler, Ertl and Matzinger, 2020; Novosadová and Van Der Knaap, 2021; Verheij and Corrêa Nunes, 2021; Chiaverina *et al.*, 2023) which strengthens the case for municipal co-creation. Finally, as economic centers, Metropolises can often rely on private participation in investments and win national funding tenders (Gardi *et al.*, 2016; March and Ribera-Fumaz, 2016; Dantas, Nagy and Nogueira, 2022; Yazar *et al.*, 2023; Kaandorp *et al.*, 2024) enabling technological innovation and climate action implementation.

Table 2: Differences and commonalities in climate action effectiveness, feasibility, co- benefits and trade-offs between city types.

Actions	Types of actions assessed	Effectiveness	Factors affecting effectiveness	Feasibility	Co-Benefits	Trade-offs
Low-carbon heating technology roll-out	Type 1: various technologies including district heating, heat pumps, solar thermal Type 2: heat pump integration in district heating systems and individual buildings Type 3: ideal pathways towards full heating decarbonization Type 4: niche heating technologies (e.g. combined photovoltaic thermal, aquifer thermal energy storage, nuclear combined heat and power plant)	more effective in colder cities (e.g. Type 1 and 3) than warmer cities (e.g. Type 3)	climate: heating degree days infrastructure: presence of district heating network buildings: composition of building stock governance: municipal cooperation for district heating policy: national regulation and financial incentives behaviour: heating and building occupancy practices	across Types: policy and technology Type 1: finance dependent on state funding or international loans Type 2: technological options explored Type 3: participation of homeowners needed Type 4: cross-departmental and multi-stakeholder coordination	across Types: lower operating cost Type 1: cleaner urban air due to avoided solid fuel heating	Type 2: payback time exceeding lifetime Type 3: energy poverty risk for households without investment capacity Type 4: environmental impacts of high-density geothermal energy use
Insulation and energy retrofits	Type 1: combined building envelope and heating technology retrofit, window replacement, phase change materials Type 2: building envelope insulation, adaptive reuse, water pipe insulation Type 3: combined building envelope insulation, mechanical ventilation, photovoltaics and heating technology retrofit Type 4: district or city-scale scenarios of building envelope insulation	more effective in colder cities (e.g. Type 1 and 3) than warmer cities (e.g. Type 3)	climate: heating degree days, humidity, solar radiation buildings: typology and age composition of building stock; energy efficiency technology: installed ventilation and heating technology policy: energy efficiency standards, heating price regime; fossil phase out targets; material cost behaviour: indoor set point temperature; building occupancy; owner engagement capacity: skilled workforce for installation geology: earth quake risk	across Types: policy and technology Type 1: implementation in response to top-down national and EU regulation; economic incentives guide implementation Type 2: implementation in response to top-down regulation; local availability materials and construction techniques Type 3: participation of homeowners and training of crafts people needed Type 4: cross-departmental and multi-stakeholder coordination	Type 1: cleaner urban air due to avoided solid fuel heating Type 2: improved thermal comfort in winter and summer Type 3: reduced fuel poverty and improved thermal comfort	Type 1: investment challenge for homeowners Type 3: overheating and mold risk due to air tightening; gentrification
Smart energy demand flexibility	Type 1: smart energy infrastructure, smart meters, dynamic tariffs, sub-metering with feedback Type 2: energy management platform, building efficiency, mobility app Type 3: smart metering, smart grids, energy communities, Energy Management Systems (EMS), ancillary markets, peak shaving, HVAC control, smart lighting Type 4: smart grids, smart buildings, smart meters, smart data platforms, EMS, intelligent district heating control, sub-metering, open data hubs, digital twin, peer-to-peer	limited quantified GHG reductions; energy savings 31-59% (sub-metering); building/district-level savings in Type 3-4	behaviour: socio-economic status, digital literacy, user acceptance, motivation regulation: ARERA, EU Clean Energy Package, UK centralisation, FIT phase-out, GDPR data privacy technology: interface design, interoperability, data quality, 2G meter interfaces prices: dynamic tariffs, time-of-use cooperation: energy communities, trust in utilities infrastructure: smart grid deployment, data standards climate: outdoor temperature, heating demand	across Types: policy and technology Type 1: finance dependent on state funding or international loans Type 2: technological options explored; citizen dialogue