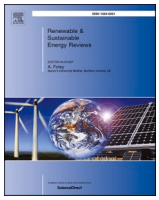
Renewable and Sustainable Energy Reviews 195 (2024) 114315

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Visions for climate neutrality and opportunities for co-learning in European cities

Şiir Kılkış [a,*], Giulia Ulpiani [b,**], Nadja Vetters [c]

[a] The Scientific and Technological Research Council of Turkey, Ankara, Türkiye
[b] European Commission Joint Research Centre, Energy, Mobility and Climate, Ispra, Italy
[c] European Commission Joint Research Centre, Energy, Mobility and Climate, Brussels, Belgium

ARTICLE INFO

Keywords:
Climate neutral city
Greenhouse gas emissions
Climate policy
Barriers
Transition
Climate governance

ABSTRACT

Cities represent unique spaces for climate mitigation where wide-ranging action to reduce emissions meets ambition and collaboration. This research work distils climate neutrality narratives for 362 cities that expressed interest in the European Mission on 100 Climate-Neutral and Smart Cities and focuses on the 112 cities selected to spearhead the process of reaching climate neutrality by 2030 (representing a mitigation potential of 318.3 megatonnes of carbon dioxide equivalent emissions). The method involves steps that profile the characteristics of these cities, enunciate cross-cutting patterns in cities' visions by thematic groupings, and compare 14 contextual factors with 77 possible main barriers. There are both similarities and differences among the results as a basis for learning together and certain barriers can be relatively more dominant in some thematic groupings, such as fragmentation of responsibilities. As a synthesis of the main findings, the original analyses are used to derive and prioritise nine high-level recommendations based on the cities' visions, contextual factors, and expected main barriers. Opportunities for mobilising transformative change relate to transforming siloed into integrated approaches, inclusive climate governance and collaborations, innovative financing, welfare and just transition as well as planning, implementation, and policy coherence. The advances provide pioneering steps for stimulating co-learning processes among Mission Cities and beyond to support the transition to climate neutrality and open up opportunities to progress together in climate action while producing impact with global reach.

1. Introduction

Cities are hotspots of opportunities for climate change mitigation given the dualism between the sheer magnitude of existing emissions and the breadth of actions that can be implemented to shift direction [1]. With 67–72% of greenhouse gas (GHG) emissions arising from urban areas in 2020 [2], ambitious climate mitigation action in cities is a vital component in the solutions forward. Globally, 420 urban areas with the largest emissions footprint exhibit a reduction potential of about 3.7 $GtCO_2eq$ between 2020 and 2030 under a very low emissions scenario [3]. Capturing such a reduction potential requires cross-sectoral mobilisation [4] and coordination of mitigation efforts in urban areas along the way. Prioritising measures that can be more effective in reducing emissions [5], boosting ambition across cities of various sizes [6], increasing transformative capacities [7], and broadening urban climate governance [8] are key enablers. Among some of the milestones, an analysis of 1066 European cities indicated that the majority of cities were on track to achieve their 2020 emission reduction targets [9]. A 23% reduction was recorded between baseline and monitoring inventories [10] – also including local authorities that exceeded their target multiple times [11] – and many frontrunner cities have advanced climate action and implementation [12].

In the process of upscaling climate ambition at the local level, the number of cities that are engaged in carbon neutrality or net-zero targets is increasing worldwide. However, their share among all cities that are engaged in climate mitigation remains at about 19% as of 2023 [13]. Of these cities, one-third has pledged to reach such targets before 2050 while the remaining cities aim to do so by mid-century and some even later [13]. In contrast, pioneering climate action to reduce global GHG emissions by 43% in 2030 from 2019 levels is essential to constrain global warming to 1.5 °C [14] as a critical physical threshold [15] in the earth system [16]. This urgency for averting the most serious consequences of climate change on ecosystems and livelihoods [17] from

* Corresponding author.
** Corresponding author.
E-mail addresses: Siir.KILKIS@tubitak.gov.tr (Ş. Kılkış), Giulia.ULPIANI@ec.europa.eu (G. Ulpiani).

https://doi.org/10.1016/j.rser.2024.114315
Received 20 June 2023; Received in revised form 13 January 2024; Accepted 2 February 2024
Available online 27 February 2024

Nomenclature

Abbreviations

EOI	Expression of Interest
EU	European Union
GHG	Greenhouse gas
SM	Supplementary material
TG	Thematic grouping(s) of Mission Cities
TG1	Wide-ranging ambition and collaboration
TG2	Collaboration-led ambition to climate neutrality
TG3	Promising elements to accelerate the process
TG4	Emerging collaboration for city-wide ambition

Symbols and Units

A	Degree of ambition (dimensionless)
C	Degree of collaboration (dimensionless)
U	Given Mission City (dimensionless)

Subscripts

j	Count of Mission Cities
m	Median value

extreme agricultural and hydrological droughts to major heatwaves, heat stress, and floods [18] necessitates unprecedented mitigation efforts, particularly in cities.

Net-zero emissions targets [19] represent key opportunities for ambitious climate mitigation [20] with cities and subnational players to provide a crucial contribution, as they situate people and places at the intersection of resource use and infrastructure requiring rapid decarbonisation [21]. Governance [22], including the involvement of citizens and political leadership, is also instrumental in climate ambition and can be used to predict the presence of net-zero equivalent targets in cities [23]. In this process, there is consensus that improving social prosperity [24] and liveability [25], increasing effort sharing [26], shifting towards sustainability [27], strengthening public support [28], and coordinating across scales [29] represent essential needs. Combining options for ambitious mitigation action with more efficient and sustainable urban infrastructure [30] while promoting urban innovation [31] and experimentation [32] represent real opportunities to be acted upon swiftly.

Against this urgency, an overwhelming majority of the scientific literature focuses on the mitigation opportunities in specific urban areas. These include studies on the optimisation of the energy supply strategy for a carbon-neutral city [33], scenarios for carbon neutrality in an urban area [34], transitioning urban energy systems toward carbon neutrality [35], and energy sharing approaches in carbon-neutral cities [36]. The energy planning practices of cities [37], deep decarbonisation plans [38], tools for modelling urban energy systems [39], their relevant gaps [40], and the role of positive energy districts [41] were also compared. Nearly zero-energy neighbourhoods [42], prioritising routes for switching to electric buses [43], and the socio-environmental benefits of fleet electrification [44] were widely investigated within specific urban case studies. Recent examples include analyses to determine clusters for thermal energy networks [45], district cooling systems based on seawater and solar photovoltaics in coastal cities [46], solar access [47], and waste management for local cases [48]. Studies that focus on barriers that can impede the diffusion of mitigation measures are substantially underrepresented and mostly explorative in nature for specific urban areas and technologies, such as urban electric mobility [49] and local renewable energy generation [50]. Major challenges that relate to data scarcity and availability [51] and possibilities for consistent data analysis across cities perpetuate this predominant form of knowledge production based on specific urban case studies [52] and sectoral investigations.

Beyond urban case studies, analyses that cover larger samples of cities and analyses that focus on the common needs or opportunities of multiple cities are exceptions rather than the norm. As an example, a benchmarking study paired 120 cities based on common strengths and weaknesses [53], yet the focus was not on cities with net-zero targets. City attributes and networks can be associated with the level of mitigation ambition, such as those observed in the mitigation targets of 327 cities in Europe [6]. The motivation and network membership of 105 cities that adopted climate emergency declarations were further compared [54]. For cities that have monitoring emissions inventories, 12,000 policies were analysed, finding municipal self-governing as the type of policy intervention with the highest occurrence [55].

Among another sample of European cities, 5000 actions were analysed, leading to 28 policy levers and the need for strategies that tackle the largest mitigation potential and the most effective mix of policies in a given context [56]. In contrast, in an era where net-zero cities are the new urban agenda [57], scientific studies that provide an integrated focus on the visions, characteristics, and the main barriers of cities that are pursuing climate-neutrality are an urgent necessity. Addressing this remaining gap is relevant in light of the many and diverse barriers [58] that may need to be overcome along the zero emissions journey [59]. These include institutional barriers to increase cross-sectoral collaboration for implementing integrated approaches in urban systems [60]. Indeed, the level of integration and holism, of operational capacity, and of financial readiness needed to eradicate even harder-to-abate emissions and reach a zero emissions balance is unprecedented. More complex and intertwined barriers are expected to be interposed in the transition process between strategic vision and implementation. Investigations that are dedicated to the unique set of challenges and opportunities in cities in the process of reaching net-zero emissions are necessary.

In the European Union (EU), the target to become a net-zero GHG emissions continent by 2050 [61] and the related climate law [62] is supported, at the subnational level, by the Mission on 100 Climate-Neutral and Smart Cities [63]. This Mission allows cities to guide the way by realising climate neutrality in their jurisdictions with an earlier timeframe of 2030. The research objectives of this research work focus on the need to elucidate the visions of these cities for 2030 on their journey for reaching climate neutrality. The research questions are three-fold to answer distinct aspects that have relevance for cities. First, what are the overarching narratives in the visions of cities by thematic grouping? Second, how do any favourable conditions and challenges differ or share commonalities across these thematic groupings? Third, what can be learned by cross-comparing cities in thematic groupings to support their collective effort to reach climate neutrality? An original research framework is established to tackle these research questions that span data collection from cities to data analyses from multiple perspectives.

In this respect, the 112 cities selected by the European Commission to participate in the Mission (hereinafter, Mission Cities) are analysed based on an unprecedented dataset of 374 questions on climate neutrality answered by 362 eligible cities representing about 650 $MtCO_2eq$ of potential emissions reduction [59]. Cross-cutting patterns and overarching narratives in cities' visions for climate neutrality by 2030 are enunciated across four thematic groupings of ambition and collaboration. The groupings are compared based on contextual factors as well as the main barriers that cities expect to encounter in the process of reaching climate neutrality at both cross-sectoral and sectoral level with a focus on the energy, transport, and waste/wastewater sectors. The underlying dataset and related analyses are unparalleled in the literature on climate neutrality considering the breadth of information and the city sample.

In characterising the opportunity space, the original research results lead to nine high-level recommendations that have high priority in leading Mission Cities towards climate neutrality. The study continues with the Methods in Section 2.0, the Results in Section 3.0,

Recommendation and Discussion in Section 4.0, and the Conclusions in Section 5.0. The advances from this research work are envisioned to support pioneering steps to bolster collaboration among Mission Cities and beyond. The results can be put into action to stimulate co-learning [64] towards reaching climate neutrality with an accelerated pace and empower cities to utilise their strengths in overcoming challenges in this critical decade.

2. Methods

The method of conducting the analysis is centred on six main steps as represented in Fig. 1. First, responses to 120 questions in the call for Expression of Interest (EOI) questionnaire (hereafter EOI questionnaire) are used to support systematic evaluations of cities' responses with relevant cross-comparisons for Mission Cities. The 120 questions include both questions used to group cities according to specific metrics and questions used to investigate city characteristics or performance in climate action. The definition of thematic groupings (TGs) for Mission Cities represents the following methodological step and serves subsequent analyses (Steps 4–6), while Step 3 provides additional characterisation and descriptive statistics on groups as well as the entire cohorts of Mission and eligible cities. The TG-specific investigation starts with an analysis of the cities' visions for reaching climate neutrality (Step 4), namely the strategic thinking that underpins the ambition to participate in the Mission. Subsequently (Step 5), the main barriers that cities envisage encountering in the realisation of zero emissions futures are analysed with and without sectoral specification to support proactive means for policy learning among cities. Finally (Step 6), specific favourable conditions and/or opportunities are used to analyse contextual factors. By focusing on a thematic view of the visions of cities based on groupings and a cross-comparison of the contextual factors and barriers, this original research work aims to fill the gaps in better understanding the strategic directions and opportunities for Mission Cities not just in delivering climate neutrality by 2030, but also in stimulating peer learning.

