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Smart carbon–neutral development: Embracing complexity with multi-level governance and convolution☆

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ABSTRACT

This paper delves into the current EU policy and strategy for advancing smart, carbon–neutral development across Europe, as outlined by the EU Missions framework. This framework aims to boost the resilience to climate change of at least 150 European regions and communities and facilitate the transformation of 100 cities into climate-neutral and smart urban centers by 2030. Our primary objective is to explore potential synergies between theoretical concepts and their practical application in realizing smart carbon–neutral development. Specifically, we examine the challenges associated with scaling processes inherent in smart carbon–neutral development alongside the transformative and systemic changes required to achieve significant levels of both mitigation and adaptation. Using the Net Zero Action Plan for Thessaloniki as a case study, we examine the efficacy of designing policies at both the operational and governance levels. We argue that a complexity-based approach is applicable in this context: as we refine our understanding of the spatial impact of interventions, our certainty regarding the necessary governance level diminishes, and vice versa. Finally, we discuss the potential for realizing the ambitious objectives of the EU Missions framework through a convolution perspective and the challenges associated with bridging the gap between theoretical concepts and practical implementation.

1. Introduction

The need for smart, carbon–neutral development has gained increased attention within the European Union's policy landscape. As expressed by the EU Missions framework (European Commission, 2022), this vision entails not only strengthening the resilience of numerous regions and communities to climate change (EU Mission "Adaptation to Climate Change" – EU ACC Mission) but also transforming cities into climate-neutral and smart urban hubs by 2030 (EU Mission "Climate-Neutral and Smart cities" – EU Cities Mission) (European Commission, 2021a, b). A central problem towards achieving this vision is the efficient integration of theoretical concepts with practical implementation strategies, a nexus that indicates significant gaps as identified by recent studies and assessment reports (Beurden et al., 2023; Kaufmann et al., 2023; Cappellano et al., 2024; Shtjefni et al., 2024). The paper further investigates this gap by analyzing the implications of applying the EU Cities Missions framework for promoting smart, carbon–neutral development in the case of Thessaloniki.

Recent literature has pointed out the complementary perspectives of theoretical discourses and practical applications in relation to the EU Missions framework, examining potential challenges of scaling processes (van der Heijden, 2023), the necessity of transformative systemic changes (Janssen et al., 2023; Komninos et al., 2021), and the intricate interplay between spatial interventions and governance structures (van der Heijden, 2023; Wittmann et al., 2021; Kaufmann et al., 2023). Scholars and policymakers have shifted their focus from solely pursuing economic growth to addressing persistent societal challenges through innovation policy. This transition has led to the emergence of new rationales that encourage comprehensive approaches combining technological, organizational, and institutional changes to facilitate socio-technical system transformations. One notable development is the revival of mission-oriented innovation policies as a means of driving transformative changes. While missions were historically associated with large-scale research initiatives, they are now recognized as a promising approach for mobilizing innovation capacities to tackle complex societal issues (Boon & Edler, 2018; Kuhlmann & Rip, 2018). However, significant ambiguities persist regarding nature and potential of missions and corresponding policies, leading to challenges in their

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formulation and implementation (Janssen et al., 2023).

Additionally, the mechanisms –expressed as actions- through which missions operate require further clarification, particularly concerning their effectiveness in achieving transformative change (Janssen et al., 2021). In response, there is a growing call for a systematic understanding of missions as 'boundary objects', which serve to foster shared understandings and coordination among diverse stakeholder communities (Janssen et al., 2023). By conceptualizing missions as boundary objects, researchers aim to unravel the dynamics of mission formulation and operationalization, offering insights into how they evolve across different policy arenas and over time. This perspective highlights the importance of managing the ambiguity inherent in missions and calls for more deliberate strategies for framing and orchestrating mission-oriented approaches to innovation policy (Wanzenböck et al., 2020; Kaufmann et al., 2023).

Research has also highlighted the need to assess the effectiveness of such approaches and to explore the role of multi-stakeholder governance structures in mission arenas across various political and geographical contexts (Calderini et al., 2023; Janssen et al., 2023). For instance, it points out the necessity for a diverse set of policy instruments beyond science, technology, and innovation funding alone, especially for missions targeting broader societal transformation (Wittmann et al., 2021). Moreover, theoretical and methodological limitations should also be considered, such as the dynamic nature of mission goals over time and the challenge of quantifying complex governance requirements (Wittmann et al., 2020; Kaufmann et al., 2023). Recent studies also suggest that further research is needed to explore its applicability across different national contexts and refine the mission-oriented innovation policies operationalization (Wittmann et al., 2021).

The paper builds on the need for aligning perceptions, mechanisms and multi-level governance in the study of mission-oriented innovation policies, promoting a holistic perspective beyond the traditional dichotomy of state intervention versus market-driven growth. Using as a case study the recent 2030 Action Plan for Climate Neutrality of Thessaloniki, it highlights the need for exploring the underlying dynamics of policy design and implementation at conceptual, operational and governance levels (Municipality of Thessaloniki, 2023). We argue that struggling with uncertainty is pivotal in this endeavor, as refining our understanding of spatial impacts requires a continuous recalibration of governance strategies. By revealing these complexities, we seek to shed light on pathways for achieving the ambitious goals set forth by the EU Missions framework while navigating the inherent challenges of bridging theory and practice in the pursuit of sustainable spatial development.

The key research question discussed in this paper explores if it is possible to define concepts, mechanisms and governance structures related to specific actions at an adequate level of detail when designing and implementing smart carbon–neutral policies for cities. A systems-innovation approach is followed, including actors, activities, and projects. We consider policies as living organisms whose evolution depends on multiple conditions, such as technology, infrastructures, governance models, social innovation and participation, funding, and learning capabilities (Komninos et al., 2023).