enables; municipal competency hampers Type 3: participation of homeowners and tenants needed; tenant non-consent blocked rollout Type 4: cross-departmental and multi-stakeholder coordination; Smart Energy Code (SEC) complexity; skills gaps limit local agency	across Types: cost reduction, switching, savings; jobs, operational efficiency Type 1: cost reduction, switching; empowerment, participation Type 2: GDP, investment; quality of life; lower temperatures, renewables Type 3: jobs, cost reduction; engagement; air quality Type 4: jobs, efficiency; quality of life, trust; air quality	Type 1: costly licenses, favouring higher-income; exclusion, digital divide Type 2: upfront costs, low-emission zone restrictions Type 3: energy poverty risk; digital divide; IAQ from ventilation DR; tenant refusal blocked rollout Type 4: environmental impacts of data infrastructure; gentrification; rent increases; Smart Energy Code (SEC) complexity
Rooftop photovoltaic roll-out	Type 1: energy storage or heating-integrated photovoltaics (PV) Type 2: utility scale PV, solar green roofs and niche applications (vehicle, floating) Type 3: bare rooftop PV and PV-solar thermal energy applications Type 4: heating-integrated PV, facade PV, solar green roofs, community managed, niche applications (vehicle, road, parking, roof-integrated)	more effective in cities with more sunshine (e.g. Type 2) and higher-emission grid electricity mix to be replaced but no clear city type distribution	climate: solar radiation, sunshine duration, snow cover, temperature buildings: composition of building stock, roof geometries settlement structure: street canyon geometry infrastructure: grid connection capacity, storage capacity, efficiency of available panels policy: feed-in-tariffs, permits, subsidies/loans, , dissemination campaigns socio-economics: trained workforce, income geology: earthquake risk governance: professional collaboration	across Types: technology mature; feed-in-tariff regime influences uptake Type 1: public, private, international loans and carbon credits as investment resource; resident participation is steered with stakeholder consultation formats Type 2: short payback time supports private investment, but finance models needed for faster upscaling Type 3: information campaigns and peer effect support uptake; municipal investments and piloting; cross-departmental coordination in municipality Type 4: inter-municipal collaboration; public-private partnerships for investment; tensions with national regulation	across Types: operational cost-savings and revenue generation Type 1: improves electricity access for underserved neighbourhoods and households; clean urban air due to avoided solid fuel use Type 2: agrivoltaics and solar green roofs reduce water stress Type 3: reduces transmission cost for operator; energy communities generate local revenue; job creation	across Types: lower-income households require support for investment Type 3: renters excluded from investment decisions; unstable subsidies affect affordability Type 4: lower albedo and windshading may aggravate urban heat island effect; owner-tenant conflicts; risk of green gentrification; environmental harms in supply chain
Electric vehicle roll-out	Type 1: public transport electrification Type 2: city-scale scenarios for private vehicles Type 3: city-scale scenarios for private vehicles Type 4: city-scale scenarios	observed differences more due to different technological alternatives and modelling assumptions than between city types	infrastructure: electricity generation mix, grid infrastructure, charging infrastructure availability settlement structure: topography and winter conditions behaviour: driving style, trip scheduling regulation: fleet emission and electrification standards, procurement, fuel pricing	across Types: dependence on subsidies and public co-finance Type 1: reliance on national or EU funds; public acceptance hindering uptake Type 2: limited space for charging and grid infrastructure; public acceptance hindering uptake Type 4: climate targets, vehicle standards and large scale public procurement driving uptake	Type 1: cleaner urban air and reduced noise, enhanced accessibility, equity in underserved neighbourhoods Type 2: cleaner urban air and reduced noise, operational cost savings	Type 1: health risks of upstream carbon-intensive electricity generation Type 2: affordability concerns about capital investment Type 3: high capital cost, reduced user convenience Type 4: charging and grid reinforcement costs