In addition to the analyses indicated in Fig. 1, the first Supplementary Material (SM1) that is available online with open access [65] provides complementary qualitative and quantitative analyses supporting the main narrative and offering more topical insights. The second Supplementary Material (SM2) that is available from the same registry in the open access server [65] contains the EOI questionnaire as a reference to the overarching investigatory framework. Based on the results of these original analyses, Fig. 1 concludes the description of the methodological approach with a process of synthesis where the top contextual factors and main barriers per TGs are utilised in prioritising high-level recommendations. This condensed information forms the basis for the discussion of the results and offers a synoptic view of ways forward for reaching climate neutrality in cities. This methodological

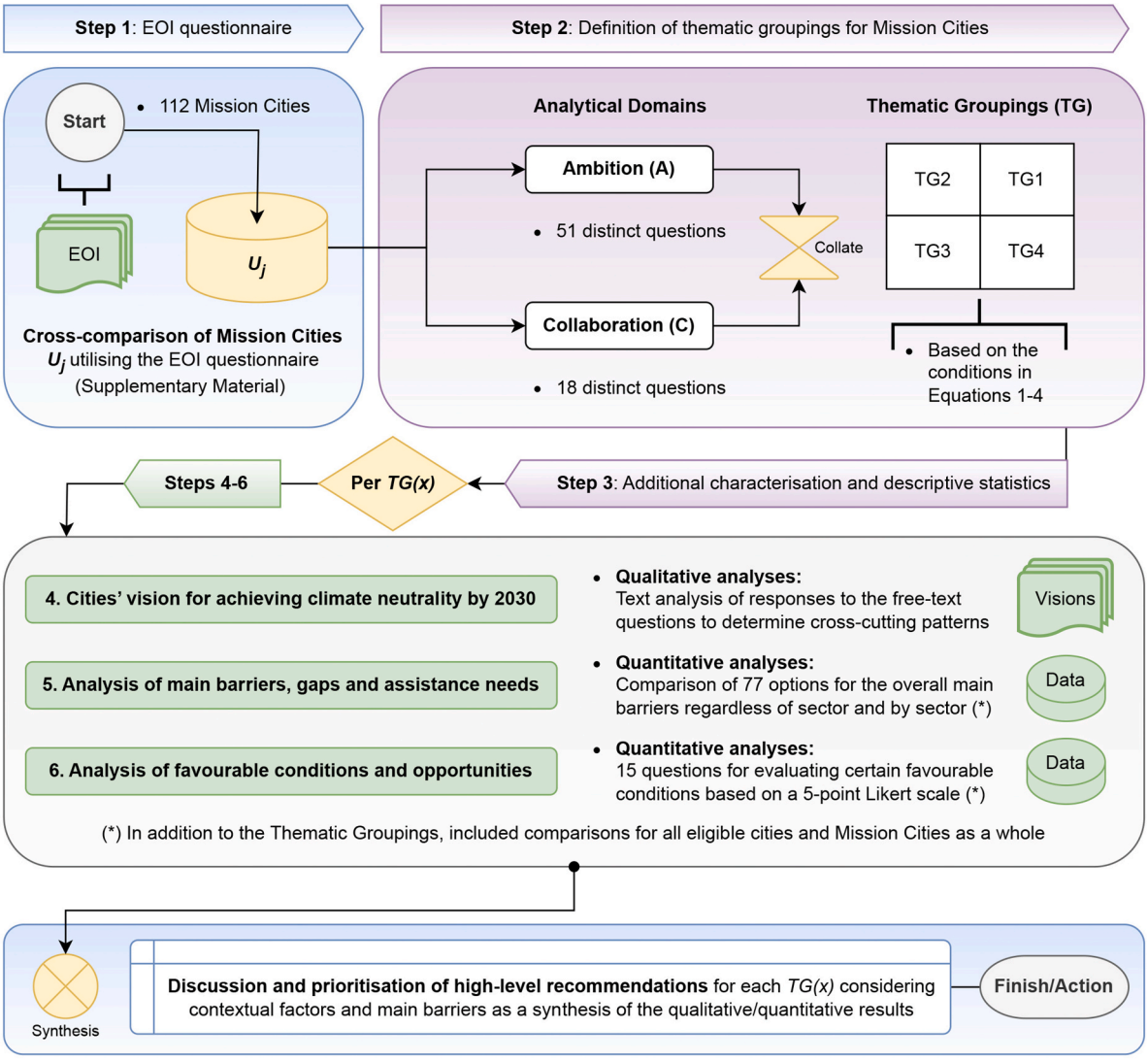


Fig. 1. Flowchart that describes sequentially the methodological steps guiding this research work.

approach allows combining the results of the original and topical analyses in a synthetic overview of enablers and barriers to climate neutrality to enunciate critical and targeted recommendations. The use of this specific approach comes with the unique advantage of allowing cities to identify entry points for action and peer learning, thus steering faster and more effective climate-neutral journeys.

2.1. Systematic evaluations of the cities' responses

The analysis starts with the EOI questionnaire and the associated data collection. The call for expression of interest in the Mission was officially launched on November 25, 2021 [66] and involved a comprehensive questionnaire of 374 questions. The EOI questions were designed to provide: (i) a systematic and complete assessment of the city's starting point (preparedness), commitment, and capacity to reach climate neutrality by 2030; (ii) an evaluation of the consistency, plausibility, and credibility of the intended approach to climate neutrality; and (iii) a preliminary identification of gaps, barriers, and the type/-extent of support cities would require to successfully participate in the Mission or to reach climate neutrality at a later stage. In total, 377 cities filled in the EOI questionnaire. Out of these cities, 362 fulfilled the eligibility criteria (eligible cities) but 16 did not consent to be identified. For this reason, the geographical mapping in this study includes 346 cities while the entire set of eligible cities ($n = 362$) are included in the data analyses.

All geographical subnational jurisdictions or territorial units that are governed by a local government as the legal entity of public administration could apply. Cities could also express their interest as a group of geographically contiguous members coordinated by a single entity having the authority to make decisions and commitments for the whole grouping. Cities from EU Member States and from Associated countries (or countries in the process of negotiating association) to Horizon Europe could participate given at least 50,000 inhabitants. Cities from countries with five or fewer cities of more than 100,000 inhabitants (Croatia, Cyprus, Estonia, Ireland, Latvia, Lithuania, Luxembourg, Malta, Slovenia, and Slovak Republic) could express their interest where more populous than 10,000 inhabitants. Of the cohort of 362 cities, the European Commission selected 112 cities to proceed through the next steps of the Mission (Mission Cities) [67]. Given the joint expression of interest of two cities, the data count for Mission Cities involves 113 cities.

2.2. Definition of thematic groupings for Mission Cities

The analysis proceeds with the systematic evaluation of the cities' responses to the EOI questionnaire. Reaching climate neutrality by 2030 will involve a challenging process with ambition and collaboration being key ingredients. Accordingly and in order to analyse groups of Mission Cities by TGs to increase co-learning opportunities, questions in the EOI questionnaire are selected and clustered to construct two analytical domains. The first analytical domain focuses on ambition, which involves 51 distinct questions. These questions relate to the ambition of existing climate mitigation targets, participation and victory in competitions for climate action, cities' vision on achieving climate neutrality by 2030, the intended 2030 target (absolute-zero or net-zero GHG emissions), and its timing and expected residual emissions. The questions also gathered insight from cities on interventions for closing the gap, relevant policy instruments, and up to three interventions to be scaled-up in the future in different sectors. The main sectors in these questions relate to stationary energy, renewable energy generation, transport, public lighting, and waste. Two more additional questions are included that deal with regular disclosure on climate action and progress towards achieving climate targets.

The second analytical domain focuses on collaboration (and working together) where 18 distinct questions are utilised. These questions relate to the main stakeholders who are currently involved in formulating and implementing climate change mitigation policies and the types of support from regional and/or national levels of government to formulate and implement policies for climate mitigation. The questions also involve descriptions of (i) most relevant regional and national activities and programmes that are helping cities accelerate the transition to achieve climate neutrality by 2030, (ii) forms of collaboration with the private sector to advance the agenda for climate policy, (iii) activities for citizen engagement, (iv) programmes and/or projects to engage citizens in climate change mitigation policies, as well as (v) actions targeting behavioural change and more sustainable lifestyles. Moreover, partnerships with research centres and academia are questioned along with the collaboration and exchanges with other cities in aspects related to the climate neutrality transition as well as the willingness to support or train other cities in designing and implementing climate neutrality policies. Working together with stakeholders to implement smart city projects as well as engaging with actors in financing and investment and with stakeholders who support data collection on issues that concern or are linked to climate change are other aspects that are taken into account.

The 51 distinct questions for ambition and the 18 distinct questions for collaboration are highlighted in SM2 [65]. This provides transparency for the questions that are used in the definition of TGs. Each of the 69 questions is given a maximum value and each answer option is represented by a fraction of the maximum value based on its relevance to climate neutrality. The median aggregated scores based on the cities' responses in each analytical domain are used to categorise the 112 Mission Cities in four groupings that represent different combinations of values above and below the median score. In particular, for a given Mission City U_j, the metric of $A(U_j)$ represents the degree of ambition and $C(U_j)$ represents the degree of collaboration obtained by summing up the scores of all questions relevant to the respective domain. Equations (1)–(4) define the conditions of each TG that compare $A(U_j)$ and $C(U_j)$ to the corresponding median values A_m and C_m of the entire cohort of Mission Cities.

$$TG1 = \{U_j : A(U_j) \geq A_m \;\&\; C(U_j) \geq C_m\} \tag{1}$$

$$TG2 = \{U_j : A(U_j) < A_m \;\&\; C(U_j) \geq C_m\} \tag{2}$$

$$TG3 = \{U_j : A(U_j) < A_m \;\&\; C(U_j) < C_m\} \tag{3}$$

$$TG4 = \{U_j : A(U_j) \geq A_m \;\&\; C(U_j) < C_m\} \tag{4}$$

with $j = 1, 2, \ldots, 113$ (Mission Cities).

2.3. Additional characterisation and descriptive statistics

The third methodological step involves additional characterisation and descriptive statistics for the TGs and for eligible and Mission cities in general. Box plots are used to analyse data on the total GHG emissions resulting from the most recent emissions inventory (metric tonnes CO_2 equivalent), the number of inhabitants, and the land area within the administrative boundary (in square km). The land area can be the same or different than the geographic boundary that corresponds to the climate neutrality target, if justified sufficiently. Data on emissions and the number of inhabitants are used to analyse emissions per capita (metric tonnes CO_2 equivalent per capita). Data on emissions, population, and land area involved at most 12 outliers (3.3% of 362 eligible cities) when defined as two times the standard deviation from the mean. Considering the different variables, there are 10 outliers greater than 11.2 $MtCO_2eq$ for emissions, seven outliers greater than 2.4 million for population, and 12 outliers greater than 7995 km^2 for land area. There were only four outliers for emissions per capita (1.1% of 362 eligible cities based on values greater than 21.6 tCO_2eq per capita). Outliers are

omitted from the box plots. The total number of cities with reported emissions is 304 (with 58 missing values). Descriptive statistics based on central tendency and variability are included in SM1 [65]. A Kruskal-Wallis H Test or one-way ANOVA on ranks is performed to determine statistical significance.

A total of 20 questions are used to analyse the sector(s), the degree of implementation (fully implemented, under implementation, not started), and scale (smaller than district/neighbourhood scale, district/neighbourhood scale, city scale, and greater than city scale) of current, particularly impactful climate mitigation measures (up to five per city). Sectors include stationary energy and/or energy generation, transport, agriculture, forestry and other land use, industrial processes and product use, waste/wastewater, or combinations. The analysis provides additional insight into integrated and holistic approaches (scale and scope) and capacity (implementation). These responses are aggregated for eligible cities, Mission Cities, and TGs based on the percentages of cities, the total number of measures, or the mean number of measures per city for comparison as reported in SM1 [65]. Another analysis is based on the percentage of cities where various actors are identified as main stakeholders. The ranks of the main stakeholders per grouping are also analysed in a correlation matrix based on Spearman rank correlation coefficients.

2.4. Qualitative and quantitative analyses by thematic grouping

The next three methodological steps involve qualitative and quantitative analyses of the cities' visions, the main barriers, gaps, and assistance needs, as well as favourable conditions and opportunities for each TG, compared with the same analysis performed for all eligible and Mission Cities. One of the questions in the section of the EOI questionnaire on vision and ambition allows entering a free-text answer to describe how achieving climate neutrality by 2030 is envisioned, i.e., how the city plans to accelerate the transition and close the gap to (net-) zero GHG emissions by 2030. The responses to this common free-text question are read for all cities in a given TG to enunciate corresponding narratives. Cross-cutting patterns are identified and compared with the text analysis as reported in SM1 [65]. Within this comprehensive process, a keywords search is conducted following a text processing procedure applied to the original free-text answers to ease spotting recurrent words and expressions, including lemmatisation, harmonisation of words by British/American spelling, and nounification (i.e., transforming adverbs, verbs, and adjectives into nouns based on the mutual degree of similarity).

Subsequently, the analysis of the main barriers, gaps, and assistance needs is performed for cities in each TG and for the two broader cohorts of eligible and Mission Cities. Specifically, the EOI questionnaire involves nine questions that are dedicated to understanding the main barriers, gaps, and assistance needs cities envisage to encounter when pursuing climate neutrality by 2030. The responses are collected across 77 options for the overall main barriers regardless of sector and for the main barriers that are more specific to the energy, transport, and waste/wastewater sectors. The responses of the cities are compared for eligible cities, Mission Cities, and TGs based on the percentage of cities where the barrier is expected to be encountered. In view of increasing co-learning among cities, the responses to the main barriers are further ranked and analysed in correlation matrices using the Spearman rank correlation coefficients. City responses to current climate governance, including horizontal oversight of climate mitigation policies, are analysed to determine ways cities are planning to address fragmentation of responsibilities or generate operational capacity. Sankey diagrams are prepared to identify patterns on how cities intend to evolve their current climate governance by linking two aspects: (1) the number of years selected governance structures or allocation of responsibilities have been in place and (2) whether the city is considering changing/adapting current governance structures.

