

Supplementary Materials 1:

A global typology of cities supporting coordinated climate action

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December 15, 2025

Check papers

Authors	Title	Journal
Lamb et al[1]	Learning about urban climate solutions from case studies	Nature Climate Change
Creutzig et al [2]	Upscaling urban data science for global climate solutions	Global Sustainability
Cheval et al[3]	A systematic review of urban heat island and heat waves research (1991–2022)	Climate Risk Management
Constantinescu et al[4]	Effective monitoring and warning of Urban Heat Island effect on the indoor thermal risk in Bucharest (Romania)	Energy and Buildings
Reckien et al[5]	How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28	Journal of Cleaner Production
Seto et al[6]	From low-to net-zero carbon cities: The next global agenda.	Annual review of environment and resources
Hale et al[?]	Sub-and non-state climate action: a framework to assess progress, implementation and impact	Climate Policy
Hsu et al[7]	Performance determinants show European cities are delivering on climate mitigation	Nature Climate Change
Rosenzweig et al[8]	Climate change and cities: Second assessment report of the urban climate change research network (UCCRN)	Cambridge University Press
Reckien et al[9]	Climate change response in Europe: What’s the reality? Analysis of adaptation and mitigation plans from 200 large cities	Climatic Change
Creutzig et al[10]	Urban infrastructure choices structure climate solutions	Nature Climate Change
Castán Broto[11]	Urban governance and the politics of climate change	World Development
Bulkeley & Betsill[12]	Rethinking sustainable cities: Multilevel governance and the ‘urban’ politics of climate change	Environmental Politics
Herslund et al[13]	A multi-dimensional assessment of urban vulnerability to climate change in Sub-Saharan Africa	Natural hazards
van der Heijden[14]	Studying urban climate governance: Where to begin, what to look for, and how to make a meaningful contribution to scholarship and practice	Earth System Governance
Garschagen[15]	Risky change? Vietnam’s urban flood risk governance between climate dynamics and transformation	Pacific Affairs
Garschagen & Romero-Lankao[16]	Exploring the relationships between urbanization trends and climate change vulnerability	Climatic Change
Olazabal & De Gopegui[17]	Adaptation planning in large cities is unlikely to be effective	Landscape and Urban Planning
Pietrapertosa et al[18]	Adaptation to climate change in cities of Mediterranean Europe	Cities
Kılış et al[19]	Visions for climate neutrality and opportunities for co-learning in European cities	Renewable and Sustainable Energy Reviews
Burley Farr et al[20]	Cities and regions tackle climate change mitigation but often focus on less effective solutions	Communications Earth & Environment
Haberl et al[21]	Built structures influence patterns of energy demand and CO2 emissions across countries	Nature Communications
Goodwin et al[22]	Measuring the contribution of nature-based solutions beyond climate adaptation in cities	Global Environmental Change
Esperon-Rodriguez et al[23]	Barriers and opportunities for resilient and sustainable urban forests	Nature Cities
Bernardo et al[24]	Pollution and congestion in urban areas: The effects of low emission zones	Economics of Transportation
Hsu et al[25]	Disproportionate exposure to urban heat island intensity across major US cities	Nature Communications
Acuto et al[26]	What three decades of city networks tell us about city diplomacy’s potential for climate action	Nature Cities

Sethi et al [27]	Urbanization and regional climate change-linked warming of Indian cities	Nature Cities
Borowska-Stefańska et al[28]	Periodic low emission zones: balancing urban transport efficiency and reducing traffic emissions	Cities
Seto et al[29]	A meta-analysis of global urban land expansion	PloS one
Bonsu[30]	Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy	Journal of Cleaner Production
Dhakai[31]	Urban energy use and carbon emissions from cities in China and policy implications	Energy policy
Pang et al[32]	Urban carbon footprints: a consumption-based approach for Swiss households	Environmental Research Communications
Meinherz & Binder[33]	The dynamics of modal shifts in (sub)urban commuting: An empirical analysis based on practice theories	Journal of transport geography
Bulkeley & Broto[34]	Government by experiment? Global cities and the governing of climate change	Transactions of the institute of British geographers
Bulkeley[35]	Cities and the governing of climate change	Annual review of environment and resources

Table 1: During the search string development, we used these check papers to ensure that our sample included articles we knew to be relevant.

Annotation rules to map solutions in city case study examples

Relevance

As our key objective is to have a comprehensive sample of climate change research in cities, we use relatively inclusive annotation rules to determine if a study is relevant for climate change and cities. Table 2 describe the criteria that we used to screen studies for their relevance based on the article abstract and title. To each article, we assigned one of the four labels. If an article abstract was considered relevant, i.e. it was related to climate change and cities and mentioned a climate solution, we then used Table 3 to determine to which solution(s) to assign it to.