Modal shift towards shared and active mobility	Type 1: policy mixes, public transport service Type 2: bus service expansion, space allocation for active mobility, campaigns, bike/carsharing, Madrid low-emission zone Type 3: active mobility infrastructure, mobility management apps, last-mile logistics Type 4: low-emission zone, congestion charging, worktrips, multimodal mobility, last-mile logistics	observed differences more due to different policy alternatives and modelling assumptions than between city types	infrastructure: public transport infrastructure and service, cycling/walking paths settlement structure: proximity and diversity of amenities, compactness, terrain behaviour: user attitudes, initial modal split, vehicle occupancy governance: local governance autonomy, multi-level alignment regulation: ambition level, planning guidelines technology: vehicle fleet, energy mix for rail, digitalization climate: snow and ice, precipitation demographics: population age	across Types: public engagement required to change user behaviour; EU air quality directives motivate adoption Type 1: limited participatory planning so far; EU programmes soft enabler Type 2: EU urban agenda policy and city network membership motivate action; hassle and distrust limits public transport adoption; educational campaigns Type 3: car-oriented planning regimes constrain; disconnect between municipal goals and visible change; citizen advocacy drives implementation; municipal and national policies support Type 4: citizen movements drive change or create opposition; tourist preferences hinders implementation; municipal strategies on environment, tourism, smart city guide implementation	across Types: environmental, social and health co-benefits of cleaner air and convivial public spaces Type 2: improved safety, lower noise and physical activity Type 3: reduced congestion, lower cost for individuals, lower health cost, enhanced access for women, elderly and children Type 4: more space for urban green and blue spaces, resource efficiency, reduced noise	Type 1: household affordability constraints for tariffs or enforcement fines; municipal budget constraints for subsidies; safety risk for active mobility if infrastructure not upgraded Type 2: local air pollution increase from buses and rerouted traffic for pedestrianization Type 4: green gentrification and displacement risk; (tourist) crowding in public transport; low-income households may not be able to pay fees or clean vehicles for LEZ entry; inequalities in access to digital tech for telecommuting
Compact urban planning	Type 1: various strategies including urban infill and master planning Type 2: new development, master planning, mixed-use, urban infill Type 3: urban infill and densification in existing city boundaries, city-level master planning Type 4: mixed use for proximity, transit-oriented development, urban infill, vertical extension, new neighbourhood development	limited quantified effects and observed differences more due to different planning alternatives than between city types	settlement structure: initial compactness, share and distribution of green and blue infrastructure buildings: diversity of building uses, destination proximity, building stock composition governance: municipal leadership and vision, master planning, landownership fragmentation market: land value, real-estate demand, population trend infrastructure: public transport accessibility behaviour: landowner attitudes, modal split, motorization rate, heating and cooling demand policy: national planning, real-estate and parking policies, local design codes and zoning	across Types: coordination across departments and with neighbouring municipalities required Type 1: dependence on cooperation with private banks for finance; low land values hinder finance; stakeholder engagement formats to generate support; lack of inter-municipal coordination Type 2: lack of inter-municipal coordination; dependence on national, EU and private funding; private financing can undermine resilience Type 3: local resistance to urban infill esp. on green space; dispersed landownership requires public-private partnerships; multi-level alignment critical Type 4: metropolitan level administrations enable implementation; heritage status constrains redevelopment; conflicts between municipal ambition and national regulation	across Types: improved accessibility of services, reduced pollution and increased land value and tax revenue Type 1: mixed-use development can generate business opportunities Type 2: reduced household transport expenses, lower infrastructure cost, strategic densification integrates underserved neighbourhoods Type 3: lower infrastructure and public health cost; proximity fosters conviviality; increased housing supply Type 4: master planning integrates underserved neighbourhoods; proximity fosters conviviality; increased housing supply	Type 2: green gentrification risk in case of private densification, congestion and exposure to air pollution, smaller dwellings, urban heat island effect Type 3: green gentrification risk; crowding in green spaces; smaller dwellings; exposure to pollution and noise Type 4: green gentrification risk; widening urban-rural divide; urban heat island effect, loss of green space access; exposure to pollution and noise