Finally, the investigation is concluded by the analysis of favourable conditions and opportunities for each TG, for eligible cities, and for Mission Cities as a whole. The EOI questionnaire contains the self-assessment of cities based on a common set of favourable conditions or opportunities. In total, 15 questions required cities to perform a self-assessment on whether they could rely on certain favourable conditions based on a five-point Likert scale from one (cannot relate) to five (very much relates). The options relate to various contextual factors, such as a growing, young and above-average educated and skilled population, favourable economic conditions (e.g., high salaries/tax revenues), and a supportive local research environment. The contextual factors further include possibilities for fast authorisation or fast funding/financing processes, the presence of a consolidated communication platform with proven success in disseminating climate awareness, the availability of own funding schemes to moderately resort to external funding for climate policies, and the existence of favourable geo-climatic conditions (e.g., proximity to water bodies, moderate occurrence of climate extremes). Where in lack of any of these favourable conditions, options are given for other opportunities, such as (i) the absence of any major obstacles to climate neutrality and (ii) the chance to exploit the policy window for placing and prioritising the topic of urban climate neutrality on the agenda or (iii) to put forth an example pathway to climate neutrality for many other similar cities to follow. The options also include (iv) the availability of recent R&I solutions that could enable at least one favourable condition, (v) the ability to engage with alternative creative approaches (e.g., collaborations or networking access to crucial knowledge, participation in exploratory studies), and (vi) the capacity to secure enough internal and external funding/financing for climate neutrality projects. Responses are shortened in phrases when visualised, but can be read in full in SM2 [65] (i.e., the EOI questionnaire). A Wilcoxon signed-rank test statistic text is performed to determine whether paired groupings of eligible cities, Mission Cities, and TGs differ with statistical significance considering the entire set of options.

3. Results

Cities seeking to reach climate neutrality represent a range of different characteristics and utilise various approaches in transforming their future trajectories. Systematic evaluations of cities' responses to the EOI questionnaire and the definition of TGs provide an analytical lens for better understanding these characteristics.

3.1. Characteristics of the cities pursuing climate neutrality

Fig. 2 profiles the 112 Mission Cities and the other eligible cities and displays their characterisation by ambition, collaboration, and other descriptive statistics. In the geographical mapping of Fig. 2a, the coordinate points are coloured by TG when the eligible city is a Mission City. EU Member States are shaded in light grey in the background map. The scatterplot in Fig. 2b provides the relative positioning of the cities in ambition (x-axis) and collaboration (y-axis). Here, the data points represent $A(U_j)$ and $C(U_j)$ for each Mission City U_j using Equations (1)–(4). The median values for ambition (A_m) and collaboration (C_m) are used to define the quadrants of the coordinate plane. Cities that excel in both ambition and collaboration form TG1 (the top right quadrant in Fig. 2b) and amount to 40 cities. Diametrically opposite are cities in TG3 for which such operational dimensions of the analytical domains are comparatively underdeveloped ($n = 39$). Finally, cities in TG2 have above-median values in collaboration ($n = 17$), and those in TG4 in ambition ($n = 17$).

A Kruskal-Wallis H Test is performed to determine statistical significance among the analysed groups where the TGs have statistical significance at $p < .01$ for emissions, population, and land area. The boxplots in Fig. 2c represent the median values and the interquartile range of data on emissions, population, emissions per capita, and land area. Mission Cities in TG3 span the widest range in emissions and population, cities in TG1/TG2 can have higher/lower emissions per

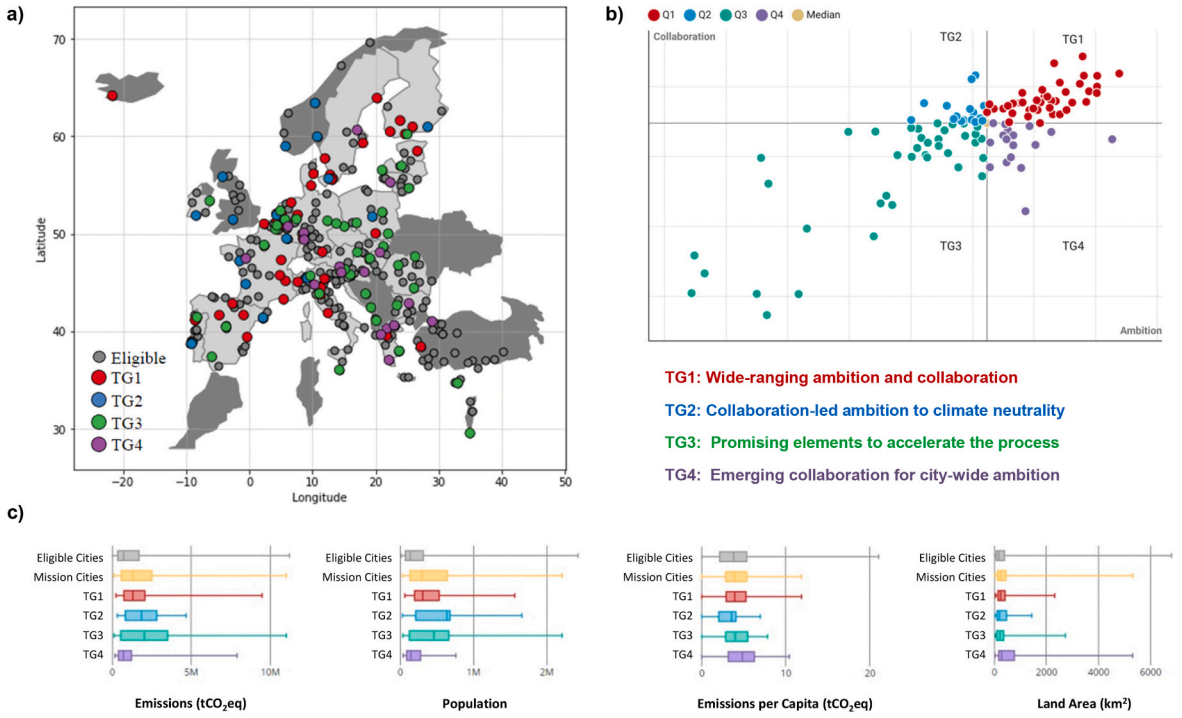


Fig. 2. Mapping of the eligible and Mission Cities (a), characteristics by ambition and collaboration (b) and descriptive statistics (c). Some eligible cities did not give consent to be identified and are excluded from the mapping while included in all analyses.

capita, and cities in TG4 can extend over wider geographical areas. In addition, cities in TG1 and TG4 have greater experience with the implementation of key climate mitigation measures at the city scale that intersect multiple emitting sectors, e.g., energy, transport, and waste as reported in SM1 [65]. Collaboration across different stakeholders is strongest in TG1 and TG2 where almost all cities identify citizens and the private sector as being among the main stakeholders.

In total, Mission Cities come with an emissions reduction potential of 318.3 $MtCO_2eq$ (nearly 50% of that associated with all 362 eligible cities). Those in the TGs add to 114.9 $MtCO_2eq$ (TG1, 36.1%), 45.3 $MtCO_2eq$ (TG2, 14.2%), 90.1 $MtCO_2eq$ (TG3, 28.3%), and 68.0 $MtCO_2eq$ (TG4, 21.4%). A better understanding of the characteristics of the cities in each TG can support ways of realising the mitigation potentials. For example, there is an overarching approach of wide-ranging ambition and collaboration in TG1 and collaboration-led ambition for climate neutrality in TG2. The other TGs involve promising elements to accelerate the process (TG3) and emerging collaboration for city-wide ambition (TG4). Fostering co-learning across the TGs can accelerate the pace of reaching climate neutrality within this decade.

3.2. *Visions for climate neutrality by thematic grouping*

Transforming cities into climate-neutral cities is a visionary process that requires a complete shift in the mobilisation of resources through creative, mission-oriented approaches. Cross-cutting patterns in the visions for climate neutrality of each group indicate the main approaches that are being planned to accelerate the transition by 2030 and enunciate the corresponding narratives. In particular, there are wide-ranging partnerships and portfolios of strategic and integrated interventions in TG1. Collaboration is a way of overcoming urban challenges in TG2, while some cities aim to be regional trendsetters with greater needs for policy-learning and twinning in TG3. In TG4, there are emerging governance structures, partnerships, and collaboration with multiple strategies and master plans in place. The text analysis in SM1 [65] summarises the cross-cutting patterns within and across the narratives.

Mission Cities in **TG1** are found to align ambitions for climate neutrality with a wide range of actions from efficient urban infrastructure and expansion of renewable energy capacity to the diversification of financial tools to catalyse local investment. TG1 cities present multiple strengths in putting forth ambitious and comprehensive transformations through partnerships and citizen engagement. Flagship projects of strategic and integrated interventions are planned in a portfolio approach, including those to phase-out fossil fuels, accelerate the energy transition, ensure fossil-fuel free municipalities, enhance carbon sinks within the municipality to manage residual emissions, and increase collective solutions at the district level. Enabling enduring behavioural change is seen in connection with changes in urban infrastructure. Large-scale rollout of mitigation measures, proximity-oriented urban planning, renewable energy systems, smart coupling of transport, heat, cold and power, sustainable land use, urban renaturing, and circularity are among the strategic actions that are planned for climate neutrality.

To realise this ambition, cities in TG1 strengthen climate governance through co-design and co-implementation, cross-departmental collaboration, working across and maximising synergies among different divisions, breaking down silos, overcoming divisional planning, and mobilising a dynamic and diverse network of actors. There is emphasis on ambitious mission-oriented partnerships to allow "next-level integration" between sectors. In TG1, ambition is also emphasised in the context of accelerating and deepening policies for energy and ecological transitions, coordinating strategies across sectors, land uses, and time scales, bringing an innovative and human-centric approach to climate neutrality, and steering peer-to-peer learning across Europe, sector coupling, and re-use of waste heat. Experimentation with new models of urban development goes in tandem with partnerships among scientific institutions and public-private stakeholders. Active participation and strengthening a quadruple helix are underlined as ways of catalysing action. Radical visions of change involve transformative dynamics in bringing together interventions mandated by the city and bottom-up initiatives, which hold promise in terms of climate mitigation potential.

In **TG2**, narratives more often emphasise complex urban challenges while collaboration is seen as a way of overcoming these issues to increase ambition toward climate neutrality. Collaboration is often placed

at the center of action to change existing pathways and shift away from environmental problems, including air pollution. A "one city approach" is indicated to be the focal point of action for coordinating across institutional and sectoral boundaries. Partnerships of civic society, businesses, researchers, and various levels of government are seen as a strategic approach for maximising decarbonisation opportunities where sectors intersect. Tools for collaboration include green capital partnerships, upscaling of innovative projects and approaches, and incentives for sustainable behaviour on a city scale. Moreover, there is a frequent emphasis on social, economic and environmental master plans, climate action plans, investment plans, and land use plans. Key measures include more compact and sustainable urban growth, decarbonisation across sectors, fossil-free energy supply, and urgent renovation actions. Renewable energy communities are seen as a way of combating energy poverty and coupling climate mitigation with sustainable development. Co-benefits involve cleaner air, green jobs, more efficient housing, and increasing resilience for the most vulnerable. Just transitions are more frequently upheld to ensure a socially fair and inclusive city that is centred on citizen needs.

TG3 includes cities where there is great potential for bringing various elements together to support climate neutrality by 2030 despite different starting points in ambition and collaboration. Some of the most populated cities originally targeted climate neutrality in later years while the Mission is the lever to step up the ambition with clear and focused targets. Multiple cities emphasise their positions as trend-setters for their regions by providing bold examples of ways forward to climate neutrality. Enhancing urban metabolism and the functions of the city as a green, innovative and digital hub represents the main opportunity that will drive climate neutrality in this grouping, along with learning from the experiences of the COVID-19 pandemic in increasing public spaces for health and well-being.

Moreover, many TG3 cities emphasise a greater need for policy-learning and twinning with other cities that may have similar needs and challenges. Cities more frequently raise needs for capacity building while underlining vast opportunities to accelerate progress. Some visions emphasise compact and connected growth with integrated management, urban planning linked with environmental planning, replacing fossil fuels, ensuring 100% renewable energy, eliminating dependence on imported energy, and increasing synergies between existing measures and initiatives. In TG3, energy more frequently forms the focal point of cities' visions for climate neutrality in such aspects as energy management, renewable energy generation technologies, energy communities, polycentric urban form, behavioural change in energy use patterns, and addressing energy and transport poverty.

Mission Cities in **TG4** have high-impact visions for transforming the city by focusing on tackling the major sources of GHG emissions. These visions include an emphasis on low-temperature district heating and cooling networks with renewable energy, transforming the building stock for energy savings, and promoting active or low-carbon mobility within a broader framework of sustainable urban planning. Multiple cities underline the importance of energy communities and co-creation with citizens in the process of supporting a city-wide approach to climate neutrality with emerging collaboration. Examples include randomly selected citizen boards, climate change directorates, workshops for engaging all relevant stakeholders in planning and implementation, and Mission teams to support climate neutrality and new social contracts. Other cities have new administrative departments to implement large-scale projects for climate neutrality. Some cities also express the need for stronger connections with the research and innovation (R&I) community, the private sector, effectively engaging citizens, integrating climate mitigation at the earliest stages of urban planning, and supporting the process of decommissioning infrastructure in the energy sector.