Annotation	Annotation rule (with examples)
Not relevant	Studies are not considered relevant when they do not address both climate change (or closely related terms such as global warming, greenhouse gas emissions, or climate variability) and human settlements (cities, towns, or urban areas) at the same time. <i>Example (excluded):</i> “Impacts of climate change on coral reef ecosystems.” <i>Example (excluded):</i> “Urban growth patterns in Southeast Asia.” (no reference to climate change)
Related to climate change and cities	Studies are considered related when they mention both (a) climate change in any form and (b) human settlements, cities, or urban systems. A minor or indirect reference to either topic is sufficient for inclusion. <i>Example (included):</i> “Assessing the impacts of climate change on water availability in the metropolitan area of Lima.” <i>Borderline example (included):</i> “Effects of changing precipitation patterns on a river basin upstream of Mexico City.” (relevant due to indirect link with city systems)
Related to climate change and cities and mentions climate solution	Studies that meet the above criteria and additionally refer to at least one climate-related solution related to adaptation or mitigation. This includes nature-based solutions, renewable energy adoption, green infrastructure, policy responses, or urban planning strategies to address climate risks. <i>Example (included):</i> “Evaluating the potential of green roofs to mitigate urban heat in Berlin under climate change scenarios.” <i>Example (included):</i> “Urban climate governance and policy integration for carbon neutrality in Singapore.”
N/A	Assigned when none of the above labels can be meaningfully applied. This includes abstracts with incomplete, corrupted, or non-English text, or cases where the abstract lacks sufficient information to determine relevance. <i>Example:</i> Abstract truncated during data extraction or composed solely of keywords.

Table 2: Refined rules and examples for determining study relevance to climate change and cities. Examples do not represent exact content of references code but are stylized illustrations to exemplify decisions.

Whenever we annotated a study as **related to climate change and cities** and **mentions climate solution** (see Table 2), we then decided which solution was discussed in the text, using the annotation rules listed in Table 3.

Solution name	Coding rule / Description	Example (included if...)
Mobility		
Switch to cycling and walking	Include if study documents walking, and cycling promotion through infrastructure (bike lanes, sidewalks), incentives, or behavioral change. The switch aims to reduce private vehicle use and related emissions.	“Bike-sharing systems to reduce urban carbon emissions.”
Highly accessible compact urban form and transit networks, and associated (AI-based) urban planning	Include if study documents integrated land use and transport planning that enhances accessibility through density, mixed uses, and efficient transit connectivity to reduce transport demand.	“Compact city planning and transit-oriented development.”
Uptake of battery electric vehicles and electric 2- and 3-wheelers	Include if study documents adoption, diffusion, or promotion of battery-electric cars, buses, motorcycles, scooters, or other small electric vehicles. This includes policies, incentives, infrastructure (charging stations), or behavioral changes that increase the use of electric-powered transport instead of fossil-fuel vehicles.	“Electric vehicle adoption programs to reduce urban transport emissions.”
Switch to public transit	Include if study documents modal shift from private vehicles to buses, subways, trams, or other public transit systems. May involve service expansion, reliability improvement, or fare incentives to increase transit ridership.	“Assessing expansion of metro lines to reduce car dependency.”
Low-carbon infrastructure materials	Include if study documents the use of alternative or optimized construction materials in large-scale urban infrastructure (e.g., roads, bridges, tunnels) that reduce embodied carbon compared with conventional materials, e.g., low-carbon cement, recycled steel, low-emission asphalt, or other innovative low-carbon substitutes.	“Low-carbon concrete in city roads.”
Shared mobility	Include if study documents mobility services enabling shared use of vehicles, such as car-sharing, ride-hailing, or micro-mobility (e-scooters, bikes), to reduce individual car ownership and trips.	“Car-sharing programs in urban areas.”
Teleworking	Include if study documents remote work arrangements that reduce commuting trips and associated energy demand, including flexible work-from-home policies or digitalization of work processes.	“Work-from-home potential to reduce commuting emissions.”
Buildings		
Compact urban form	Include if study documents dense, mixed-use, walkable urban development that minimizes travel distances and per-capita infrastructure needs, and land use.	“High-density development to reduce energy use.”
High-efficiency appliances	Include if replacement or diffusion of efficient appliances is discussed. These are devices designed to use less electricity, water, or gas while providing the same function (e.g., A-rated devices, efficient lighting, ENERGY STAR appliances).	“Refrigerator replacement program for efficiency.”
Limiting growth in floor space / sufficiency	Include if study documents reducing average residential or commercial floor area per capita to lower energy and material use, and other sufficiency strategies in the building sector.	“Smaller living spaces can reduce per capita emissions.”
Smart home systems (incl. smart thermostats and HVAC)	Include if digitally connected technologies that monitor and control household energy use, such as smart thermostats or automated HVAC systems, are discussed, e.g., automation, sensors, or learning algorithms are used to optimize temperature, lighting, or appliance use.	“Smart thermostats reduce heating demand.”
Low-carbon building materials	Include if alternatives to conventional carbon-intensive materials are discussed, for instance, materials with reduced embodied carbon, such as timber, recycled concrete, or low-emission cement.	“Using bamboo as a structural material.”