Actions	Types of actions assessed	Effectiveness	Factors affecting effectiveness	Feasibility	Co-Benefits	Trade-offs
Low-carbon use of consumables (food, clothing, etc.)	Type 1: NA only single study Type 2: urban agriculture, food procurement, eco-driving Type 3: environmental behaviour campaigns, food procurement Type 4: environmental behaviour campaigns, regionalized food supply chains, food procurement, urban agriculture	observed differences more due to different policy alternatives and modelling assumptions than between city types	behaviour: current diets and consumption habits, willingness to adapt; local production practices; community engagement; trust settlement structure: availability of open spaces infrastructure: distribution and processing hub density, community centers, digitalization local ecological capacity: soils, sunshine, humidity, water availability policy: food safety regulations, agriculture bans/permits, funding availability, municipal land-use plans, food prices, pledges governance: ownership structures; political leadership; stakeholder collaboration socio-economics: time/workforce availability, income, education level	across Types: resident engagement and skill development as prerequisites; top-down deployment can weaken participation Type 2: lack of public funding for urban agriculture; participatory planning enables procurement Type 3: EU, regional, municipal and private funding of pilots; participation fatigue; social networks maintain new norms; perceived distributional fairness shapes acceptance; facilitation skill critical for campaigns; citizen advocacy drives initiatives Type 4: citizen advocacy drives initiatives; acceptance hinges on digital literacy; EU, national and private finance of pilots; expert consultation facilitates implementation; small businesses lack time and resources for cooperation and marketing	across Types: resource and biodiversity conservation, ecosystem services from urban agriculture; community building from urban agriculture and events Type 2: environmental awareness raising; stress management; strengthened urban-rural connection Type 3: improved access to healthy food; restored connection to nature; capacity building; reduced waste; participation and agency Type 4: carbon sequestration; reduced deforestation	across Types: personal carbon budgeting can discriminate underserved residents; risk of nutritional deficiencies from dietary shift; contamination risk from farming polluted soils Type 3: vilifying behaviours can increase prejudice; frustration and distrust due to dissonance between appeals and visible change Type 4: risk excluding lower-income households in case of high-cost product alternatives
Waste management	Type 1: landfill to biogas capture, biorefinery, incineration and anaerobic digestion Type 2: unmanaged waste or incineration to recycling and anaerobic digestions Type 3: landfill or waste-to-energy incineration to organic waste treatment, carbon capture and storage, and separate waste collection Type 4: landfill to waste-to-energy incineration	observed differences more due to different technological alternatives and modelling assumptions than between city types	infrastructure: installed treatment plants to be replaced, available sorting infrastructure settlement structure: density of waste producers, storage space for separation behaviour: waste composition, public participation in waste separation policy: EU and national landfill and recycling regulation market: demand for recyclates	across Types: policy, technology, participation Type 1: limited availability of low-carbon waste management infrastructures; EU and national regulation driving uptake Type 2: limited capacity of installed infrastructure; EU regulation driving uptake Type 3: resident awareness and participation required for enhanced waste separation; specialized recycling plants costly for individual cities Type 4: resident awareness and multi-stakeholder coordination required for implementation	across Types: reduced contamination and eutrophication; recyclates replace higher cost primary raw material and energy; job creation Type 1: lower land use for landfills; avoided fires due to flue gas capture; energy security; less odour Type 2: compost replaces industrial fertilizer; less odour; lower land use for landfills Type 3: community building through sharing; minimizing food waste improves equity and food security Type 4: waste avoidance lowers waste management cost	across Types: risk of contamination of not entirely treated recyclates; longer distance transport for processing and collection diminishes emission reduction
Carbon dioxide removal	Type 1: point source carbon capture and storage (CCS), soil organic carbon management (biochar, compost) Type 2: vegetation in parks, forests and urban agriculture Type 3: vegetation; soil organic carbon (biochar, compost, wetlands); point source CCS Type 4: vegetation; soil organic carbon (biochar, compost, wetlands); building materials; DACCS	observed differences more due to different species and modelling assumptions than between city types	infrastructure: type and density of vegetation; machinery emission intensity; pipelines for carbon transport climate: temperature, precipitation, solar radiation, moisture geology: soil nutrient and clay content; underground storage capacity settlement type: greenness; compactness of the built environment; impervious surface share Behaviour: pruning practices; irrigation practices; CCS acceptance; community involvement Policy: legal conservation of green space; monitoring of CCS storage; sustainable sourcing guidelines for timber construction	across Types: emergent CCS technologies face upscaling challenges; waste separation guidelines support compost application to soils; EU funding for pilots Type 1: private funding for pilots; technical expertise demonstrated Type 3: municipal strategies and goals support vegetation expansion; criteria-based tendering for development rights as lever; coordination with private owners critical; carbon price influences uptake of CCS; citizen opposition against CCS Type 4: national funding for pilots; expert consultation for technical implementation; concept-based tendering for development rights; municipal strategies guide action; regulation lags behind innovation; underground storage may require inter-municipal or cross-national coordination; carbon credits for funding	across Type: improved thermal comfort, flood resilience, air quality, physical activity, conviviality, stress management, biodiversity, and ecosystem services related to green infrastructure Type 1: erosion protection and phytoremediation of contaminated soils from vegetation; less emission-based eutrophication from CCS Type 3: stormwater management and reduced industrial fertilizer from biochar addition Type 4: higher real estate value from greening; business opportunities	Type 1: contamination risk if compost not well sorted; methane emission from compost Type 2: monocultures for maximized uptake risk pest susceptibility Type 3: air pollution trap under street trees; light blocked through street trees; resource use and pollution from some biochar products and CCS; reduced recreational access to green spaces for optimized uptake Type 4: contamination risk if compost not well sorted; rebound from lower albedo of vegetation; irrigation cost for green roofs; lock-in of industrial processes or risk of stranded assets from high capital cost CCS; leakage risk from intermediate storage of captured carbon in dense areas