Another cross-cutting pattern for TG4 relates to the presence of multiple strategies and master plans in different domains covering energy, urban planning, transport, buildings, resource use and waste, and/or digitalization. This scope is an advantage to increasing avoid-shift-improve approaches [68], circular economy principles, and/or zero waste targets. Smart charging of electric vehicles and smart operation of heat pumps are emphasised as flexibility options on the demand side. Digitalization-based measures involve data platforms for data-driven management, big data computing, and digital solutions. Some visions place more emphasis on cross-sectoral partnerships within and across cities with the ambition to place climate neutrality at the center of strategic urban planning in the Mission City.

3.3. Contextual factors and main barriers

The 112 Mission Cities represent a wide range of characteristics that give rise to both shared and differing contextual factors underlying their visions. Fig. 3 compares the way different groupings of cities relate with a set of 14 contextual factors. The axis of the dot plot in Fig. 3 is based on a five-point Likert scale from one (cannot relate) to five (very much relates). Ordering is based on the average value for the Mission Cities. The colour coding represents the different TGs of cities from TG1 to TG4 as labelled in the legend. In total, eight of the contextual factors represent favourable conditions while six relate to opportunities (i.e., those that start with "none, but"). The shaded areas around the data points for each contextual factor are relative density curves.

According to their self-assessment, cities in TG1 most closely relate to multiple favourable conditions, including a supportive local research environment, a growing, young, educated and skilled population, consolidated communication platforms to disseminate climate awareness, and fast authorisation, funding, and financing processes. In contrast, cities in TG3 lag behind identifying any favourable conditions while seeing the opportunity of a policy window to pursue and prioritise climate neutrality. Other TGs have a different set of conditions that are seen most favourably, such as economic conditions and own funding schemes in TG2 that holds promise for realising alternative creative approaches, including collaborations and access to critical knowledge. In TG4, cities more closely relate to the absence of favourable conditions while also anticipating the opportunity of opening an example pathway for other cities on the same journey. The larger group of eligible cities represents a mix of different responses while showing less confidence in the use of alternative creative approaches (e.g., collaborations or networking access to crucial knowledge, and participation in exploratory studies). The results are also analysed with the Wilcoxon signed-rank test statistic. Significance with $p < .01$ and $p < .05$ is given in SM1 [65].

The transition toward reaching climate neutrality involves multiple barriers that need to be overcome during the process, including through innovation and collaboration within the urban system. Based on an analysis of 77 main barriers for cities with and without sector specification, there are both similarities and differences in those barriers cities expect to encounter. In this scope, Fig. 4 first compares the 24 possible main barriers that cities envisage to be of relevance in the process of pursuing climate neutrality by 2030 without sector specification across all eligible cities, Mission Cities, and the TGs. The ordering is based on the percentage of cities that expect to encounter a given barrier among Mission Cities ($n = 113$). Each coloured dot represents the percentage value for all eligible cities (grey dots), Mission Cities (yellow dots), and the TGs of Mission cities (TG1 red, TG2 blue, TG3 green, and TG4 purple dots). The shaded areas around the data points represent relative concentrations as density curves.

Lack of funding and financing schemes as well as fragmentation of responsibilities are relevant for 66.0% and 46.4% of all eligible cities and 74.1% and 59.8% of Mission Cities, respectively. In TG2, both of these barriers are relevant for 76.5% of cities as the top main barrier. At the city scale, a siloed approach can further inhibit more integrated urban planning and the delivery of related co-benefits, including better social opportunities [69], health [70], and climate adaptation, such as improved resilience to floods [71] and water scarcity [72]. Other critical

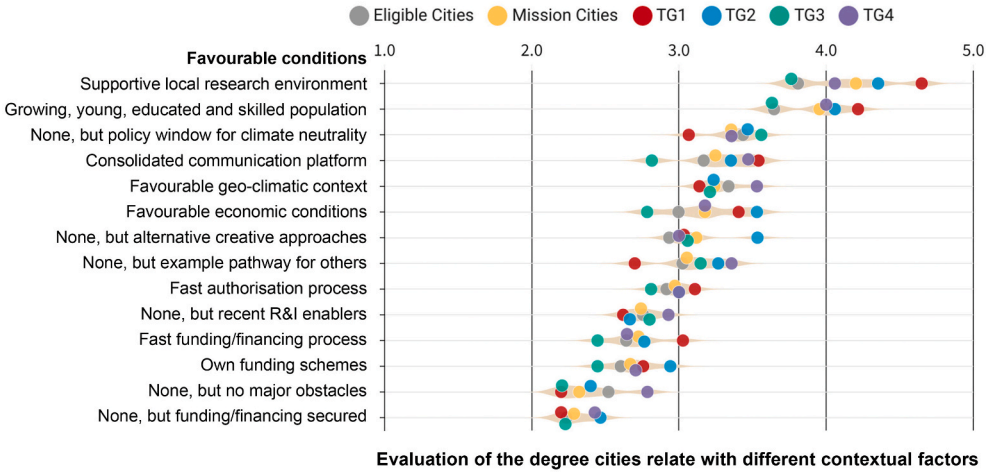


Fig. 3. Comparison of a set of 14 contextual factors across eligible cities, Mission Cities, and the thematic groupings.

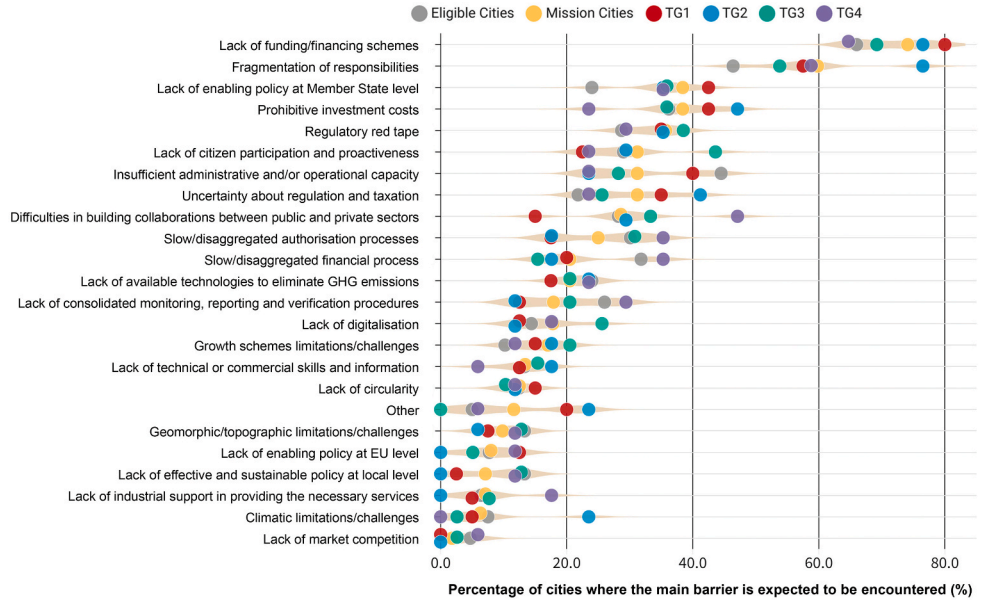


Fig. 4. Envisaged main barriers that are expected to be encountered by eligible cities, Mission Cities, and the thematic groupings.

barriers are more differentiated across the various cities. Difficulties in building collaborations between public and private sectors as a barrier is ranked third in TG4, which is relevant for 47.1% of cities while having lower relevance in the other TGs (15.0%–33.3%). Another barrier that is relatively more relevant for TG4 than others involves slow and disaggregated authorisation processes (35.3%), representing a need for acceleration and coordination. Lack of citizen participation and proactiveness – essential components for societal engagement [73] – stand out as a barrier in TG3 flagged by 43.6% of the cities. Insufficient administrative and/or operational capacity is expected to be a main barrier in 44.5% of all eligible cities and a similar share (40.0%) of cities in TG1. Co-learning between cities with similar barriers will be instrumental in identifying and increasing ways of targeting common needs.

These results are further analysed in a correlation matrix based on Spearman rank correlation coefficients to determine the groupings with the least and most associated rankings for the main barriers as reported in SM1 [65]. The correlation matrices provide another means of finding similarities and differences among the main barriers that are expected in the groupings. Here, the least associated rankings take place among TG2 and TG4 and the most associated rankings are among the Mission Cities and both TG1 and TG3.

Fig. 5 provides the analyses of the main barriers with sector specification across the different TGs. In the energy sector (Fig. 5a), cities identify the main barrier to be high initial capital costs with a share of 52.9%–88.2% relevance. For TG4, unfavourable power pricing rules are the next most relevant barrier with 52.9% of cities indicating its importance. Perceived technology performance uncertainty and risk is deemed relevant for 47.1% of cities in TG2, possibly requiring greater collaborations with academia, R&I institutions, and the private sector. Alternatively, business models and market design oriented to energy communities, decision schemes [73] and preferences for peer-to-peer trading [74], and issues of fairness [75,76] among prosumers [77] can be used to facilitate system-level advances. Considering needs for multi-level climate governance [78] and upscaling actions [79], the lack of enabling energy policy at the country level has relatively high relevance in TG1 at 40.0%. In comparison, responses of all eligible cities concerning the main barriers in energy are most similar to those of Mission Cities in the lack of a legal framework for independent power producers (19.9% and 19.6%).

In the transport sector (Fig. 5b), the main barriers, gaps, and assistance needs that cities most frequently expect to encounter are high initial capital costs. The barriers that follow have a more diverse range

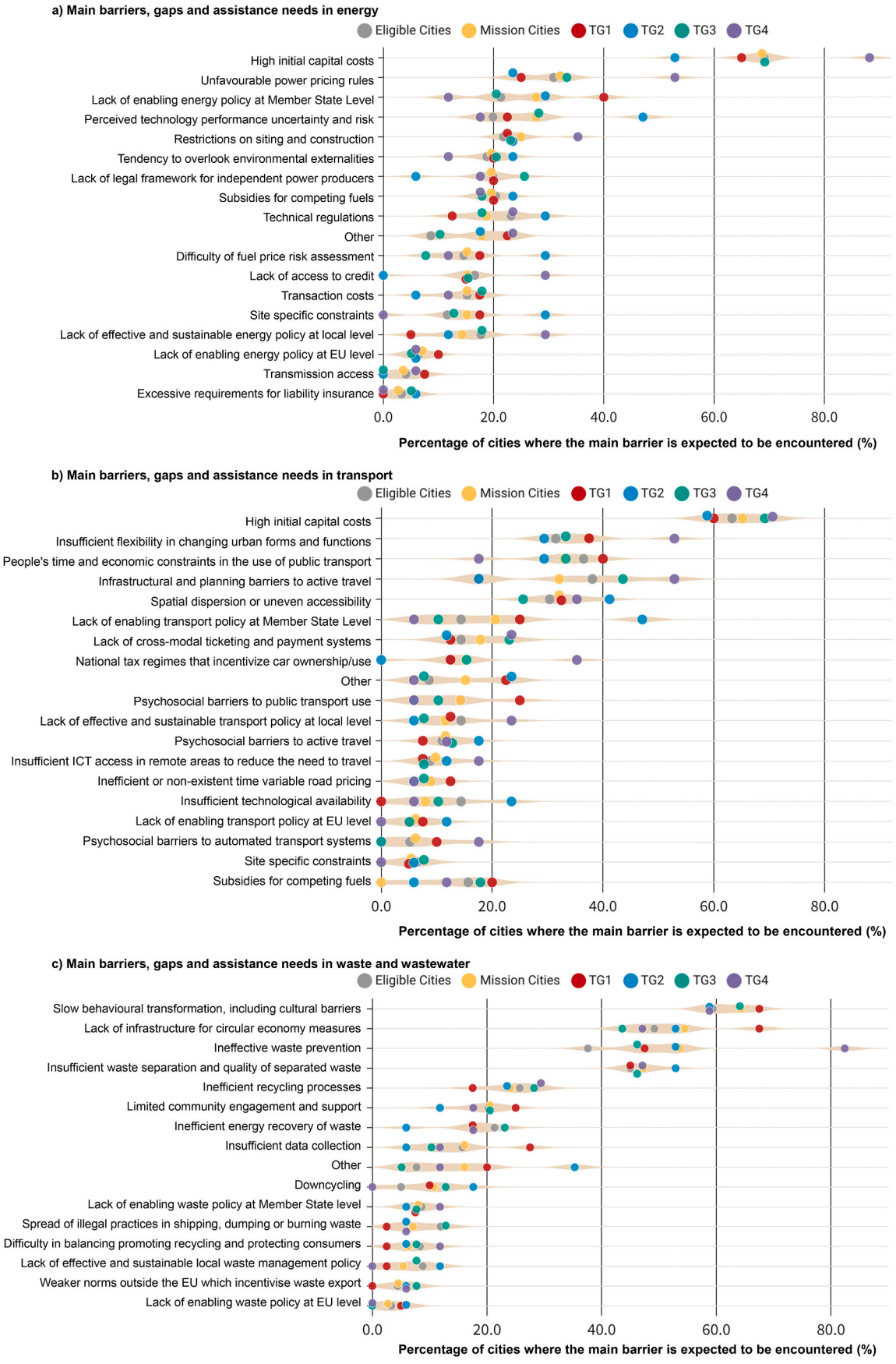


Fig. 5. Main barriers, gaps, and assistance needs that are expected to be encountered by cities in the energy (a), transport (b), and waste and wastewater (c) sectors across eligible cities, Mission cities, and the thematic groupings.

across the various cities. Insufficient flexibility in changing urban forms and functions, particularly to reduce trip lengths, is a top selection among Mission Cities in TG4 (52.9%). Cities in the same grouping further expect infrastructural and planning barriers to active travel, such as a lack of sidewalks and cycling lanes (again 52.9%). Both of these selections suggest that the existing urban layouts in these cities are seen to pose a potential barrier to avoid, shift, and improve strategies for transport [80]. Another main barrier that is expected by cities in TG2 far above other Mission Cities is the lack of enabling transport policy at the country level (47.1%), which will require greater effort for multi-level governance [78]. In the same group of cities, spatial dispersion or uneven accessibility is also selected as a predominant barrier (41.2%), which can be a cause of carbon lock-in [80] and result in additional emissions [81] due to dispersed urban growth schemes. Cities in TG1 relate to the main barrier of time and economic constraints in the use of public transport by their citizens (40.0%) that will require dedicated interventions. Cross-modal ticketing and payment systems can also encourage modal shifts. While selected less frequently by cities, various values [82] and psychosocial barriers [83] to public and active travel are indicated, which may require extra awareness raising and appreciation of co-benefits to be overcome within the societal landscape.