The structure of this paper is as follows. Section 2 offers an overview of the theoretical discourse surrounding smart spatial development and carbon neutrality. It combines two streams of literature, starting with the scaling challenge inherent in net-zero policies, spanning not only at the city but also at regional, national, and international levels. It then delves into the EU Missions framework and presents the transformative and systemic changes necessary for achieving both mitigation and adaptation outcomes within this framework. Section 3 builds upon these theoretical foundations and examines the Net Zero Action Plan for Thessaloniki as a case study, illustrating the need for a more coherent coordination among identified concepts, mechanisms and governance structures. Section 4 discusses how the EU Cities Mission empowers smart carbon–neutral cities by helping them to mitigate risks and adapt to climate change and highlights the importance of applying a systems-innovation perspective, especially in their governance framework. Section 5 moves one step further and introduces the idea of the uncertainty principle, arguing that it is impossible to define both the spatial impact and the governance levels of a policy with perfect accuracy; the more we nail down the spatial impact of the intervention, the less we know about the governance levels that need to be triggered and vice versa. Moreover, the section highlights the limitations stemming from path-dependence in both actions and governance models, emphasizing the need for adopting a systems perspective for smart carbon–neutral development. It advocates for a convolution-based approach, which integrates actions and governance structures, to address these challenges effectively.

2. Smart spatial development for carbon neutrality under the EU Missions framework

2.1. Smart spatial development and carbon neutrality

Literature on smart carbon–neutral development focuses mainly at the city level highlighting concepts, approaches, barriers and drivers for transition to carbon neutrality, as well as the lack of consistency in environmental monitoring methods (Huovila et al. 2022). Starting from the concepts related to this field, the discourse around smart cities has been increasingly converging with that of sustainable cities, thus broadening the scope of what constitutes a smart city (Park and Yoo, 2023). An in-depth examination of the relationship between smart city and sustainable development underscores a focus on smart governance, mobility, and economic sustainability (Vainio and Sankala, 2022). Major challenges in developing smart carbon–neutral cities are related to leadership, governance, citizen support, investment, human capacity, smart device heterogeneity, and efficient modelling and management of resources, especially the energy systems (Shafiullah et al., 2022).

At the same time, evidence suggests that datasets and modelling are essential components to manage the transition to smart carbon–neutral cities. A review of technologies across various applications for achieving neutrality highlights the importance of key technological innovations, such as digital twins, ontological knowledge bases, and data-driven high-dimensional surrogate parameterization. These technologies facilitate the optimal design and operation of systems across different temporal and spatial scales (Cao et al., 2023). Achieving neutrality requires consensus, intelligence, and networking within cities, therefore, large datasets are crucial for understanding dynamics in urban systems and fostering synergies among the various subsystems of cities (Lai, 2022). Moreover, integrating data across sectors is vital for accurately forecasting and mitigating CO_2 emissions, promoting a unified approach to modelling carbon emissions and analysing reduction opportunities (Plachinda et al., 2022).

Existing literature also highlights the importance of policies related to smart cities, as they can significantly reduce carbon emissions produced by persisting effects, such as household activities and transportation (Wu, 2022). Practical guidance on city digital transformation towards achieving carbon neutrality includes recommendations on how to reduce the carbon footprint using digital technologies, emphasizing their contribution in enhancing efficiency (Ziozias et al., 2023; Saranrom, et al., 2023). However, smart city policies fall short very often in addressing climate change challenges, treating climate adaptation more as a technical issue rather than a complex social challenge (Ma and Wu, 2022; Mendes, 2022).

When it comes to pathways to carbon neutrality, literature indicates several aspects related to smart carbon–neutral transition processes. First, digital transformation contributes to reducing carbon emissions in cities by facilitating industrial upgrades, enhancing energy efficiency, and improving environmental regulation (Wang and Zhong, 2023). Smart city solutions significantly benefit green technological innovation, which is an essential aspect of and pathway to green development

(Xia et al., 2023; Yan et al., 2023). The implementation of smart city systems has a significant positive impact on promoting urban green economy development, reducing emissions, and lowering energy intensity (Liu et al., 2023). Second, comprehensive climate policy packages work towards promoting strong collaboration across all sectors and stakeholders, and timely financial and technological assistance (Phupadtong et al., 2023). Third, the quantitative evaluation of carbon neutrality through empirical data is a key factor for assessing and updating pathways by exploring the correlation between paths and industries, the measurement of carbon reduction capability, and the assessment of potential costs and benefits are of great importance (Wu et al., 2022). Finally, best practices derived from transnational projects related to sustainable transition of cities, such as the use of forecasting models and multi-criteria decision-making to design and assess transition scenarios are crucial aspects for promoting the pathway-related perspective of smart carbon–neutral cities (Csete and Baranyi, 2023).

Moving to a more applied perspective, a widespread implementation of net-zero districts, or even more ambitiously, positive energy districts, can significantly contribute to the emergence of smart carbon–neutral cities (Bisello et al., 2023; Fatima et al., 2022). Life cycle carbon assessments of residential areas can uncover strategies and opportunities for achieving carbon neutrality. Key factors influencing the carbon footprint of residential precincts include energy efficiency and demographics, which affect their carbon performance (Huang et al., 2022). Moreover, community-based systems, such as district heating, can result in significant primary energy savings (Hiltunen et al., 2022). In industrial districts, drivers of neutrality include energy management hotspots, industrial symbiosis, and carbon emission assessments (Yan et al., 2022). Models that estimate emissions based on demographics and district activities, along with a spectrum of carbon neutrality measures ranging from technological innovations to nature-based solutions, can evaluate the potential and define the necessary conditions for transitioning districts to net-zero emissions. This includes evolving towards self-sufficient, net-zero districts that rely on locally produced renewable energy (Komninos, 2022).