Air conditioning roll-out	Type 1: AC in public transport; few studies on building HVAC Type 2: controlled natural ventilation, insulation, heat exchanger Type 3: natural ventilation, district cooling, mechanical ventilation Type 4: solar powered chillers, mechanical ventilation, personalized ventilation, AC in public transport	observed differences more due to different technological alternatives and modelling assumptions than between city types	climate: humidity, solar radiation, temperature building: type affecting economies of scale; energy efficiency settlement structure: compactness affecting UHI Infrastructure: ventilation system, photovoltaics behaviour: building occupancy, window opening market: electricity prices	across Types: material and software requirements, relevance of regulatory frameworks; modernized or passive cooling systems can mitigate vulnerability to electricity prices Type 3: heritage regulations need to be considered for implementation Type 4: EU regulations and norms guide implementation	across Types: energy use reduction of passive cooling systems	across Types: high capital cost with long payback time, maintenance cost pose challenge, operational costs dependent on energy price
Urban design for cooling	across Types: green spaces, blue infrastructure, street trees Type 1: de-sealing, street morphology, district cooling Type 2: albedo management, street morphology, green roofs, cooling shelters Type 3: green building envelopes, de-sealing, street morphology, shading, albedo management Type 4: green building envelopes, de-sealing, shading, albedo management, street morphology, cool materials, building ventilation, cooling shelters, district cooling	limited cross-city comparative studies with quantitative results do not allow for city type comparison	settlement type: greenness, spatial distribution of green space, compactness of the built environment, building/street orientation, impervious surface, proximity to surface waters infrastructure: type of vegetation, roof load limits and shape, onsite heat emission (transport, industry), water supply for irrigation; installed chiller climate: precipitation, temperature, wind behaviour: outdoor activity, clothing, air conditioning socio-economics: age, income, gender policy: legal protection and planning standards for green space, land value and real estate speculation governance: land/building ownership, community engagement for maintenance	Across Types: citizens initiate/demand implementation; volunteering critical for green space maintenance; master plans and zoning guide implementation of green spaces Type 1: lack of technical expertise on nature based solutions; heritage protection of green spaces; resident opposition countered with co-creation Type 2: EU nature-based solutions discourse and national heat prevention policy drive adoption; limited modelling skills in municipality, crowdfunding; EU funding for pilots; top-down information and education of citizens for acceptance Type 3: local, national and EU climate adaptation plans drive adoption; private ownership presents a challenge addressed with public private partnerships or acquisition; heritage rules constrain green roofs Type 4: lack of return hinders private investment; stakeholder workshops to raise support and willingness to pay from homeowners; national funding support	across Types: improved thermal comfort, flood resilience, air quality, physical activity, stress management, biodiversity, and ecosystem services related to green infrastructure; conviviality through public spaces Type 1: energy expense savings; place identity; recreational benefits Type 2: cooling expense savings, tourist attractiveness; higher real estate value; low-cost implementation Type 3: higher real estate values and investment attractiveness Type 4: reduced noise; human-scale child-friendly spaces; green roofs as space efficient approach	across Types: air pollution trap of dense street trees; pollen pollution from vegetation Type 1: unequal access to green spaces; lack of open data for participatory decision-making Type 2: winter thermal discomfort; high albedo materials can raise pedestrian heat exposure Type 3: green gentrification risk; unequal distribution of green space; high capital cost for green building envelopes; heating rebound during winter; mosquitoes and ticks as disease vectors Type 4: water resource strain from irrigation; heating rebound during winter; groundwater contamination through permeable soils
Sponge city roll-out	across Types: nature-based solutions—green infrastructure, permeable surfaces, and water-management systems; restoration and expansion of blue-green corridors and public natural spaces Type 1: dual drainage, infiltration processes and descaling Type 2: new development corridors and areas integrating risk planning and blue and green infrastructure Type 3: urban green blue infrastructures in existing compact urban context, descaling Type 4: broad systemic measures, large sized green and blue infrastructures (rivers, waterfront, landscaping, forest and large parks development, wide descaling initiatives, large brownfield retrofit)	limited cross-city comparative studies with quantitative results do not allow for city type comparison	climate: extreme rainfall, storm intensity/duration, sea-level rise infrastructure: capacity and layout of drainage system, network connectivity, bottlenecks, existing storage and infrastructure capacity urban planning: risk mapping, emergency plans, zoning, standards settlement structure: coastal location, topography, permeable land cover governance: public-private cooperation, citizen involvement	across Types: requires embedding risk mapping in urban planning Type 1: inter-agency data sharing and coordination; EU and national funded pilots; long-term local financial planning Type 2: land use plans with default NBS implementation; investment dependent on public funding and green bonds; inter-agency collaboration, and risk mapping Type 3: municipality-citizen co-creation for public support; NIMBY challenge; financed through public funding and loans Type 4: co-creation and communication for acceptance; capacity building of urban design professionals and external expertise required for implementation; multi-stakeholder collaboration; private finance and dedicated municipal budgets; dispersed ownership of existing assets complicates large-scale projects	across Types: reducing inundation nuisance, heat stress and noise, air pollution; biodiversity; carbon sequestration; recreational benefits Type 1: public space adaptation and heritage preservation attracting real-estate investment and tourism; reducing cost of oversized drainage; Type 2: public space adaptation and heritage preservation attracting real-estate investment and tourism; nature-based solutions cost-effective alternatives to grey infrastructure; Type 3: reducing cost of water management; pollutant retention, resource protection, new amenities, wellbeing Type 4: public space adaptation and heritage preservation attracting real-estate investment; lower operational costs	Type 1: slower implementation of nature-based solutions compared to grey infrastructure; maintenance challenges; fees/rules may hinder equal access to urban green Type 2: slower implementation of nature-based solutions compared to grey infrastructure; heritage conflicts; limited engagement of vulnerable groups exacerbates inequalities in green space access Type 3: slow implementation; high upfront cost; maintenance challenges; high financial risk if poor implementation; risk of green gentrification; heritage conflicts; limited engagement of vulnerable groups exacerbates inequalities in green space access Type 4: high cost of retrofits in existing areas; high capital costs; safety concerns for open water; risk of gentrification; conflicts among users of public spaces