In the waste and wastewater sector (Fig. 5c), Mission Cities expect to encounter certain barriers due to slow behavioural transformation, including cultural barriers, at 64.3%. This barrier is further reinforced by the second most frequently identified barrier of lack of infrastructure for circular economy measures at 54.5% (and even higher in TG1, 67.5%). For example, choice architectures usually require interactions between efficient infrastructures that can shape societal norms [84] and provide nudges for behavioural change [85,86]. Better infrastructure for circular economy practices [87] can also open new options in municipal waste management systems [88], building retrofitting [89], electronic waste [90], textiles [91], photovoltaic panels [92], electric vehicle batteries [93] and secondary uses [94], and biomass overharvests [95]. Ineffective waste prevention – relating to the initial stage of the waste hierarchy – is more intensively identified in one of the groupings (TG4) at 82.4% of cities while overall, all eligible cities are far less concerned with this possible barrier, at 37.6%. Insufficient waste separation and quality of separated waste spans a narrower range (45.0%–52.9%) with other sectoral barriers identified by at most 35% of the cities.

Two additional analyses support the results for determining opportunities among Mission Cities. Correlation matrices using the Spearman rank correlation coefficients are used to analyse the main barriers to support co-learning processes between TGs having the most associated rankings. The values of the Spearman rank correlation coefficients (ρ) for the main barriers regardless of sector range between 0.56 and 0.93 as observed from Fig. 6. The main barriers regardless of sector have the most associated rankings among the Mission Cities and both TG1 and TG3 ($\rho = 0.93$). In contrast, the ranks for the main barriers regardless of sector are least associated among TG2 and TG4 ($\rho = 0.56$). The values of the Spearman rank correlation coefficients for the main barriers in energy, transport, as well as waste and wastewater have a bigger range between 0.19 and 0.92, which can be observed from the sector specific analyses in SM1 [65]. Hence, there are both similarities and differences across the TGs that need to be leveraged in the effort of stimulating co-learning among cities and reaching climate neutrality.

Moreover, cities are recognising that implementing deep changes in urban governance [96] driven by the imperative of addressing climate change is an opportunity to address some of these main barriers. The Sankey diagram in Fig. 7 is based on the cities' aggregated responses to the duration of current climate governance or allocation of responsibilities, including horizontal oversight of climate mitigation policies. The findings provide evidence on a range of durations in climate governance structures. Among the Mission Cities, only 51 cities and mostly those in TG1 followed by TG3 had climate governance structures for more than 5 years while still largely planning to change or adapt these structures. This attests to the proactive approach of Mission Cities to transform processes to reach climate neutrality. Across all TGs, 77% of Mission Cities are planning to change or adapt current climate governance structures. In the remaining 23%, such options can be considered as a capacity-building manoeuvre. In TG3, two cities did not respond to the duration of the current climate governance while expecting to change and adapt current climate governance structures, which is not included in the Sankey diagram. Based on corresponding responses in the scope of urban climate governance structures, there are multiple cities where separate departments for transport, environment, buildings, construction, and/or urban planning exist. Such situations are highly conducive to a fragmentation of responsibilities that would need dedicated attention under the Mission.

4. Recommendations and discussion

The results of the analyses that are performed in this research work are useful for synthesizing findings to determine instances where recommendations can provide direct matches to the relevant enablers and/or needs raised by cities in various TGs. As such, this section discusses nine high-level recommendations derived for the different TGs, including a focus on (i) the transformation of siloed into integrated approaches, (ii) inclusive climate governance and collaborations, (iii) innovative financing, welfare and just transition, and (iv) planning, implementation and policy coherence. Moreover, cases where the identified enabler of a given recommendation and/or barrier has a higher percentage relevance in the TG rather than across all Mission Cities are given high priority. In this evaluation, high priority is distinguished by the types of H1 (based on enablers), H2 (based on the barriers to be addressed), H3 (based on both enablers and barriers to be addressed), and H4 (based on the cities' vision only). Such a prioritisation can indicate the main entry points in the pathway towards climate neutrality by 2030. The discussions are then placed in the context of recent advances for Mission Cities and the contributions that analytical perspectives based on TGs bring to the field.

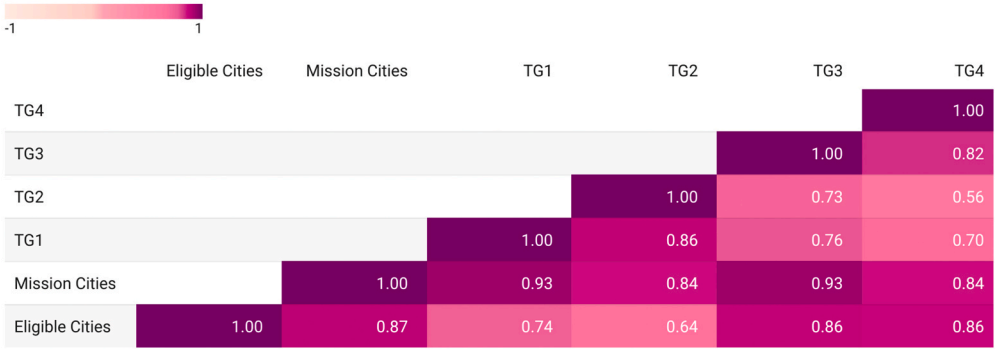


Fig. 6. Correlation matrix for the main barriers that are expected to be encountered by eligible cities, Mission Cities, and the thematic groupings.

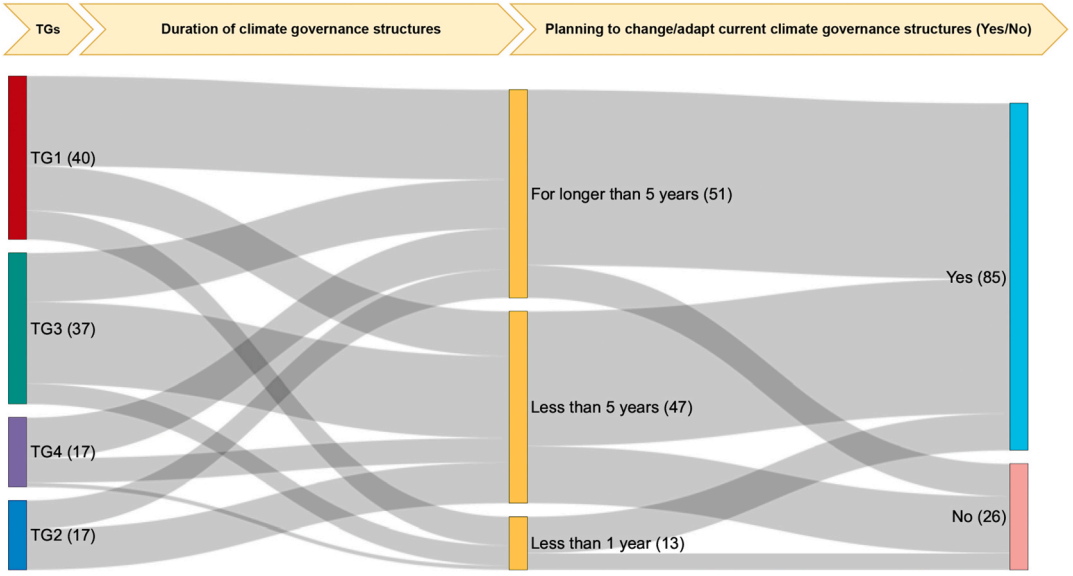


Fig. 7. Responses on current climate governance and plans for changes across thematic groupings.

4.1. Advancing towards climate neutrality together

A thorough analysis of the cities' visions, contextual factors, and expected main barriers as provided in the results allow the synthesis in Table 1 that derives nine high-level recommendations for the 112 Mission Cities. These high-level recommendations cover various aspects of integration [97], governance [98], collaboration [99], climate finance [100], social welfare [101], just transition [102], planning tools [103], implementation, and policy coherence. Each of these recommendations is associated with priorities for the TGs considering the enablers that can be present among contextual factors and the main barriers that can be addressed or even prevented. The opportunity space for realising these high-level recommendations can be amplified when cities have both enablers and needs based on a main barrier to be addressed (marked as H3 in Table 1 and emphasised by double dots). These high-level recommendations can also increase scientific and policy support that can guide approaches to promote "transformational" change. This includes strategic interventions that focus on governance and also deep radical interventions to address inequality, materialism, and lock-in of extractive systems [104]. While the recommendations are derived for Mission Cities, any "follower" or "twin" city willing to embark on the climate neutrality mission can prioritise the recommendations that come closest to their profiles.

The high-level recommendations are discussed in four tracks. The first track is transforming siloed into integrated approaches. Reaching climate neutrality requires an all-encompassing approach across the entire urban system based on opportunities that are present in a given context. This entails coupling sectors with urban planning [105], supporting behavioural change [106], and enhancing carbon sinks. Currently, cities have varying levels of experience in tackling siloed

Table 1
High-level recommendations for the Mission Cities and their priorities for the thematic groupings considering enablers and barriers.

Policy Area	High-Level Recommendations	TG1	TG2	TG3	TG4	Recommendations can be enabled by (E) and used to address barrier(s) (B)
Integration	Transforming siloed into integrated approaches	H1 •	H3 • •	H1 •	H1 •	**E:** Policy window for climate neutrality; growing, young, educated and skilled population; supportive local research environment; recent R&I enablers, **B:** Fragmentation of responsibilities
Governance	Strengthening inclusive climate governance	H1 •	H3 • •	H3 • •	H1 •	**E:** Consolidated communication platform; example pathway for others, **B:** Fragmentation of responsibilities; lack of citizen participation and proactiveness
Collaboration	Broadening collaborations for advancing together	H1 •	H3 • •	H3 • •	H3 • •	**E:** Consolidated communication platform; example pathway for others; Alternative creative approaches, **B:** Difficulties in building collaborations between public and private sectors
Climate Finance	Boosting and managing innovative financing	H3 • •	H3 • •	H4 •	H1 •	**E:** Own funding schemes; fast funding and/or financing process, **B:** Lack of funding and/or financing schemes; prohibitive investment costs
Social Welfare	Increasing co-benefits for social welfare	H1 •	H3 • •	H3 • •	H1 •	**E:** Growing, young, educated and skilled population; example pathway for others, **B:** Growth schemes limitations and challenges
Just Transition	Addressing energy poverty and social issues	H1 •	H3 • •	H3 • •	H1 •	**E:** Growing, young, educated and skilled population, **B:** Growth schemes limitations and challenges
Planning Tools	Increasing science-based approaches in planning	H1 •	H3 • •	H3 • •	H3 • •	**E:** Supportive local research environment; recent R&I enablers **B:** Lack of technical or commercial skills and information; Lack of consolidated monitoring, reporting and verification procedures
Implementation	From co-design to a co-implementation process	H1 •	H3 • •	H4 •	H1 •	**E:** Fast authorisation process; Alternative creative approaches, **B:** Fragmentation of responsibilities
Coherence	Aligning incentives and regulations across scales	H2 •	H1 •	H3 • •	H3 • •	**E:** Policy window for climate neutrality, **B:** Lack of enabling policy at Member State level; lack of effective, sustainable policy at local level

approaches [107], implementing measures to capture synergies for climate mitigation [108], and engaging society at large. For example, Mission Cities in TG1 have relatively more experience in implementing cross-sectoral measures and city-scale measures. Cities in TG1 also express proximity-oriented urban planning and next-level integration between sectors in their visions. At the same time, all Mission Cities can be empowered to transform siloed approaches into integrated strategies, including cities in TG2 that express a larger concern for fragmentation of responsibilities. Despite the challenges of the process, multiple contextual factors, such as a growing, young, educated, and skilled population, a supportive local research environment, recent R&I enablers, and the aspiration to act upon the policy window for climate neutrality can be used to support increasing enablers to build capacity and shift directions.