High-efficiency building envelopes and passive houses	Include if study documents design and construction measures (insulation, airtightness, windows) that minimize heating and cooling demand, e.g., “passive house,” “high-performance envelope.”	“Passive house standards in cold climates.”
Heat pumps and heat recovery systems	Include if systems that transfer or recover heat from air, water, or waste sources for building heating or cooling are discussed, e.g., air-source, ground-source, or wastewater heat pumps.	“Air-source heat pumps for apartment blocks.”
Nearly-zero energy and zero-emission buildings	Include if buildings designed to meet near-zero energy consumption through efficiency and on-site renewable generation, e.g., NZEB, net-zero, or zero-carbon building standards are discussed.	“NZEB regulations in EU urban housing.”
Energy		
Citizen and renewable energy communities initiatives	Include if study documents local cooperative models where citizens collectively own, operate, or invest in renewable energy systems.	“Community-owned solar cooperative.”
District heating/cooling systems	Include if study documents centralized systems distributing heat or cooling to multiple buildings using efficient or low-carbon energy sources (e.g., waste heat, renewables).	“Waste heat recovery for district heating.”
Renewable electricity generation	Include if study documents generation of electricity from renewable sources (solar, wind, hydro, geothermal, biomass) within the urban context, including distributed generation such as rooftop PV.	“Rooftop solar PV deployment in cities.”
Integrating renewable energy into infrastructure	Include if study documents integration of renewable energy systems into buildings, transport networks, or urban infrastructure (e.g., solar façades, PV roads, or renewable-powered transport).	“Solar-integrated façades.”
Smart meters for VRE integration (incl. dynamic tariffs)	Include if study documents digital metering systems that enable real-time monitoring, demand response, or dynamic electricity pricing to better integrate variable renewable energy (VRE).	“Dynamic electricity pricing to balance solar generation.”
Grid reinforcement and storage	Include if study documents grid infrastructure upgrades or installation of energy storage systems (e.g., batteries, thermal storage) to improve reliability and accommodate renewables.	“Battery storage in urban grids.”
Hydrogen and e-fuels	Include if study documents hydrogen production, storage, or use (e.g., fuel cells, hydrogen mobility) or synthetic fuels for decarbonizing energy systems.	“Hydrogen refueling infrastructure for buses.”
Thermal comfort and Heat stress management		
Adaptive behavior and norms	Include if study documents social, cultural, or behavioral changes that enable individuals or communities to adjust to climate-related stresses such as heat, flooding, or resource scarcity. This includes practices like adjusting clothing or schedules during heatwaves, community-level adaptation habits, or evolving social norms that promote preparedness and resilience.	“Residents changing daily routines to avoid outdoor activity during heatwaves.”
Nature-based solutions, including blue-green infrastructure	Include if study documents use of ecosystems (wetlands, urban forests, green roofs) to manage heat stress	“Urban green corridors for cooling and flood control.”
Albedo management	Include if study documents the use of reflective or light-colored surfaces (roofs, pavements) to reduce urban heat absorption and mitigate heat island effects.	“White roof program in southern cities.”
Heat shelters and cooling spaces	Include if study documents public or community facilities designed to provide thermal comfort during extreme heat, e.g., cooling centers or heat shelters.	“Cooling centers for vulnerable populations.”
Food provisioning systems		
Diet shift	Include if study documents measures or campaigns promoting plant-based diets or reducing meat or other emission-intensive food consumption to low-emission diets.	“City-level campaigns for plant-based diets.”
Growing food locally (urban and peri-urban agriculture)	Include if study documents urban farming, rooftop gardens, community gardens, or peri-urban agriculture that enhance local food production.	“Rooftop gardens for local food supply.”