Actions	Types of actions assessed	Effectiveness	Factors affecting effectiveness	Feasibility	Co-Benefits	Trade-offs
Resistant building materials and structures	Type 1: subsidence/earthquake resistance; frost/fungal resistance; low-carbon materials Type 2: materials and designs for lower cooling demand, flood/moisture resistance, subsidence resistance, low-carbon materials Type 3: low-carbon materials; phase change materials; energy efficient designs; flood/moisture resistance; durability Type 4: low-carbon materials; phase change materials; cool materials; flood/waterproof materials; frost/earthquake resistance	limited quantified effects	Climate: humidity, precipitation, temperature, frost, seasonality, solar radiation Geology: earthquake risk, soil bearing capacity Buildings: building age and type composition; presence of basements Settlement structure: proximity to sea; topography; compactness; greenness for evapotranspiration Behaviour: maintenance frequency, vandalism Market: real estate value and market pressure Regulation: zoning	across Types: dependent on EU or national funds for initial investment Type 1: limited local fiscal capacity dependent on public grants, Type 2: building and design standards guide material choice; challenges in financial sustainability of maintenance Type 3: acceptance among authorities, owners and professionals required; capacity building of technical skills and specialized expertise enables uptake; cross-stakeholder coordination Type 4: public funding enables pilot projects, but high capital cost limits upscaling	Type 2: less pollution Type 3: avoided flood damages Type 4: improved indoor comfort and well-being	Type 1: potential pollution from material degradation Type 2: reduced place identity with prefabricated structures Type 3: conflicts with heritage conservation
Water source diversification and access	Type 1: water quality control, rainwater harvesting, permeable surfaces Type 2: water reuse, desalination, rainwater harvesting, bulk water transport Type 3: rainwater harvesting and storage, greywater use Type 4: closed-loop grey/blackwater treatment and reuse, rainwater harvesting and storage, permeable surfaces	observed differences more due to different technological alternatives and modelling assumptions than between city types	climate: precipitation settlement structure: geology of the watershed, topography, impermeable land cover share, storage space infrastructure: capacity of water infrastructure, specific technological setup policy: technology choices, operational procedures	Type 1: professional capacity building for water reuse; inter-agency and multi-stakeholder coordination; compliance with regulation Type 2: multi-level master plans guide implementation; speed dependent on funding and energy cost for desalination Type 3: co-creation, financial support and capacity building for small-scale capture and reuse Type 4: multi-stakeholder coordination and technical standards scales capture and reuse; need to counter local opposition, capacity bottlenecks and long-term maintenance	across Types: operational cost savings; improved green space access Type 1: water quality improvements; reduced contamination; flood risk reduction Type 2: water security for residents and tourists; reduced contamination; flood risk reduction Type 3: local food production from nutrient-rich sediments as co-product; heat stress reduction Type 4: cleaner urban air; heat stress reduction; reduced contamination; flood risk reduction	across Types: high capital cost Type 1: potential affordability impacts of tariff schemes Type 2: higher tariffs due to high energy intensity of desalination; distributional conflicts across sectors (agriculture, tourism) Type 3: uncertain cost-effectiveness of rainwater harvesting Type 4: potential affordability impacts of tariff schemes
Water demand management	Type 1: leakage monitoring and pipe renovation Type 2: irrigation rationing, leakage and pressure control, pipe renovation Type 3: leakage monitoring, efficient water infrastructure, water storage, grey and rainwater harvesting, tariffs Type 4: irrigation control, water metering, leakage control, grey and rainwater reuse, demand reduction through awareness, tariffs, water use restrictions	limited quantified effects	behaviour: consumer awareness climate: precipitation, seasonal variability infrastructure: infrastructure age and leakage demography: population trend for scaling infrastructure settlement structure: topography, storage capacity	Type 1: utility leadership, procedural discipline and regulatory alignment for leakage reduction; funding dependent on internal budgets Type 2: multi-stakeholder (users, operators, farmers) coordination and collaboration enables implementation; requires technical expertise; tariffs shape user behaviour; funding supported by national public investment Type 3: user awareness, social acceptance and affordability shape adoption of water saving behaviour Type 4: strong governance and regulatory frameworks guide coordinated implementation; civil society involvement acts as enabler and challenger; financial incentives for households; perceived unfairness can hinder implementation	across Types: reduced contamination from leakage and runoff Type 1: cost savings, increasing revenue from water billing Type 2: operational cost savings; increased durability of infrastructure; reduced emissions related to leakage; more reliable supply Type 3: cost savings; equitable access; improved living conditions Type 4: various environmental co-benefits including reduced heat and water stress, improved stormwater management, biodiversity	Type 1: cost-effectiveness dependent on return Type 2: limited financial sustainability without external funding; potentially unequal allocation of water Type 3: high capital investment with limited return; limited acceptance of greywater use; tariffs may burden low-income households Type 4: touristic reputation damage from mandatory restrictions; privacy concerns with smart metering, fairness concerns regarding restrictions
Early warning systems	Type 1: flood and heat forecasting and communication Type 2: wildfire crowdsourcing; heat warning; mosquito surveillance; drought forecasting; tsunami warning and evacuation Type 3: flood forecasting and mapping; pollen monitoring; heat stress mapping; drought; co-creative risk reduction Type 4: heat monitoring, forecasting, mapping, alerts; flood forecasting and warning; drought forecasting; preparedness	limited quantified effects	behaviour: self-efficacy, evacuation willingness technology: forecasting accuracy, sensors, models	Type 1: multi-level institutional coordination and legal mandates required; trust in emergency services critical Type 2: open data; monitoring and surveillance technology Type 3: plug-and-play legal environments; challenge for integrating high-tech sensors in established urban fabrics Type 4: clear institutional roles and obligations required; high resolution environmental modelling enabler	across Types: social co-benefits Type 1: protecting isolated elderly and social housing residents Type 2: participation through crowdsourcing and co-creation Type 3: climate literacy and social learning among municipality departments Type 4: participation through crowdsourcing and co-creation, protecting isolated elderly and social housing residents	not mentioned in literature