Second, there is a need for inclusive climate governance and collaborations. Reforming climate governance to counter the fragmentation of responsibilities is an important entry point for ensuring an effective transformation into a climate-neutral city. Most cities recognise that the process of reaching climate neutrality extends beyond the mandates of any single institution and are taking action rapidly. For example, most of the Mission Cities that identified fragmentation of responsibilities as a main barrier have current climate governance structures that are being considered to be changed and/or adapted. Even newer structures include city councils that proclaimed climate emergency and new departments in sustainable development and climate protection. Other cities have established climate steering committees, climate action teams, climate policy divisions, and climate advisory councils. Many cities are starting to promote cross-departmental collaboration while increasing the coordination and horizontal oversight of climate mitigation policies. New transition teams that are involving local departments, businesses, academia, and communities can also learn from more experienced teams for integrated urban planning and cross-sectoral coordination. Other cities are in the process of structuring new public-private partnerships with the mandate of realising specific milestones and pursuing partnerships with universities and research institutes for supporting climate neutrality. In existing collaborations, the private sector and citizens are more active in TG1 and TG2 (also reported in SM1 [65]), which needs to be broadened to all cases. In other cities, hybrid commissions with citizens and co-shared governance models are emerging. Going forward, all Mission Cities will need to deploy creative approaches in broadening collaborations and realising inclusive approaches. Beyond Mission Cities, all cities with climate neutrality ambition can start evolving their current climate governance structures whenever needed.

Third, innovative financing, welfare, and just transition are necessary. Boosting innovative financing tools and managing their simultaneous deployment requires increased local capacity. More advanced cities are already taking steps to realise innovative financing tools, including special funding and stimulus programmes to catalyse green transformation, participatory budgeting, multi-level funds, and crowdfunding campaigns. For instance, several cities have introduced loan schemes with banking institutions or crowdfunding schemes for local energy communities with the city taking part as a partner, also renting public building roof area for solar photovoltaic installations [109]. Revolving funds with equity participation for renewable energy and energy efficiency projects are among other financial instruments while most cities still need to find ways of tapping into capital markets [109]. Joint programming of innovation, thematic calls, multi-sector partnerships, and carbon cooperatives are other examples that should be explored across cities. In addition, increasing co-benefits for public health, generating new green jobs, promoting linkages with sustainable development, taking action against energy and transport poverty, and improving affordable housing [110] are essential. In TG2 and TG3, where growth schemes' limitations and challenges are relatively more frequently expected as a main barrier, attention to increasing co-benefits and addressing social issues with climate mitigation will be valuable in enlarging and acting upon the opportunity space. Overall, all Mission Cities must undertake a comprehensive approach to realising and communicating the co-benefits of climate mitigation for both people and the planet, which can also motivate more stakeholder engagement. Cities need bold action to reach climate neutrality through a sustainable transition that treasures climate justice in the process of designing and implementing climate efforts [111]. Greater levels of climate justice awareness in Mission Cities can also interact with the presence of government financial support, breadth of cities' legal powers, and their ability to identify barriers to climate action [111]. Through increased climate justice awareness and action, a just transition will lead to attaining more attractive, liveable, inclusive and resilient cities for all inhabitants.

The fourth track relates to planning, implementation, and policy coherence. Increasing science-based approaches in planning processes can be facilitated by supportive local research environments and emerging R&I enablers. Increased collaboration with these institutions should be used to transform situations where technical or commercial skills and information are insufficient. For example, data strategies [112] and science-based modelling tools [113] are being deployed across Mission Cities with varying capacities. There is also a need to increase monitoring processes for a green and digital transition [114], including the outcomes of implemented digitalization measures [115]. In addition, ensuring continuity in a process of co-design, co-production [116], empowerment [117], and co-implementation requires capacity as well as creativity in transition management and co-creation. Focusing on processes for sustainability transformations is essential [118] and Mission Cities should uphold a focus on polycentric processes directed towards climate neutrality. Moreover, aligning incentives and regulations across scales is essential for policy coherence. This may include introducing mandatory solar photovoltaic regulations, zoning for renewable energy-based district heating and cooling networks, and ensuring energy-efficient buildings that are also earthquake-resistant. When enabling policies at the national level or effective and sustainable local policy are lacking, such alignment is challenging. This may also be compounded by authorisation processes that are lengthy or disaggregated. In such cases, new climate governance structures that build on the urgency of climate neutrality can provide a means to boost decision-making power and gain speed for a more targeted, mission-oriented approach.

4.2. Recent advances for Mission Cities and ways forward

Beyond the thematic framework that is taken in this research work to cross-compare and connect groupings of cities with their visions, contextual factors, and barriers, scientific literature on cities that are willing to reach climate neutrality is newly emerging. However, the scientific production on the Mission Cities is growing rapidly given the political attention around this one-of-its-kind initiative. For example, another investigation based on the same EOI dataset reveals that many eligible cities already achieved significant emissions reductions in the past through building interventions, upscaled renewable energy production, expanded public transport, and other energy efficiency measures [59]. Nonetheless, the unprecedented pace of emissions reductions dictated by the Mission's target and timeline would require a quadrupling of mitigation efforts in half the time across most eligible cities [59]. For this reason, cross-sectoral planning and implementation with an integrated approach [97] will continue to gain priority, especially in cities that seek absolute zero emissions without any residual emissions.

A rich literature is emerging around the barriers and potential solutions eligible cities have to juggle in chasing climate neutrality by 2030, which nicely complements this study and supports its main findings. In Ulpiani et al. [109], financial barriers are scrutinised considering the estimated capital requirements that are needed to materialise climate neutrality. A complex framework of uncertainties is disclosed around securing private investment, increased interest rates, ineffective

legislative control of the indebtedness level, national underfunding, high fiscal risk, legislative and regulatory variability, political instability, and insufficient internal capacity. Financial barriers are closely linked to financial risks, analysed critically in Ref. [119] together with other eight risk domains to reproduce the complete riskscape around deep decarbonisation in the framework of the Cities Mission [119]. In the social domain, barriers and risks are frequently borne from the difficulties and expertise needed to deliver a transformation that embeds principles of social justice and equity [111]. Other barriers are more sector-specific, for instance those that are associated with the implementation, expansion, and/or diversification of renewable energy sources [120], energy conservation and efficiency in the built environment [121], the deep transformations required in the transport and mobility sector [122], or waste management and the circularity of processes and products [123]. How these barriers interlace and interact with the city-specific context determines the conceptual framework that should guide the design of lower-risk climate-neutral pathways and the prioritisation of certain capacity-building activities over others.

5. Conclusion

Reaching climate neutrality by 2030 will have a crucial role in leading the way to implementing ambitious and collaborative action to address the urgency of climate mitigation across scales. This is the first study that characterises the 112 cities selected for the EU Mission on 100 Climate-Neutral and Smart Cities in groupings to facilitate the process of co-learning among cities and accelerate the climate-neutral journey. More tailored approaches based on the TGs as in this research work is essential for supporting guidance for cities. Cities are found to be engaging in a transformative process while utilising a mix of overarching approaches that can be driven by strengths in ambition, collaboration, or both. More specifically, the new findings advance an understanding of Mission Cities based on five main processes: (i) profiling cities based on key characteristics, (ii) comparing the cities' visions for climate neutrality by 2030 in TGs, (iii) identifying the most prominent contextual factors among TGs relevant to climate neutrality, (iv) comparing the main barriers to be overcome in the process, and (v) deriving and prioritising nine high-level recommendations for the Mission Cities based on enablers and barriers. The implementation of these recommendations has the potential to accelerate climate mitigation action and its co-achievement with the Sustainable Development Goals.

Building on these advances, cities are strongly urged to utilise their strengths to increase synergies between ambition and collaboration during the implementation process. Contextual factors, such as supportive local research environments and emerging R&I enablers, need to be put into action to support stepped-up ambitions. Moreover, barriers revolving around funding and financing as well as fragmentation of responsibilities are relatively more prominent, requiring more and deeper co-learning processes. Strengthening climate governance structures can open new opportunities for integration, climate finance, and policy coherence. The nine high-level recommendations that are derived and prioritised in this study should be used to reinforce a synergistic approach in transformative pathways for climate neutrality and to promote shared approaches to barriers lifting and removal. In doing so, cities in a particular TG can be expected to advance their degree of ambition and collaboration while implementing the objectives of the Mission. Future studies can focus on monitoring the progress in the Mission Cities to inform on advances and evaluate the role of enablers within the observed changes. The unprecedented data that is analysed in this study based on the EOI questionnaire also provides unique value by taking stock of cities' responses and evaluations within a harmonised framework. Similar processes can be considered to complement monitoring phases and site visits by expert personnel may be designed to improve stocktaking processes in the future.

The ongoing implementation of the Cities Mission is mobilising a rich network of actors and stimulating wide-ranging progress in cities [124], which can benefit from the recommendations enshrined in this research work. As cities juggle unprecedented challenges in the transformative process to become climate-neutral by 2030, new insights, strategies, and best practices will be generated. A vibrant environment that fosters exchanges of good practices and experiences among cities with rapid communication and diffusion continues to be essential in building local capacities. The urgency of addressing climate change requires stringent implementation of measures in a credible manner. These advances could inform future analytical support to keep following these pioneering cities in their unprecedented but crucially needed journey towards zero-emissions futures. Further, pioneering efforts for reaching climate neutrality by 2030 based on the Mission Cities in Europe can generate spill over effects for accelerating the pace of other initiatives, including the Race to Zero initiative and Mission Innovation, which have global reach.

Disclaimer

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

Inclusion and ethics

Local and regional research relevant to the field of study has been taken into account in the references.

CRediT authorship contribution statement

Şiir Kılkış: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Giulia Ulpiani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nadja Vetters:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

This study was funded under the Horizon Europe Missions Work Programme 2021–2022 (European Commission Decision C(2022)2975 of May 10, 2022). The analysis by Associate Professor Şiir Kılkış was performed as part of a contract with the Joint Research Centre of the European Commission, in full respect of the confidentiality clause that comes with the use of the underlying dataset.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114315.

References

[1] Lwasa S, Seto KC, Bai X, Blanco H, Gurney KR, Kılkış Ş, et al. Urban systems and other settlements. In: Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R,