In the energy sector, the challenges lie in designing net-zero emissions systems along two main directions. First, the retrofitting of existing buildings offers significant savings in cities' energy consumption, given that the building sector accounts for approximately 37 % of energy consumption, surpassing other sectors such as industry, agriculture, and commerce (Valencia et al., 2022; Park et al., 2023). Additionally, the transition from a traditional centralized energy systems to decentralized ones, combining both small- and large-scale renewable energy producers is critical (Biegańska, 2022). This transition may also encompass the deployment of smart energy systems and next-generation energy technologies that leverage artificial intelligence, the Internet of Things, and technologies to collect and analyse big data in real-time (Himeur et al., 2022; Panori et al., 2023). Furthermore, the development of novel energy materials aimed at increasing battery cells' storage capacity and durability, reducing the vulnerability of renewable energy sources, and enhancing the use of optimization modelling are also vital (Woon et al., 2023).

Finally, smart green transport is a key sector for decarbonization in cities, promoting the electrification of urban transport (Christidis et al., 2023). Achieving carbon neutrality in urban transportation requires considering the status of vehicle and fuel decarbonization technologies, the potential to reduce CO2 emissions through land use policies, and the impact of smart technologies on transportation systems and user behaviour (Kii et al., 2023). However, the necessary investments and their impact on citizens' mobility costs are major concerns. Technological advancements can contribute, such as vehicle re-identification technology to optimize traffic flow, enhance energy efficiency, and reduce carbon emissions (Liang et al., 2023), or Vehicle to Grid (V2G) technology, which allows idle or parked electric vehicles to act as distributed sources that can store or release energy, embracing a green urban future (Oad et al., 2023).

Table 1 presents the key elements identified in this literature review regarding smart carbon–neutral development, with a particular focus on cities and their role in fostering and promoting smart spatial planning and carbon neutrality.

2.2. The EU Missions framework for cities and climate change

Recently, the European Union has adopted a missions-oriented approach for promoting smart spatial development and carbon neutrality for addressing climate change. The EU Missions policy framework focuses on enhancing Europe's resilience and capacity to adapt to the impacts of climate change. The primary goal is to accelerate the development and implementation of mitigation and adaptation measures across various sectors and regions within the EU (European Commission, 2021b). The missions aim to support the achievement of the EU's climate goals outlined in the European Green Deal, which include reducing greenhouse gas emissions and achieving climate neutrality by 2050 (European Commission, 2019).

The EU Missions framework includes multiple objectives. First, it aims at enhancing knowledge and understanding of the impact of climate change. This involves conducting research to better understand how climate change is affecting different regions, ecosystems, and

Table 1
Key elements of smart carbon–neutral development in cities.

Smart carbon–neutral development elements	Key aspects	Sources
Concepts	Move from smart cities to sustainable cities	Shafiullah et al., 2022 Vainio and Sankala, 2022 Park and Yoo, 2023
Datasets and modelling	Provide optimal design and operation of systems for understanding dynamics, fostering synergies and promoting a unified approach	Lai, 2022 Plachinda et al., 2022 Cao et al., 2023
Policies	Provide practical guidance and recommendations.	Ma and Wu, 2022 Mendes, 2022
	Focus on complex social challenge instead of technical aspects	Wu, 2022 Saranrom, et al., 2023 Ziozias et al., 2023
Pathways	Foster transition through digital transformation, climate policy packages, quantitative evaluation and best practices.	Wu et al., 2022 Csete and Baranyi, 2023 Liu et al., 2023 Phupadtong et al., 2023 Wang and Zhong, 2023 Xia et al., 2023 Yan et al., 2023
Implementation	Energy sector can benefit from retrofitting of existing buildings, decentralized energy systems, development of novel energy materials.	Biegańska, 2022 Himeur et al., 2022 Valencia et al., 2022 Panori et al., 2023 Park et al., 2023 Woon et al., 2023
	Transport sector can benefit from electrification, land use policies, user behaviour.	Christidis et al., 2023 Kii et al., 2023 Liang et al., 2023 Oad et al., 2023

sectors, as well as identifying vulnerable populations and areas. Second, it focuses on developing and implementing adaptation strategies. It seeks to promote the development and adoption of adaptation strategies and measures to reduce vulnerability and enhance resilience to climate change impacts. This may involve measures such as infrastructure upgrades, land-use planning, and ecosystem restoration. Third, the EU Missions target fostering innovation and collaboration by stimulating innovation in adaptation technologies, practices, and policies, while also fostering collaboration among stakeholders across sectors and regions. This collaboration may involve partnerships between governments, businesses, research institutions, and civil society organizations. Finally, they involve mobilizing financial resources and providing support to EU member states and regions to implement mitigation and adaptation measures. This could include funding for research, demonstration projects, capacity building, and technical assistance.

In this context, the EU Cities Mission represents an initiative for engaging local, regional, and national authorities, citizens, businesses, and investors with the goal of transforming 100 EU cities into climate-neutral smart cities by 2030 (European Commission, 2023). Additionally, it seeks to capitalize on the insights gained from this experimentation to facilitate the transition of all European cities towards the same goal by 2050 (European Commission, 2021a). The EU Cities Mission encourages governments, academia, the private sector, and civil society organizations to collaborate and form cohesive partnerships and ecosystems, set out Climate Contracts and Action Plans for net zero emissions (European Commission, 2021b). The specifications recommended to all cities advocate for a modular approach that covers the main source sectors of greenhouse gas (GHG) emissions: stationary energy, buildings, transport, waste, industrial processes and product use, agriculture, forestry, and other land use, plus CO2 offsetting to compensate any residual emissions (European Commission, 2021b; Net Zero Cities, 2023a).