4. Discussion

4.1. Climate action hotspots: Where are concentrated efforts needed?

The analysis of needs, capacities and implementation feasibility across different city types in Europe reveals important hotspots for concerted efforts to mitigate and adapt to climate change (Figure 5).

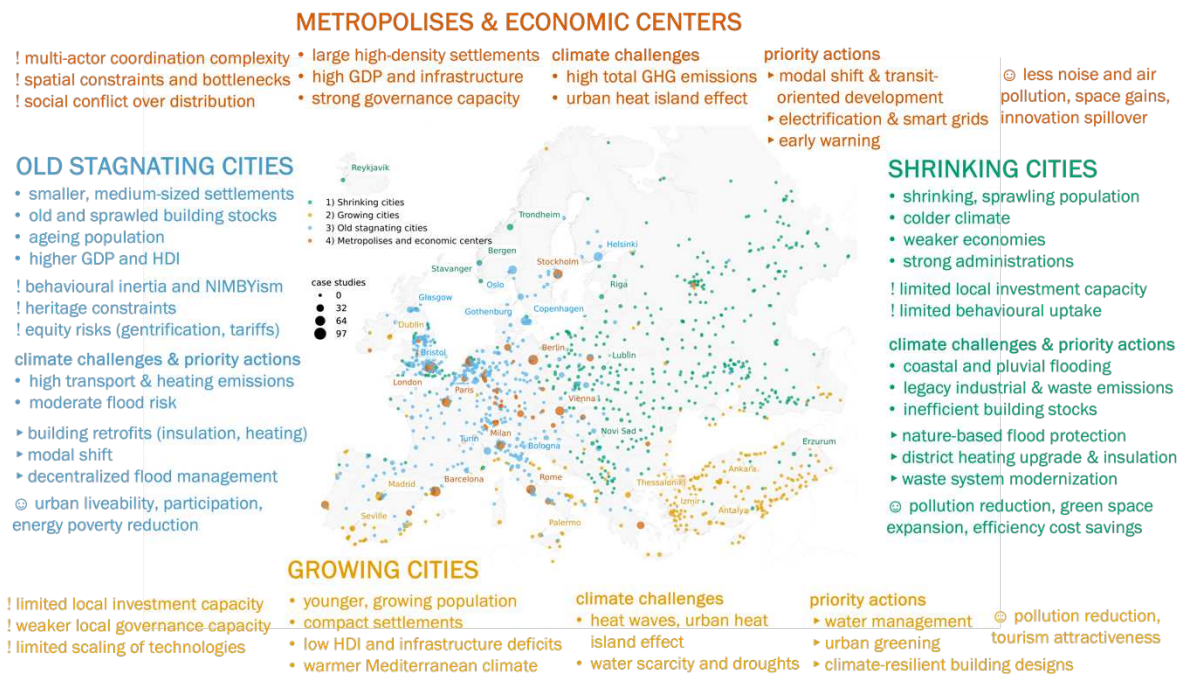


Figure 5: Climate action hotspots by city type based on city characteristics, climate challenges requiring to mitigate and adapt to climate change, and priority actions alongside co-benefits (⊙) and feasibility constraints (!). The map shows each city colored by the city type that most aligns with the city's unique characteristics. The size of the point indicates the number of case studies included in this review which cover the city. City names are displayed for cities with the highest case study coverage for each city type.

Growing cities in Southern Europe are expected to face strong increases in heat waves and droughts but have limited green spaces and limited financial capacity to invest. Literature reports climate actions in these cities to be driven by national and regional policy, and with a younger population these cities have a relatively large potential workforce to implement climate actions. Hence, these cities would benefit from national framework regulations with connected (inter)national finance schemes for infrastructure investments and capacity building for the local workforce.

The challenges of Shrinking cities such as higher waste and industry emissions onsite as well as an increase in floods could be countered with the strong administrative capacities of these cities. However, the declining population trend and limited economic power complicates investments. Hence, Shrinking cities would benefit from strong financial support for infrastructure upgrades, as well as from guidance on low-cost options such as nature-based solutions.

In contrast, Metropolises and economic centers and Old stagnating cities have particularly high onsite emissions related to buildings and mobility in combination with a relatively strong political, administrative and fiscal power to implement climate mitigation actions. At the same time, resident participation and multi-actor coordination present challenges for these cities. The abundant literature on these cities can provide ground for cross-city learning on these issues.

4.2. Literature alignment with climate action needs

Overall, we find case studies to address the most pressing issues for the different types of cities. Heat- and drought-related climate adaptation is particularly analyzed for Growing cities, waste management and flood protection are researched in Shrinking cities, transport emissions through modal shifts and electrification are assessed in Old stagnating cities, and low-carbon technologies in Metropolises and economic centers.

However, some actions seem to be evaluated mostly in places where they are already operational at full scale rather than exploring the potential in places with the highest marginal benefits. For instance, actions related to urban greening such as sponge city approaches, nature-based water management, and urban design for cooling appear to be assessed mostly in cities with abundant urban green such as Old stagnating cities, with only limited evidence in Growing cities and Metropolises and economic centers. Similarly, compact urban planning is currently mostly evaluated in Metropolises and economic centers and less for Growing cities which have considerable potential for shaping future mobility demand with urban development now. Additionally, compact urban development is seldom explored in Old stagnating cities which could have high benefits from reducing mobility demand but face notably different challenges due to slower population growth and existing urban layouts.

4.3. Cross-city learning

The typology suggests that Shrinking cities in Eastern Europe could learn from Norwegian cities with richer case study coverage, as well as Bretonian and English coastal cities may learn more from their Eastern European counterparts than from their neighboring cities. However, we must acknowledge that the qualitative results from the case study literature still differ substantially between for instance Trondheim and Oradea with Trondheim often resembling more patterns observed for Old stagnating cities than for Shrinking cities. A way forward for more attuned cross-city learning could be to calculate the distance between individual cities using our approach as demonstrated by Montfort *et al.* (2026) for a global typology of cities.