Reduced food waste, food sharing	Include if study documents initiatives that prevent, reuse, or redistribute surplus food, including storage, logistics, or sharing networks.	“Food-sharing apps in cities.”
Enabling food sharing networks through digitalisation	Include if study documents digital or app-based tools facilitating redistribution of surplus food between producers, retailers, and consumers.	“Mobile app connecting restaurants and charities.”
Tech advancement in food production and storage (urban scale)	Include if study documents high-tech urban agriculture or controlled-environment farming (e.g., vertical farms, hydroponics) or innovations in cold-chain efficiency.	“Vertical farming to enhance food security.”
Access to food during and post hazards	Include if study documents policies or infrastructure ensuring food access and distribution in emergencies, such as disaster-resilient food hubs or supply chains.	“Food hubs for emergency distribution.”
Urban food environments	Include if study documents interventions shaping access to healthy, affordable, and sustainable food through urban planning or regulation.	“Healthy food zoning policies.”
Water		
Water-saving practices and norms	Include if study documents behavioral change promoting water efficiency, reuse, or conservation.	“Public campaigns for reduced water use.”
Flood infrastructure: Sponge cities, dams, road elevation	Include if study documents how to retain, delay, or manage stormwater and floods through natural or man-made networks of green-grey infrastructure (e.g., sponge cities, retention basins, raised roads).	“parks and permeable pavements to reduce flood risks.”
Advanced control of the water supply system	Include if study documents smart, sensor-based, or automated systems managing urban water supply or leak detection.	“Sensors for real-time monitoring and control of water pressure, flow, and quality.”
Water-sensitive communities and engagement	Include if study documents participatory water management approaches, awareness programs, or citizen monitoring initiatives.	“Community water monitoring programs.”
Droughts and water infrastructure: freshwater access and recycling	Include if study documents drought mitigation strategies, water recycling, desalination, or alternative freshwater sourcing systems.	“Greywater recycling for irrigation.”
Access to safe and affordable water, sanitation, and hygiene (WASH)	Include if study documents infrastructure or governance measures improving access to safe, reliable, and affordable WASH services, especially for vulnerable populations.	“WASH upgrades in informal settlements.”
Waste management		
Waste management practices and norms	Include if study documents behavioral, regulatory, or educational practices and interventions encouraging waste reduction, sorting, or recycling.	“Sorting household waste for recycling.”
Waste management infrastructure	Include if study documents waste collection, treatment, recycling, or disposal infrastructure.	“Upgrading municipal waste collection systems.”
Smart and digital waste management	Include if study documents data-driven, sensor-enabled, or automated waste tracking, sorting, or optimization systems.	“Smart bins for waste tracking.”
Circular economy and industrial symbiosis	Include if study documents reuse, repair, remanufacturing, or exchange of by-products between firms to reduce waste and resource demand.	“Circular economy park projects.”
Disaster and risk management		
Adaptive behaviours and normative practices in disasters	Include if study documents social or behavioral adaptation practices (e.g., community preparedness, drills, or risk perception) improving disaster readiness.	“Community drills and preparedness culture.”
Risk-sensitive planning and housing	Include if study documents planning or building regulations designed to reduce exposure and vulnerability to hazards (e.g., flood-resistant or seismic housing).	“Flood-resilient housing regulations.”
Early warning systems (digital and smart systems)	Include if study documents monitoring, forecasting, or alert systems (e.g., sensors, AI-based prediction) for hazards such as floods or heatwaves.	“AI-based flood early warning systems.”

Access to social protection for vulnerable and informal residents	Include if study documents measures expanding social protection (e.g., cash transfers, safety nets, or insurance) for those most affected by climate risks.	“Climate risk insurance for informal workers.”
Insurance	Include if study documents schemes transferring or managing climate risk through financial instruments, such as weather-indexed or parametric insurance.	“Parametric flood insurance pilot.”
Climate-resilient health care	Include if study documents measures strengthening health systems to withstand or respond to climate-related shocks (e.g., cooling retrofits, resilient hospitals).	“Hospital cooling retrofits for heatwaves.”
Carbon dioxide removal		
Urban forestry	Include if study documents management, conservation, or expansion of trees and forested areas within urban environments. Urban forestry encompasses the planning and maintenance of street trees, parks, and green belts to sequester carbon from the atmosphere.	“Tree canopy expansion to reduce heat island.”
Improved forest and soil management by citizens	Include if study documents citizen- or community-led stewardship of urban green spaces, forests, or soils, focusing on activities such as composting, mulching, community gardening, reforestation, or soil restoration. These actions enhance soil carbon storage.	“Urban composting to enhance soil carbon.”
Biochar for urban soil applications	Include if study documents the use or production of biochar (a carbon-rich material derived from biomass pyrolysis) for application in urban soils, green roofs, or landscaping. Biochar improves soil fertility, water retention, and long-term carbon sequestration.	“Biochar in green roofs.”
Bioenergy with carbon capture and storage (BioCCS) and direct air carbon capture and storage (DACCS)	Include if study documents carbon dioxide removal (CDR) technologies in the urban context. BioCCS involves capturing CO ₂ emissions from biomass-based energy systems, while DACCS extracts CO ₂ directly from ambient air. Both aim to achieve negative emissions and may be integrated with urban waste or energy systems.	“Waste-to-energy plant with CO ₂ capture.”

Table 3: Binary coding rules for identifying urban climate solutions in literature. Code each solution as 1 = mentioned or 0 = not mentioned.

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