Following this policy perspective, the Net Zero Cities (NZC) consortium has been developed for providing technical support towards implementing the EU Cities Mission. The NZC has elaborated an ecosystem approach to achieve carbon neutrality across these source sectors. It endorses the activation of an "inclusive ecosystem for change", in all its diversity, encompassing knowledge institutions, innovative companies and start-ups, grassroots organizations and civic innovators. The transition towards carbon neutrality is expected to evolve along the capacity of this ecosystem to act, opening windows of opportunity, creating conditions to exchange, learn, reflect and work on challenges and opportunities of transition. Also, a systemic approach (mapping, building relationships, creating shared visions, supporting co-creation and system innovation) has been considered necessary to deal with interconnected and interdependent city activities (Net Zero Cities, 2022). The transition pathway for each sector of GHG emissions is based on a participatory model that engages the climate stakeholder ecosystem and implements systemic levers for change, such as technology, governance, policy and regulation, finance and business models, culture, citizen participation and social innovation (Fig.1).

Overlaps and complementarities among actions implemented within the EU Missions policy framework rise in the form of integrated strategies for cities and regions that encompass both mitigation and adaptation efforts. On one hand, it focuses on reducing greenhouse gas emissions within urban areas through initiatives such as transitioning to renewable energy sources and enhancing energy efficiency in buildings and transportation. On the other hand, the EU Missions framework aims to increase urban resilience to climate impacts by implementing measures such as green infrastructure development and urban planning strategies that mitigate heatwaves, flooding, and other extreme events. By aligning concepts, mechanisms and governance structures, urban areas not only decrease their carbon footprint but also reinforce their defenses against the adverse effects of climate change, creating more sustainable and resilient communities.

2.3. Complexity and the systems-innovation perspective in EU Missions

The pursuit of systemic changes that is essential for the rapid transformation of cities towards climate resilience within the EU Missions framework demands a critical appraisal of existing approaches. Van der Heijden (2023) highlights the challenge faced by cities in integrating new technologies and governance innovations cohesively, often resulting in fragmented efforts. Despite the proliferation of climate activities and governance interventions, a coherent global shift in norms, values, and rules remains elusive. This underscores the necessity of adopting a systems-innovation perspective to navigate the complexities inherent in addressing societal challenges like climate change. By employing a modular approach to manage the complexity of missions, coordination across different levels of government, sectors, policies, and funding tools can be facilitated, as emphasized by recent research (van der Heijden, 2023). However, this complexity also poses evaluation

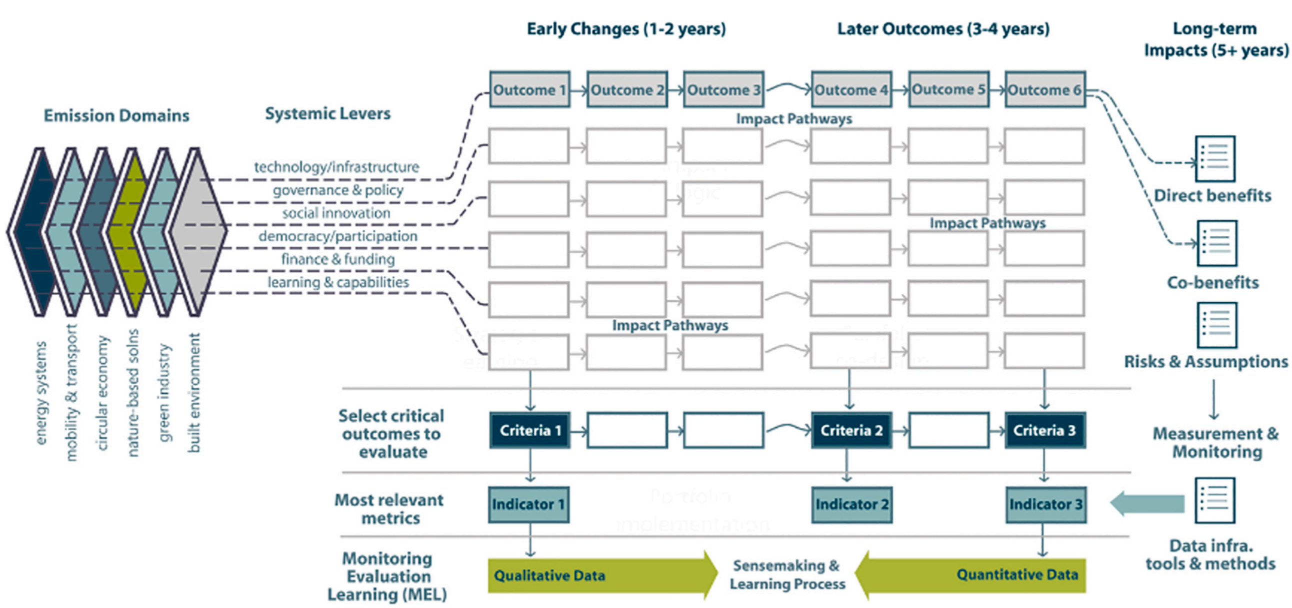

Fig. 1. NZC model of change: Emission domains, systemic levers, impacts.
Source: Net Zero Cities (2023b).

challenges, with differing assessments from scholars regarding their effectiveness (Wittmann et al., 2021).

The complexity of the mission-oriented framework extends beyond its organizational structure to encompass its interaction with territorial dynamics. Territories serve as both sources of inputs for mission-oriented approaches and recipients of economic and social externalities generated by mission activities (Cappellano et al., 2023). This complex relationship underscores the need for coherent governance mechanisms aligned and effectively integrated within the EU Cohesion Policy framework. While mission-oriented approaches can streamline decision-making processes within Cohesion Policy, challenges such as bureaucratic burdens and mismatched priorities at different levels may hinder effective policy implementation (van der Heijden, 2023; Brown, 2021; Rohracher et al., 2023). Furthermore, the inherently uncertain and dynamic nature of climate change exacerbates the complexity of mission-oriented endeavors, as existing risk assessment models struggle to capture fundamental uncertainties (Mazzucato and Mikheeva, 2020). In navigating these complexities, policymakers must avoid layering policy instruments indiscriminately, which can lead to wasteful transaction costs and hinder the catalytic effect of missions in addressing societal challenges (Mazzucato and Mikheeva, 2020; van der Heijden, 2023).