McCollum D, et al., editors. Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022. p. 92. https://doi.org/10.1017/9781009157926.010.
[2] Gurney KR, Kılkış Ş, Seto KC, Lwasa S, Moran D, Riahi K, et al. Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100. Glob Environ Chang 2022;73:102478. https://doi.org/10.1016/j.gloenvcha.2022.102478.
[3] Kılkış Ş. Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems. Renew Sustain Energy Rev 2022;167:112733. https://doi.org/10.1016/j.rser.2022.112733.
[4] Sethi M, Lamb W, Minx J, Creutzig F. Climate change mitigation in cities: a systematic scoping of case studies. Environ Res Lett 2020:15. https://doi.org/10.1088/1748-9326/ab99ff.
[5] Burley Farr K, Song K, Yeo ZY, Johnson E, Hsu A. Cities and regions tackle climate change mitigation but often focus on less effective solutions. Commun Earth Environ 2023;4:439. https://doi.org/10.1038/s43247-023-01108-6.
[6] Salvia M, Reckien D, Pietrapertosa F, Eckersley P, Spyridaki N-A, Krook-Riekkola A, et al. Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU. Renew Sustain Energy Rev 2021;135:110253. https://doi.org/10.1016/j.rser.2020.110253.
[7] Peris-Blanes J, Segura-Calero S, Sarabia N, Ribó-Pérez D. The role of place in shaping urban transformative capacity. The case of València (Spain). Environ Innov Soc Transitions 2022;42:124–37. https://doi.org/10.1016/j.eist.2021.12.006.
[8] Vedeld T, Hofstad H, Solli H, Hanssen GS. Polycentric urban climate governance: creating synergies between integrative and interactive governance in Oslo. Environ Policy Gov 2021;31:347–60. https://doi.org/10.1002/eet.1935.
[9] Hsu A, Tan J, Ng YM, Toh W, Vanda R, Goyal N. Performance determinants show European cities are delivering on climate mitigation. Nat Clim Chang 2020;10:1015–22. https://doi.org/10.1038/s41558-020-0879-9.
[10] Kona A, Monforti-Ferrario F, Bertoldi P, Baldi MG, Kakoulaki G, Vetters N, et al. Global Covenant of Mayors, a dataset of greenhouse gas emissions for 6200 cities in Europe and the Southern Mediterranean countries. Earth Syst Sci Data 2021;13:3551–64. https://doi.org/10.5194/ESSD-13-3551-2021.
[11] Rivas S, Urraca R, Bertoldi P. Covenant of Mayors 2020 achievements: a two-speed climate action process. Sustainability 2022:14. https://doi.org/10.3390/su142215081.
[12] Rivas S, Urraca R, Palermo V, Bertoldi P. Covenant of Mayors 2020: drivers and barriers for monitoring climate action plans. J Clean Prod 2022;332:130029. https://doi.org/10.1016/j.jclepro.2021.130029.
[13] Copernicus Institute Data-Driven EnviroLab, CDP. Global climate action 2023: ambition of cities. Regions and Companies; 2023.
[14] Intergovernmental Panel on Climate Change. Summary for Policymakers. In: Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, et al., editors. Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022. https://doi.org/10.1017/9781009157926.001.
[15] Kloenne U, Nauels A, Pearson P, DeConto RM, Findlay HS, Hugelius G, et al. Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds. Nat Clim Chang 2022. https://doi.org/10.1038/s41558-022-01566-4.
[16] Wunderling N, Winkelmann R, Rockström J, Loriani S, Armstrong McKay DI, Ritchie PDL, et al. Global warming overshoots increase risks of climate tipping cascades in a network model. Nat Clim Chang 2022. https://doi.org/10.1038/s41558-022-01545-9.
[17] Hoegh-Guldberg O, Jacob D, Taylor M, Guillén Bolaños T, Bindi M, Brown S, et al. The human imperative of stabilizing global climate change at 1.5°C. Science 2019;80:365. https://doi.org/10.1126/science.aaw6974.
[18] Gambhir A, George M, McJeon H, Arnell NW, Bernie D, Mittal S, et al. Near-term transition and longer-term physical climate risks of greenhouse gas emissions pathways. Nat Clim Chang 2022;12:88–96. https://doi.org/10.1038/s41558-021-01236-x.
[19] van Soest HL, den Elzen MGJ, van Vuuren DP. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. Nat Commun 2021;12:2140. https://doi.org/10.1038/s41467-021-22294-x.
[20] Höhne N, Gidden MJ, den Elzen M, Hans F, Fyson C, Geiges A, et al. Wave of net zero emission targets opens window to meeting the Paris Agreement. Nat Clim Chang 2021;11:820–2. https://doi.org/10.1038/s41558-021-01142-2.
[21] Shabb K, McCormick K. Achieving 100 climate neutral cities in Europe: investigating climate city contracts in Sweden. Npj Clim Action 2023;2:6. https://doi.org/10.1038/s44168-023-00035-8.
[22] Linton S, Clarke A, Tozer L. Strategies and governance for implementing deep decarbonization plans at the local level. Sustainability 2021;13:1–22. https://doi.org/10.3390/su13010154.
[23] Sachdeva S, Hsu A, French I, Lim E. A computational approach to analyzing climate strategies of cities pledging net zero. Npj Urban Sustain 2022;2:21. https://doi.org/10.1038/s42949-022-00065-x.
[24] D'Alessandro S, Cieplinski A, Distefano T, Dittmer K. Feasible alternatives to green growth. Nat Sustain 2020;3:329–35. https://doi.org/10.1038/s41893-020-0484-y.
[25] Bedi C, Kansal A, Mukheibir P. A conceptual framework for the assessment of and the transition to liveable, sustainable and equitable cities. Environ Sci Policy 2023;140:134–45. https://doi.org/10.1016/j.envsci.2022.11.018.
[26] Steininger KW, Williges K, Meyer LH, Maczek F, Riahi K. Sharing the effort of the European Green Deal among countries. Nat Commun 2022;13:3673. https://doi.org/10.1038/s41467-022-31204-8.
[27] Winkler H, Lecocq F, Lofgren H, Vilariño MV, Kartha S, Portugal-Pereira J. Examples of shifting development pathways: lessons on how to enable broader, deeper, and faster climate action. Clim Action 2022;1:27. https://doi.org/10.1007/s44168-022-00026-1.
[28] Bechtel MM, Scheve KF, van Lieshout E. Improving public support for climate action through multilateralism. Nat Commun 2022;13:6441. https://doi.org/10.1038/s41467-022-33830-8.
[29] Hsu A, Rauber R. Diverse climate actors show limited coordination in a large-scale text analysis of strategy documents. Commun Earth Environ 2021;2:30. https://doi.org/10.1038/s43247-021-00098-7.
[30] Stokes EC, Seto KC. Characterizing urban infrastructural transitions for the Sustainable Development Goals using multi-temporal land, population, and nighttime light data. Remote Sens Environ 2019;234. https://doi.org/10.1016/j.rse.2019.111430.
[31] Peng Y, Bai X. Experimenting towards a low-carbon city: policy evolution and nested structure of innovation. J Clean Prod 2018;174:201–12. https://doi.org/10.1016/J.JCLEPRO.2017.10.116.
[32] Peng Y, Wei Y, Bai X. Scaling urban sustainability experiments: contextualization as an innovation. Clean Prod 2019;277:302–12. https://doi.org/10.1016/j.jclepro.2019.04.061.
[33] Horak D, Hainoun A, Neumann H-M. Techno-economic optimisation of long-term energy supply strategy of Vienna city. Energy Policy 2021;158:112554. https://doi.org/10.1016/j.enpol.2021.112554.
[34] Pulselli RM, Broersma S, Martin CL, Keeffe G, Bastianoni S, van den Dobbelsteen A. Future city visions. The energy transition towards carbon-neutrality: lessons learned from the case of Roeselare, Belgium. Renew Sustain Energy Rev 2021;137:110612. https://doi.org/10.1016/j.rser.2020.110612.
[35] Si F, Du E, Zhang N, Wang Y, Han Y. China's urban energy system transition towards carbon neutrality: challenges and experience of Beijing and Suzhou. Renew Sustain Energy Rev 2023;183:113468. https://doi.org/10.1016/j.rser.2023.113468.
[36] Kang H, Jung S, Lee M, Hong T. How to better share energy towards a carbon-neutral city? A review on application strategies of battery energy storage system in city. Renew Sustain Energy Rev 2022;157:112113. https://doi.org/10.1016/j.rser.2022.112113.
[37] Maya-Drysdale D, Krog Jensen L, Vad Mathiesen B. Energy vision strategies for the EU green new deal: a case study of European cities. Energies 2020;13. https://doi.org/10.3390/en13092194.
[38] Linton S, Clarke A, Tozer L. Technical pathways to deep decarbonization in cities: eight best practice case studies of transformational climate mitigation. Energy Res Soc Sci 2022;86:102422. https://doi.org/10.1016/j.erss.2021.102422.
[39] Horak D, Hainoun A, Neugebauer G, Stoeglehner G. A review of spatio-temporal urban energy system modeling for urban decarbonization strategy formulation. Renew Sustain Energy Rev 2022;162:112426. https://doi.org/10.1016/j.rser.2022.112426.
[40] Yazdanie M, Orehounig K. Advancing urban energy system planning and modeling approaches: gaps and solutions in perspective. Renew Sustain Energy Rev 2021;137:110607. https://doi.org/10.1016/j.rser.2020.110607.
[41] Derkenbaeva E, Halleck Vega S, Hofstede GJ, van Leeuwen E. Positive energy districts: mainstreaming energy transition in urban areas. Renew Sustain Energy Rev 2022;153:111782. https://doi.org/10.1016/j.rser.2021.111782.
[42] Nematchoua MK, Marie-Reine Nishimwe A, Reiter S. Towards nearly zero-energy residential neighbourhoods in the European Union: a case study. Renew Sustain Energy Rev 2021;135:110198. https://doi.org/10.1016/j.rser.2020.110198.
[43] Wenz K-P, Serrano-Guerrero X, Barragán-Escandón A, González LG, Clairand J-M. Route prioritization of urban public transportation from conventional to electric buses: a new methodology and a study of case in an intermediate city of Ecuador. Renew Sustain Energy Rev 2021;148:111215. https://doi.org/10.1016/j.rser.2021.111215.
[44] Kouridis C, Vlachokostas C. Towards decarbonizing road transport: environmental and social benefit of vehicle fleet electrification in urban areas of Greece. Renew Sustain Energy Rev 2022;153:111775. https://doi.org/10.1016/j.rser.2021.111775.
[45] Ríos-Ocampo JP, Olaya Y, Osorio A, Henao D, Smith R, Arango-Aramburo S. Thermal districts in Colombia: developing a methodology to estimate the cooling potential demand. Renew Sustain Energy Rev 2022;165:112612. https://doi.org/10.1016/j.rser.2022.112612.
[46] Zi Z, Ji D, Jie L, Di W, Guanghao C. Enhancing energy–climate–economy sustainability in coastal cities through integration of seawater and solar energy. Renew Sustain Energy Rev 2023;183:113477. https://doi.org/10.1016/j.rser.2023.113477.
[47] Fernández ME, Gentili JO, Campo AM. Solar access: review of the effective legal framework for an average argentine city. Renew Sustain Energy Rev 2022;156:112008. https://doi.org/10.1016/j.rser.2021.112008.
[48] Shadbahr J, Ebadian M, Gonzales-Calienes G, Kannangara M, Ahmadi L, Bensebaa F. Impact of waste management and conversion technologies on cost and carbon footprint - case studies in rural and urban cities. Renew Sustain Energy Rev 2022;168:112872. https://doi.org/10.1016/j.rser.2022.112872.
[49] Bastida-Molina P, Ribó-Pérez D, Gómez-Navarro T, Hurtado-Pérez E. What is the problem? The obstacles to the electrification of urban mobility in Mediterranean cities. Case study of Valencia, Spain. Renew Sustain Energy Rev 2022;166:112649. https://doi.org/10.1016/j.rser.2022.112649.