For more accurate matching between individual cities, the outcomes of the factors affecting effectiveness (Table 2) may provide a way forward. While the typology currently comprises relevant factors such as temperature profiles (relevant for heating

and cooling, EV), population density (relevant for waste treatment options), population trend (relevant for scaling infrastructures) and proxies for funding and implementation capacity such as the local GDP and the population age, the typology could be complemented using indicators for precipitation (relevant for sponge city and water management), topography (relevant for EV, sponge city, water management), share of permeable land cover (relevant for sponge city and urban cooling), density of the built-up (relevant for adding storage capacities); composition of the building stock (relevant for heating) and, where available, more specific indicators on national regulations, installed infrastructure and electricity generation mixes.

4.4. Research gaps for more actionable knowledge on urban climate mitigation and adaptation

To match the need for actionable evidence on urban climate mitigation and adaptation, case study literature needs to expand in scope of cities covered, kinds of actions assessed, and quality of evaluations performed.

First, case studies tend to focus on a few university cities per city type which are not necessarily those cities that best correspond to the city type (compare Figure 1 and 5). For instance, for Shrinking cities these include Trondheim, Bergen, Riga, Lublin, and Stavanger and for Growing cities these include Madrid, Izmir, Seville, Thessaloniki and Dublin. Hence, more knowledge on climate action implementation is especially required in non-university cities of all sorts, in Growing cities of Southern Europe which are particularly vulnerable to heat stress and droughts, as well as for Shrinking cities in countries of Eastern Europe that are not part of the European Union which face particular challenges in providing decarbonized and resilient infrastructures and which have very limited literature coverage so far.

Second, for some climate actions such as building occupancy increases, air conditioning, early warning systems, climate-resilient electricity systems and demand-side management of water and electricity use, we could only identify less than 50 case studies each over the last 25 years. These climate actions require more attention for targeted intervention design and cross-city learning.

Finally, despite reviewing an extensive body of literature comprising 1613 studies on urban climate actions, we were not able to identify quantitative differences in climate action effectiveness by city type due to inconsistent system boundaries, modelling assumptions, and climate action alternatives assessed. Already in 2010, Prowse and Snilstveit argued that “the selection and design of climate change mitigation and adaptation interventions should be based on evidence of what works, what doesn't work, under what circumstances and at what cost.” The authors point to the challenge of a minimal evidence base of rigorous impact evaluations with ex-post, real world data on the actual feasibility and effectiveness of mitigation and adaptation interventions. For example, only in 2024, Bianco and Tobin forcefully argue for implementing impact

evaluations in conservation efforts to strengthen performance measurement. Contrary to much of the existing hypothetical study scenarios, these authors call for real projects and the evaluation of realized project outcomes on environmental and human wellbeing, including unintended effects and efforts to identify which underexplored mechanisms prevent theoretically meaningful interventions from developing their full proposal once they are implemented in a real-world context.

The current review further highlights that little has changed since 2010 to fill the gap. The studies under review are mainly simulations (47%) and individual non-comparative case studies (33%) and are very much in the tradition of forecasting but lack validation with information on people's actual behavior and response to climate strategies. The comparative case studies tend to simulate climate action effectiveness modifying only single parameters such as climate between case study sites which disguises dependence of the performance on multiple differences between cities. Importantly, even if validations are conducted, they are not necessarily with real world data but vis-à-vis the existing literature and/or prior research of the study authors {Citation} (D'Agostino 2016, Pacak 2019). The validation concern is particularly pronounced as the individual studies indicate serious limitations like the exclusion of other influential factors (Dorokhov 2018), lack of long-term studies (Prozuments 2023), lack of economic impact and/or feasibility analysis (Prozuments 2023, Güğül 2018, D'Agostino 2016), limited representativeness (Murtagh 2022, Sánchez-García 2020), and most importantly, strong modelling assumptions and model boundaries (Παπακώστας 2018, 2128, Šíma 2014, Belleri 2017, Pacak 2019, Lavtižar 2023, Sbaity 2021, Vollaro 2013, Buchin 2016, Jin 2020, Viana-Fons 2024). Especially these latter strong assumptions question the credibility of the findings and the applicability in real-world contexts. For example, unintended effects cannot be accounted for in simulated forecasts and technological viable climate adaptation and mitigation options might not be taken up because of behavioral, cultural or other barriers.

Against rising resistance towards climate adaptation and mitigation interventions, (partially) triggered by populist leaders and parties, the scientific literature risks a credibility trap if its findings cannot be matched with real world observations and experiences. The current review points to the need for a shift from the narrow focus on constrained simulation-based modelling of technological options towards more systematic collection of real-world data and rigorous implementation designs of climate interventions that allow for the evaluation of uptake and impact in an experimental or quasi-experimental design (Puri *et al.*, 2020). Simulations if applied to estimate potentials for goal attainment and substantiate visions should be informed by this enhanced evidence base. The list of factors influencing climate action effectiveness compiled as part of this review (Table 2) may serve as a starting point for real-world evaluations and simulations that consider a greater diversity of factors influencing effectiveness beyond technological set-up. In this regard, longitudinal geospatial data is a still underexplored source to assess environmental impacts of realized adaptation and

mitigation projects with real world spatial data, pointing towards the need to move from hypothetical cases scenarios to actual implementation.

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CRediT statement

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