When it comes to the EU Cities Mission, complementarities arise among the implemented actions, especially at the mitigation and adaptation level. Therefore, fostering synergies between these actions is crucial for enhancing policy efficiency. However, this can also introduce additional complexity, making it essential to adopt a system-innovation approach to achieve the desired outcomes in systemic transformation, as previously discussed.

More specifically, the EU Cities Mission embodies a blend of digital and green perspectives. These encompass various facets, including the utilization of key technologies for achieving carbon neutrality, addressing urban carbon emissions, promoting a green economy, and optimizing the management, sharing, and utilization of renewable energy. Furthermore, it entails the implementation of climate-driven smart applications and the integration of urban intelligence to foster the development of carbon–neutral cities. The emphasis on adaptation to climate change, climate-neutral practices, and smart city planning underscores the strong interdependence between digital and green transitions. The digital transition contributes to environmental sustainability by facilitating the dematerialization of activities, shifting them from physical to digital realms; whereas, the green transition integrates digital optimization and data-driven operations to enhance overall efficiency. Thus, each transition embodies a dual nature, where the digital inherently incorporates a green dimension, and vice versa. This duality reflects contemporary trends aimed at seamlessly integrating environmental sustainability with digital transformation efforts.

Moreover, decision-making challenges are common indicating the need for more well-orchestrated coordination not only between several levels of governance, but also among systems at the urban, regional, national, and international levels. Even though green and digital transitions use specific sectors as their starting points, their efficiency with regard to EU Missions relies on their ability to adapt to different contexts and be applicable to various sub-systems for promoting innovation. This adaptability underscores the importance of flexible frameworks that can accommodate diverse socio-economic, cultural, and geographical conditions, fostering synergies between different sectors and stakeholders. Effective coordination across multiple levels and domains is essential for leveraging the transformative potential of EU Missions, ensuring that they resonate across diverse contexts and contribute meaningfully to the overarching goal of smart carbon–neutral development.

3. Learning from a case study: The 2030 Action Plan for climate neutrality of Thessaloniki

The Climate Contract and the Action Plan of Thessaloniki, which was elaborated within the framework of the EU Cities Mission, highlights a pathway to carbon neutrality that combines various technologies and organizational measures, across domains of emissions and systemic levers of change. Anticipated outcomes include the transformation of Thessaloniki into a smart climate-neutral city, yielding environmental advantages and enhancing citizen well-being. Central to the Action Plan are sectoral ecosystems and a systemic approach, fostering interconnectedness and integration among transition initiatives aimed at achieving carbon neutrality (Municipality of Thessaloniki, 2023).

The EU's Mission for 100 Climate-Neutral and Smart Cities by 2030, known as the Cities Mission, was launched by the European Commission in 2022. The initial group of 112 cities selected for the EU Mission for 100 Climate-Neutral and Smart Cities by 2030 was chosen through an open call for expressions of interest. The call invited cities to apply, demonstrating their commitment to ambitious climate action and readiness to achieve carbon neutrality by 2030. In total, 377 cities from all EU member states and nine associated countries submitted expressions of interest. From these applicants, 100 cities from EU member states and 12 from associated countries were selected in April 2022 to participate in the Mission.

These cities received tailored support from the Mission Platform, managed by NetZeroCities, to achieve carbon neutrality by 2030. While the initial cohort was announced in April 2022, the Cities Mission continues to engage additional cities through various initiatives, such as the Pilot Cities Programme and the Twinning Learning Programme, to expand the network of cities working towards carbon neutrality. Thessaloniki's inclusion in the third cohort that received the corresponding EU Mission Label followed the elaboration and approval of the 2030 Action Plan for Climate Neutrality, the Investment Plan, and the Climate City Contract, documenting its commitment to sustainable urban development and alignment with the EU's climate objectives. This Label is an important milestone as it acknowledges a successful development of Climate City Contract and facilitates access to EU, national, and regional funding.

The 2030 Action Plan for Climate Neutrality for Thessaloniki considers the context, stakeholders, previous initiatives, and the energy and emissions for each sector or activity ecosystem. It encompasses 58 actions/projects addressing all emission-producing sectors within the city. These projects employ a variety of technologies, including building renovation (through retrofitting, passive systems, and heat pumps), smart systems and platforms for energy optimization, electromobility and transport management, renewable energy production, urban redevelopment, and nature-based solutions for carbon sequestration. Collectively, the 58 projects target six city ecosystems and are expected to achieve an 80 % reduction in GHG emissions, from 2.84 to 0.57 tons of CO2 equivalent per capita by 2030 (Table 2).

For further understanding the GHG reduction measures in this case study, it is essential to take a closer look at the projects proposed within each sector to identify potential complementarities rising between them and their overall relation to climate adaptation and mitigation challenges (Fig.2). Starting from the electricity ecosystem, there are four projects supporting the widespread installation of renewable energy generation in public spaces and buildings, the certification of green electricity production, and energy optimization to reduce electricity consumption in buildings and facilities. In relation to buildings and heating, the action plan proposes 19 projects for renovation and upgrade of the building stock encompassing all types of buildings, private residences and businesses, municipal, and other public buildings, while new buildings complying with the highest energy efficiency standards, and heating will extensively turn to high-efficiency electric systems. In transport and logistics, the fifteen identified projects aim at replacing transport mobility by polluting passenger cars with green modes of transport, private or shared bicycles, micro-mobility vehicles, private or shared electric cars, public transportation, coordinated by a multimodal, Mobility-as-a-Service system. Finally, in waste, the seven identified projects focus on facilitating the recycling of packaging to meet the

Table 2
GHG Emissions by sector (CO_2 equivalent) and corresponding reduction measures.