[50] Wu J, Zuidema C, de Roo G. Collaborative efforts on energy transition in urban China: institutional enabling and constraining conditions. Renew Sustain Energy Rev 2022;168:112873. https://doi.org/10.1016/j.rser.2022.112873.
[51] Hsu A, Wang X, Tan J, Toh W, Goyal N. Predicting European cities' climate mitigation performance using machine learning. Nat Commun 2022;13:7487. https://doi.org/10.1038/s41467-022-35108-5.
[52] Lamb WF, Creutzig F, Callaghan MW, Minx JC. Learning about urban climate solutions from case studies. Nat Clim Chang 2019;9:279–87. https://doi.org/10.1038/s41558-019-0440-x.
[53] Kılkış Ş. Benchmarking the sustainability of urban energy, water and environment systems and envisioning a cross-sectoral scenario for the future. Renew Sustain Energy Rev 2019;103:529–45. https://doi.org/10.1016/j.rser.2018.11.006.
[54] Salvia M, Reckien D, Geneletti D, Pietrapertosa F, D'Alonzo V, De Gregorio Hurtado S, et al. Understanding the motivations and implications of climate emergency declarations in cities: the case of Italy. Renew Sustain Energy Rev 2023;178:113236. https://doi.org/10.1016/j.rser.2023.113236.
[55] Palermo V, Bertoldi P, Apostolou M, Kona A, Rivas S. Assessment of climate change mitigation policies in 315 cities in the Covenant of Mayors initiative. Sustain Cities Soc 2020;60:102258. https://doi.org/10.1016/j.scs.2020.102258.
[56] Croci E, Lucchitta B, Molteni T. Low carbon urban strategies: an investigation of 124 European cities. Urban Clim 2021;40:101022. https://doi.org/10.1016/j.uclim.2021.101022.
[57] Seto KC, Churkina G, Hsu A, Keller M, Newman PWG, Qin B, et al. From low- to net-zero carbon cities: the next global agenda. Annu Rev Environ Resour 2021;46:377–415. https://doi.org/10.1146/annurev-environ-050120-113117.
[58] Hsu A, Logan K, Qadir M, Booysen MJ, Thinus, Montero AM, Tong K(KK, et al. Opportunities and barriers to net-zero cities. One Earth 2022;5:739–44. https://doi.org/10.1016/j.oneear.2022.06.013.
[59] Ulpiani G, Vetters N, Melica G, Bertoldi P. Towards the first cohort of climate-neutral cities: expected impact, current gaps, and next steps to take to establish evidence-based zero-emission urban futures. Sustain Cities Soc 2023:104572. https://doi.org/10.1016/j.scs.2023.104572.
[60] Steg L, Veldstra J, de Kleijne K, Kılkış Ş, Lucena AFP, Nilsson LJ, et al. A method to identify barriers to and enablers of implementing climate change mitigation options. One Earth 2022;5:1216–27. https://doi.org/10.1016/j.oneear.2022.10.007.
[61] European Commission. Communication on the European Green Deal. COM(2019) 640 final; 2019. p. 1–24.
[62] European Union. European climate law. Regul 2021/1119 eur parliam counc 30 June 2021. 2021. https://ec.europa.eu/clima/eu-action/european-green-deal/european-climate-law_en.
[63] European Commission. European missions: 100 Climate-Neutral and Smart Cities by 2030 Info Kit, vol. 129; 2021. https://ec.europa.eu/info/sites/default/files/research_and_innovation/funding/documents/ec_rtd_eu-mission-climate-neutral-cities-infokit.pdf.
[64] Kılkış Ş. Sustainable Development of Energy, Water and Environment Systems (SDEWES) Index for policy learning in cities. Int J Innov Sustain Dev 2018;12:87–134. https://doi.org/10.1504/IJISD.2018.10009938.
[65] Kılkış Ş, Ulpiani G, Vetters N. Visions for climate neutrality and opportunities for co-learning in European cities (Supplementary Material). 2024. p. 1–94. https://osf.io/d8naq.
[66] European Commission. EU Mission: Climate-Neutral and Smart Cities. 2022. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en.
[67] European Commission. Commission announces 100 cities participating in EU Mission for Climate-Neutral and Smart Cities by 2030. 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2591.
[68] Zhang R, Hanaoka T. Cross-cutting scenarios and strategies for designing decarbonization pathways in the transport sector toward carbon neutrality. Nat Commun 2022;13. https://doi.org/10.1038/s41467-022-31354-9.
[69] Diezmartínez CV, Short Gianotti AG. US cities increasingly integrate justice into climate planning and create policy tools for climate justice. Nat Commun 2022;13:5763. https://doi.org/10.1038/s41467-022-33392-9.
[70] Nieuwenhuijsen MJ. Influence of urban and transport planning and the city environment on cardiovascular disease. Nat Rev Cardiol 2018;15:432–8. https://doi.org/10.1038/s41569-018-0003-2.
[71] Lu X, Chan FKS, Li N, Chen C, Chen W-Q, Chan HK. Improving urban flood resilience via GDELT GKG analyses in China's Sponge Cities. Sci Rep 2022;12:20317. https://doi.org/10.1038/s41598-022-24370-8.
[72] He C, Liu Z, Wu J, Pan X, Fang Z, Li J, et al. Future global urban water scarcity and potential solutions. Nat Commun 2021;12:4667. https://doi.org/10.1038/s41467-021-25026-3.
[73] Chilvers J, Bellamy R, Pallett H, Hargreaves T. A systemic approach to mapping participation with low-carbon energy transitions. Nat Energy 2021;6:250–9. https://doi.org/10.1038/s41560-020-00762-w.
[74] Pena-Bello A, Parra D, Herberz M, Tiefenbeck V, Patel MK, Ujj Hahnel. Integration of prosumer peer-to-peer trading decisions into energy community modelling. Nat Energy 2022;7:74–82. https://doi.org/10.1038/s41560-021-00950-2.
[75] Georgarakis E, Bauwens T, Pronk A-M, AlSkaif T. Keep it green, simple and socially fair: a choice experiment on prosumers' preferences for peer-to-peer electricity trading in The Netherlands. Energy Policy 2021;159:112615. https://doi.org/10.1016/j.enpol.2021.112615.
[76] Gjorgievski VZ, Cundeva S, Markovska N, Georghiou GE. Virtual net-billing: a fair energy sharing method for collective self-consumption. Energy 2022;254:124246. https://doi.org/10.1016/j.energy.2022.124246.
[77] Parag Y, Sovacool BK. Electricity market design for the prosumer era. Nat Energy 2016;1:16032. https://doi.org/10.1038/nenergy.2016.32.
[78] Fuhr H, Hickmann T, Kern K. The role of cities in multi-level climate governance: local climate policies and the 1.5 °C target. Curr Opin Environ Sustain 2018;30:1–6. https://doi.org/10.1016/J.COSUST.2017.10.006.
[79] Kern K. Cities as leaders in EU multilevel climate governance : embedded upscaling of local experiments in Europe. Env Polit 2019;28:125–45. https://doi.org/10.1080/09644016.2019.1521979.
[80] Creutzig F, Niamir L, Bai X, Callaghan M, Cullen J, Díaz-José J, et al. Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nat Clim Chang 2022;12:36–46. https://doi.org/10.1038/s41558-021-01219-y.
[81] Seto KC, Davis SJ, Mitchell RB, Stokes EC, Unruh G, Ürge-Vorsatz D. Carbon lock-in: types, causes, and policy implications. Annu Rev Environ Resour 2016;41:425–52. https://doi.org/10.1146/annurev-environ-110615-085934.
[82] Erickson P., Tempest K. Keeping cities green: avoiding carbon lock-in due to urban development. 2015. SEI Working Paper 2015-11.
[83] Jakovcevic A, Steg L. Sustainable transportation in Argentina: values, beliefs, norms and car use reduction. Transp Res Part F Traffic Psychol Behav 2013;20:70–9. https://doi.org/10.1016/j.trf.2013.05.005.
[84] Steg L, Perlaviciute G, van der Werff E. Understanding the human dimensions of a sustainable energy transition. Front Psychol 2015;6:1–17. https://doi.org/10.3389/fpsyg.2015.00805.
[85] Thaler RH, Sunstein CR. Nudge: improving decisions about health, wealth, and happiness. New Haven, CT, USA: Yale University Press; 2008. p. 1–293.
[86] Johnson EJ, Shu SB, Dellaert BGC, Fox C, Goldstein DG, Häubl G, et al. Beyond nudges: tools of a choice architecture. Mark Lett 2012;23:487–504. https://doi.org/10.1007/s11002-012-9186-1.
[87] Parravicini V, Nielsen PH, Thornberg D, Pistocchi A. Evaluation of greenhouse gas emissions from the European urban wastewater sector, and options for their reduction. Sci Total Environ 2022;838:156322. https://doi.org/10.1016/j.scitotenv.2022.156322.
[88] Gómez-Sanabria A, Kiesewetter G, Klimont Z, Schoepp W, Haberl H. Potential for future reductions of global GHG and air pollutants from circular waste management systems. Nat Commun 2022;13:106. https://doi.org/10.1038/s41467-021-27624-7.
[89] Densley Tingley D. Embed circular economy thinking into building retrofit. Commun Eng 2022;1:28. https://doi.org/10.1038/s44172-022-00027-2.
[90] Awasthi AK, Li J, Koh L, Ogunseitan OA. Circular economy and electronic waste. Nat Electron 2019;2:86–9. https://doi.org/10.1038/s41928-019-0225-2.
[91] Savage N. How to fit clothing into the circular economy. Nature 2022;611. https://doi.org/10.1038/d41586-022-03651-2. S20–1.
[92] Heath GA, Silverman TJ, Kempe M, Deceglie M, Ravikumar D, Remo T, et al. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat Energy 2020;5:502–10. https://doi.org/10.1038/s41560-020-0645-2.
[93] Richter JL. A circular economy approach is needed for electric vehicles. Nat Electron 2022;5:5–7. https://doi.org/10.1038/s41928-021-00711-9.
[94] Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, et al. Recycling lithium-ion batteries from electric vehicles. Nature 2019;575:75–86. https://doi.org/10.1038/s41586-019-1682-5.
[95] Muscat A, de Olde EM, Ripoll-Bosch R, Van Zanten HHE, Metze TAP, Termeer CJAM, et al. Principles, drivers and opportunities of a circular bioeconomy. Nat Food 2021;2:561–6. https://doi.org/10.1038/s43016-021-00340-7.
[96] Castán Broto V. Urban governance and the politics of climate change. World Dev 2017;93:1–15. https://doi.org/10.1016/j.worlddev.2016.12.031.
[97] Kılkış Ş. Transition towards urban system integration and benchmarking of an urban area to accelerate mitigation towards net-zero targets. Energy 2021;236:121394. https://doi.org/10.1016/j.energy.2021.121394.
[98] Melica G, Bertoldi P, Kona A, Iancu A, Rivas S, Zancanella P. Multilevel governance of sustainable energy policies: the role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors. Sustain Cities Soc 2018;39:729–39. https://doi.org/10.1016/j.scs.2018.01.013.
[99] Matson P. Systems-level partnerships for sustainability at scale. Nat Sustain 2022;5:1–2. https://doi.org/10.1038/s41893-021-00813-4.
[100] Peng Y, Bai X. Financing urban low-carbon transition: the catalytic role of a city-level special fund in Shanghai. J Clean Prod 2021;282:124514. https://doi.org/10.1016/j.jclepro.2020.124514.
[101] Corbett J, Mellouli S. Winning the SDG battle in cities: how an integrated information ecosystem can contribute to the achievement of the 2030 Sustainable Development Goals. Inf Syst J 2017;27:427–61. https://doi.org/10.1111/isj.12138.
[102] Muttitt G, Kartha S. Equity, climate justice and fossil fuel extraction: principles for a managed phase out. Clim Policy 2020;20:1024–42. https://doi.org/10.1080/14693062.2020.1763900.
[103] Shi Z, Fonseca JA, Schlueter A. A review of simulation-based urban form generation and optimization for energy-driven urban design. Build Environ 2017;121:119–29. https://doi.org/10.1016/j.buildenv.2017.05.006.
[104] Morrison TH, Adger WN, Agrawal A, Brown K, Hornsey MJ, Hughes TP, et al. Radical interventions for climate-impacted systems. Nat Clim Chang 2022;12:1100–6. https://doi.org/10.1038/s41558-022-01542-y.
[105] Asarpota K, Nadin V. Energy strategies, the urban dimension, and spatial planning. Energies 2020;13:3642. https://doi.org/10.3390/en13143642.

[106] Roy J, Some S, Das N, Pathak M. Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search. Environ Res Lett 2021;16:43003. https://doi.org/10.1088/1748-9326/abd81a.
[107] Grandin J, Haarstad H, Kjærås K, Bouzarovski S. The politics of rapid urban transformation. Curr Opin Environ Sustain 2018;31:16–22. https://doi.org/10.1016/j.cosust.2017.12.002.
[108] Kılkış Ş, Krajačić G, Duić N, Rosen MA, Al-Nimr MA. Effective mitigation of climate change with sustainable development of energy, water and environment systems. Energy Convers Manag 2022;269:116146. https://doi.org/10.1016/j.enconman.2022.116146.
[109] Ulpiani G, Rebolledo E, Vetters N, Florio P, Bertoldi P. Funding and financing the zero emissions journey: urban visions from the 100 Climate-Neutral and Smart Cities Mission. Humanit Soc Sci Commun 2023;10:647. https://doi.org/10.1057/s41599-023-02055-5.
[110] Viguié V, Hallegatte S. Trade-offs and synergies in urban climate policies. Nat Clim Chang 2012;2:334–7. https://doi.org/10.1038/nclimate1434.
[111] Della Valle N, Ulpiani G, Vetters N. Assessing climate justice awareness among climate neutral-to-be cities. Humanit Soc Sci Commun 2023;10:440. https://doi.org/10.1057/s41599-023-01953-y.
[112] Creutzig F, Lohrey S, Bai X, Baklanov A, Dawson R, Dhakal S, et al. Upscaling urban data science for global climate solutions. Glob Sustain 2019;2:e2. https://doi.org/10.1017/sus.2018.16.
[113] Pignatelli M, Torabi Moghadam S, Genta C, Lombardi P. Spatial decision support system for low-carbon sustainable cities development: an interactive storytelling dashboard for the city of Turin. Sustain Cities Soc 2023;89:104310. https://doi.org/10.1016/j.scs.2022.104310.
[114] Creutzig F, Acemoglu D, Bai X, Edwards PN, Hintz MJ, Kaack LH, et al. Digitalization and the anthropocene. Annu Rev Environ Resour 2022;47:479–509. https://doi.org/10.1146/annurev-environ-120920-100056.
[115] Tahmasseby S. The implementation of smart mobility for smart cities: a case study in Qatar. Civ Eng J 2022;8:2154–71. https://doi.org/10.28991/CEJ-2022-08-10-09.
[116] Chambers JM, Wyborn C, Klenk NL, Ryan M, Serban A, Bennett NJ, et al. Co-productive agility and four collaborative pathways to sustainability transformations. Glob Environ Chang 2022;72:102422. https://doi.org/10.1016/j.gloenvcha.2021.102422.
[117] Chambers JM, Wyborn C, Ryan ME, Reid RS, Riechers M, Serban A, et al. Six modes of co-production for sustainability. Nat Sustain 2021;4:983–96. https://doi.org/10.1038/s41893-021-00755-x.
[118] Reyers B, Moore M-L, Haider LJ, Schlüter M. The contributions of resilience to reshaping sustainable development. Nat Sustain 2022;5:657–64. https://doi.org/10.1038/s41893-022-00889-6.
[119] Ulpiani G, Vetters N. On the risks associated with transitioning to climate neutrality in Europe: a city perspective. Renew Sustain Energy Rev 2023;183:113448. https://doi.org/10.1016/j.rser.2023.113448.
[120] Ulpiani G, Vetters N, Shtjefni D, Kakoulaki G, Taylor N. Let's hear it from the cities: on the role of renewable energy in reaching climate neutrality in urban Europe. Renew Sustain Energy Rev 2023;183:113444. https://doi.org/10.1016/j.rser.2023.113444.
[121] Ulpiani G, Vetters N, Maduta C. Towards (net) zero emissions in the stationary energy sector: a city perspective. Sustain Cities Soc 2023;97:104750. https://doi.org/10.1016/j.scs.2023.104750.
[122] Christidis P, Vega Gonzalo M, Ulpiani G, Vetters N. Post-pandemic trends in urban mobility. 2023. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC133322/JRC133322_01.pdf.
[123] Möslinger M, Ulpiani G, Vetters N. Circular economy and waste management to empower a climate-neutral urban future. J Clean Prod 2023;421:138454. https://doi.org/10.1016/j.jclepro.2023.138454.
[124] European Commission. In: Mission in Progress – Climate-Neutral and Smart Cities Conference; 2023. https://research-and-innovation.ec.europa.eu/events/upcoming-events/mission-progress-climate-neutral-and-smart-cities-conference-2023-2023-06-26_en.