Baseline 2020			Reduction 80 % by 2030		
GHG generation sectors	*kt-CO2e per year*		**Net-zero measures**	*kt-CO2e per year*	
Electricity	423	47 %	Decarbonisation of energy production	330	46 %
Buildings and heating	238	26 %	Building renovations	35	29 %
			New energy-efficient buildings	1	
			Efficient lighting and electrical appliances	57	
			Decarbonisation of heat production	115	
Transport	209	23 %	Reduction of passenger motorised transport	26	22 %
			Transition to public transport	24	
			Increase in carpooling	8	
			Electrification of cars	15	
			Electrification of buses	26	
			Electrification of trucks	9	
			Optimisation of urban freight transport	48	
Waste	33	4 %	Increase in Recycling	25	3 %
Total GHG emissions	903	100 %	**Total GHG reduction**	**720**	100 %
Per head	2.84		**Per head**	2.27	

corresponding European levels, the management of biowaste through composting infrastructure, and the wasteful disposal of food to be dramatically reduced.

In land use and the environment ecosystem, the four projects aim to shape an urban form with low emissions by implementing extensive tree planting and expanding the city's tree canopy. This includes increasing tree density and replacing low greenery (grass, ornamental plants) with high greenery (trees). Additionally, pilot projects focus on mitigating heat islands, absorbing noise, and protecting biodiversity. The contribution of this sector extends beyond the 80 % GHG reduction target by offsetting remaining emissions through Nature-Based Solutions.

Finally, the block referring to smart city and governance encompasses nine projects targeting the upgrading of the Internet infrastructure, the use of cloud computing for municipal services, data analysis through artificial intelligence, the creation of a Carbon Dioxide Footprint Assessment and Monitoring Platform, monitoring the decarbonization progress, establishing a climate transition observatory, upgrading sensors and devices for data collection to measure air quality.

The implementation cost for the 58 projects for achieving carbon neutrality in Thessaloniki amounts to approximately €2 billion, with distribution among all stakeholders involved. Of this total, €457 million (approximately 23 %) is allocated to projects under the purview of the Municipality of Thessaloniki. These financial estimates are based on the Economic Model provided by the NZC Consortium to all cities engaged in the EU Cities Mission

The decarbonisation Action Plan of Thessaloniki is ambitious in measures, investments and timeline, aiming for a radical transformation of the city by 2030. However, this plan should be understood as a dynamic framework, evolving with projects being added or adjusted based on challenges, opportunities, and optimisation. A major challenge lies in the investment plan that supports the GHG reduction strategy, relying on contributions from both the public and private sectors. The benefits are direct, including lower emissions and reduced energy costs, as well as indirect, such as an improved urban environment, reduced pollution, and healthier living conditions for citizens. Additionally, there is a broader benefit by advancing to carbon neutrality, as Europe moves toward energy self-sufficiency, reducing dependence on both fossil fuels

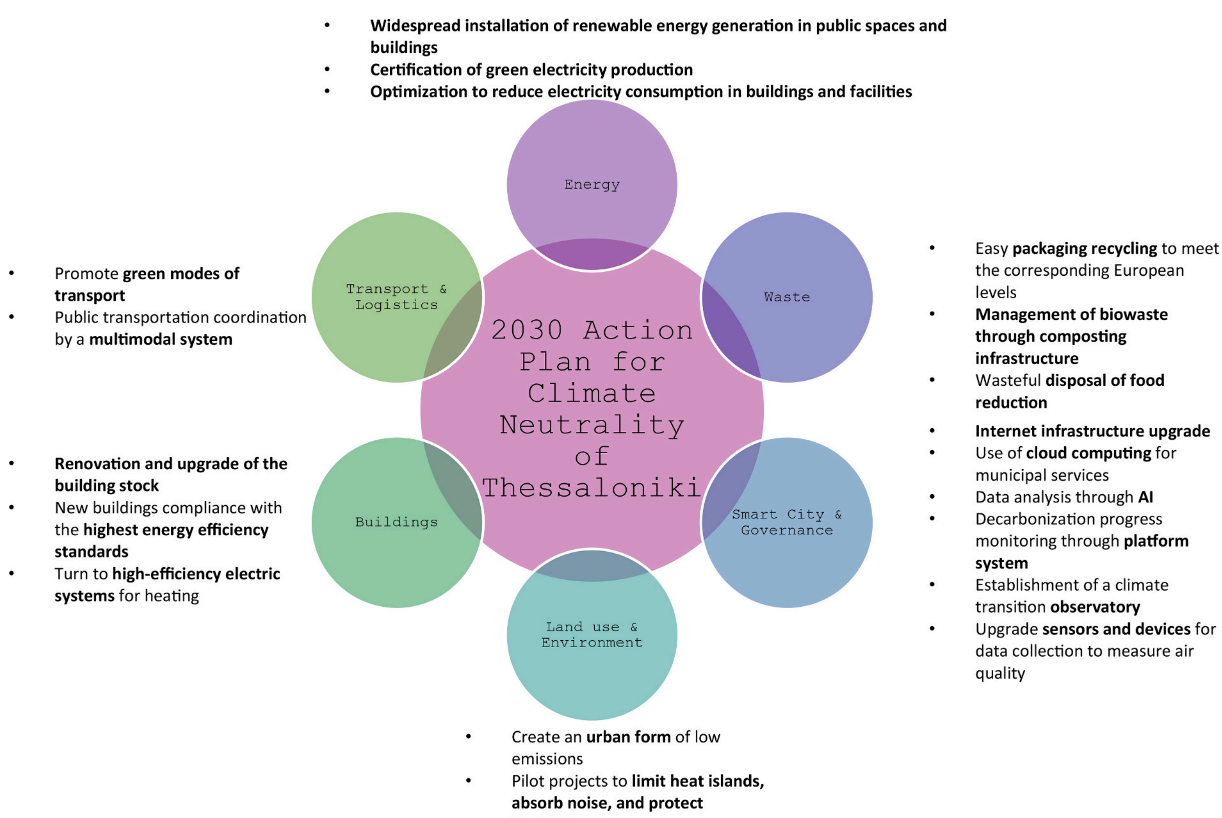

Fig. 2. Thessaloniki's Action Plan projects across sectors.
Source: Municipality of Thessaloniki (2023)

and energy imports. The pathway outlined in the Action Plan for Climate Neutrality for Thessaloniki incorporates a range of technological, government, and management solutions across multiple emissions domains. It represents a systems-innovation where solutions for reducing emissions are applied through various levers of change. Within the six ecosystems focused on by the Action Plan — which include actors, activities, and projects — three distinct types of systemic interdependencies and integrations have been established.

First, the transition to net-zero emissions is initially obtained across the ecosystems of energy, transport, waste, and building. This is achieved through portfolios of projects for energy conservation, green practices, replacing fossil fuels with renewable energy, electromobility, redesign of physical spaces, nature-based solutions, and organizational or institutional reforms. To achieve the goal of an 80 % reduction in emissions, interventions across these four ecosystems work complementary and the outcome is cumulative.

Second, projects targeting land use, the environment, and natural ecosystems contribute to carbon neutrality by absorbing CO_2 generated from the emission sectors. The absorption of carbon dioxide serves as an offset and is considered in addition to efforts aimed at achieving an 80 % reduction in emissions, thereby helping to balance out any residual emissions, and getting closer to net zero emissions.

Third, smart city initiatives are deployed horizontally to make all ecosystems smart and enhance efficiency through digital services, platforms, data analytics, and artificial intelligence. Feedback loops, where feasible between digital solutions and the data they generate, inform optimization of solutions for carbon neutrality. Moreover, there exists further potential for optimization, both in terms of CO2 reduction and costs, across the entire portfolio of projects. For each of the 58 projects within the Action Plan, three key metrics are provided: the total cost (Euros), the reduction in CO2 emissions (tons), and the cost per unit of CO2 reduction (Euro/ton). Considering that all projects exhibit some degree of scalability, optimization can adjust the scale of projects to achieve the carbon neutrality target while minimizing overall costs.

It is important to stress that the action plan is akin to a living organism. Projects may be introduced or phased out in response to new opportunities, changes in funding, or optimization efforts. In this context, benefits, costs, and opportunities dictate the evolution of the action plan. Even though the direct benefit of these projects is emissions' reduction, the indirect benefits to quality of life are also significant. An additional major indirect benefit is enhancing Europe's energy self-sufficiency, thereby reducing dependence on imported fossil fuels. This is a top priority for Europe. Another equally important indirect benefit is the development of industries for low-emission products, demand for which is expected to rise in the coming years.

3.1. Data challenges

The design of the Thessaloniki Action Plan for carbon neutrality relied on a model provided by the NZC consortium. Using models is good practice, since effective design can be facilitated by robust models. However, in the design of the action plan for Thessaloniki there was some ambiguity due to the lack of access to the model's internal structure and algorithms. Although the NZC consultants were extremely supportive in testing solutions, the inability to run many simulations made it challenging to statistically identify specific thresholds and tipping points in the emission sectors. The model used could be replaced by an agent-based model, with the 58 projects of the Action Plan serving as agents, rules defining their change, in continuous or discrete states. In this case, the model could consider overall constraints such as network capacity, infrastructure availability, budget limitations, and other relevant factors.

Some projections provided by the NZC model would also need further verification. It is estimated for instance that GHG emission for 2030, in business-as-usual context, will be 2.84 tn/cap. However, Eurostat data for the entire country shows GHG for 2020 at 8.56 tn/cap. Although there was a significant reduction in emissions from 2010 to 2020, the projection for 2030 appears rather optimistic. The last three years, the level of GHG emissions is stable and the potential for further reductions of emissions is constrained by the electricity network's capacity to handle increased generation from renewable energy sources. There is a lack of plans for further investments to enhance network capacity in the immediate future.

Moreover, the estimations used to define the tipping point towards carbon neutrality at an 80 % emissions reduction need further investigation. There is a significant demand for city-level data to estimate various factors, such as the annual renovation rate of building envelopes, energy efficiency improvements from building renovations, the adoption of electric heat pumps or geothermal systems, changes in transportation needs due to urban planning, digitalization, and remote work, as well as mobility electrification estimates, and afforestation densities. While statistics are available at national, regional, and sub-regional levels, only a few datasets exist for individual cities or conglomerations comprising multiple cities. To bridge this gap, innovative methodologies are needed to extrapolate city-level datasets from national or regional statistics, given that the scarcity of data at the city level is likely to persist (Samara et al., 2024).

Some of these data-related challenges can be addressed. Delving into the details of the data and refining the models used requires time and effort. However, eventually, with access to richer datasets, barriers that may not be surmountable within the 2030 timeframe, which is relatively short for system-level transformations, will also be identified.

3.2. Implementation challenges

When testing climate neutral smart cities interventions, implementation is considered as one of the top challenges. More specifically, it is stressed that *"the main obstacle to climate transition is not a lack of climate-friendly and smart technologies, but the capacity to implement them. The present silo-based form of governance, designed and developed for traditional city operations and services, cannot drive an ambitious climate transition. Therefore, a systemic transformation is urgent" (*Net Zero Cities, 2023b; p.7).

The implementation strategy proposed by the EU Cities Mission is based on the NZC model of change and its systemic levers. These constitute combinatorial drivers of change to be applied across the emission domains. As shown in Fig.1, six types of systemic levers can be outlined: technology and infrastructure; governance and policy; social innovation; democracy and participation; finance and funding; learning and capabilities. The Action Plan for Thessaloniki specifies 33 systemic levers for carbon neutrality across the lever categories and emission domains (Table 3). The challenge in this case lies in the interconnected association and interaction among different systemic levers.

Achieving carbon neutrality presents significant financial challenges, necessitating innovative approaches to funding. The implementation of the Action Plan of Thessaloniki requires over 2 billion investments from various funding sources, including a large number of SMEs and households. Traditional funding mechanisms are often insufficient to cover the extensive investments required for a transition to a low-carbon economy. Consequently, there is a pressing need for new business models that can leverage co-funding strategies, combining public and private financial resources to amplify impact. The mobilization of many different types of funding plays a crucial role in this equation, offering a substantial pool of capital that can be directed towards sustainable projects. However, unlocking these funds requires creating attractive investment opportunities that align with the financial and environmental goals of private investors. Additionally, engaging households to renovation and energy optimization is vital; fostering a culture of consumption that supports carbon neutrality can drive demand for green products and services, further incentivizing investment in sustainable solutions. Together, these levers can overcome financial barriers, paving the way for a comprehensive and effective approach to achieving carbon

Table 3
Thessaloniki's Action Plan for Climate Neutrality – Systemic levers.

General categories	Specific levers
Technology & infrastructure	New infrastructure New services Re-design Technological solutions Intelligent systems/automation Nature Based Solutions Data systems and analytics
Government & policy	Ecosystem building Stakeholder collaboration Organizational improvement Observatory, monitoring Project planning Risk assessment E-government
Social innovation	Citizen sensibilization Living labs Re-use culture Social entrepreneurship Social media
Democracy & participation	Working groups Collaboration platforms Open governance
Finance & funding	New business models Provision of incentives Co-funding Co-funding Mobilization of private funds mobilization of non-profit funds
Learning & capabilities	Seminars & workshops Replication of natural ecosystems Training to LEED-ND Training to NBSs Citizen training to emission monitoring Training to digital entrepreneurship

Source: Municipality of Thessaloniki (2023).

neutrality.

Beyond financial incentives, other levers need to be utilized to mobilize the engagement of small private stakeholders who may not be convinced that climate neutrality is a priority compared to other daily life needs. Social innovation and governance are pivotal here, sustaining a multifaceted approach that includes ecosystem building, stakeholder collaboration, citizen sensitization, establishment of living labs, and fostering a culture for sharing. Developing supportive ecosystems is essential for facilitating collaboration among businesses, government entities, and the community, creating fertile ground for sustainable practices to flourish. Sensitizing citizens to the importance of climate raises awareness and encourages personal responsibility towards the environment. Living labs play a unique role by providing real-world environments where innovative solutions can be tested and refined in close collaboration with end-users, ensuring that new initiatives are both practical and community oriented. By integrating these levers, social innovation can significantly advance the collective shift towards carbon neutrality, making it an inclusive and community-driven effort.

4. Discussion

In response to the pressing challenges posed by designing and delivering efficient smart carbon–neutral development, both mitigation and adaptation strategies are essential components of comprehensive climate action plans. Mitigation actions aim to reduce greenhouse gas emissions and limit the extent of climate change, while adaptation actions focus on building resilience and adapting to the impacts of climate change. Within the context of the EU Cities Missions, a diverse array of mitigation and adaptation measures can be implemented to create sustainable, climate resilient, and livable regions and cities.

In considering the 2030 Action Plan for Climate Neutrality of Thessaloniki, the highlighted projects underscore the city's commitment to addressing climate change impacts comprehensively (Table 4). Within the energy, buildings and waste sectors, the focus on mitigation actions reflects efforts to reduce greenhouse gas emissions and transition towards sustainable practices. In these sectors, initiatives often center around improving energy efficiency, promoting renewable energy sources, and implementing green building standards. Energy efficiency measures, such as upgrading insulation, installing energy-efficient appliances, and optimizing heating, ventilation, and air conditioning (HVAC) systems, aim to minimize energy consumption and decrease carbon emissions associated with building operations. Additionally, promoting the adoption of renewable energy sources, such as solar panels and wind turbines, not only reduces reliance on fossil fuels but also contributes to decarbonizing the energy grid. Moreover, green building standards, such as LEED (Leadership in Energy and Environmental Design) certification, prioritize sustainable building practices, including efficient resource use, waste reduction, and indoor environmental quality, thereby fostering environmentally responsible construction and operation of buildings.

On the contrary, the adaptation projects within the land use and environment sector emphasize the importance of enhancing urban resilience and safeguarding against the impacts of climate change on infrastructure and ecosystems. These projects often involve measures such as green infrastructure development, flood management strategies, and biodiversity conservation efforts. Green infrastructure projects, such as the creation of urban parks, green roofs, and permeable pavement, aim to mitigate urban heat island effects, improve air quality, and provide natural habitats for wildlife, thereby enhancing the overall resilience of cities to climate change impacts. Similarly, flood management strategies, including the construction of retention ponds, flood barriers, and vegetated swales, help mitigate the risk of flooding in urban areas, reducing the potential damage to infrastructure and communities. Additionally, biodiversity conservation efforts, such as the preservation

Table 4
Categorization of a sample of Thessaloniki's Action Plan actions for climate neutrality as either mitigation or adaptation strategies.

Sector	Type of action	Action
Energy	Mitigation	• Widespread installation of renewable energy generation in public spaces and buildings • Certification of green electricity production • Optimization to reduce electricity consumption in buildings and facilities
Buildings	Mitigation	• Renovation and upgrade of the building stock • New buildings compliance with the highest energy efficiency standards • Turn to high-efficiency electric systems for heating
Waste	Mitigation	• Easy packaging recycling to meet the corresponding European levels • Management of biowaste through composting infrastructure • Wasteful disposal of food reduction
Trasport & Logistics	Mitigation Adaptation	• Promote green modes of transport • Public transportation coordination by a multimodal system
Smart City & Governance	Mitigation	• Internet infrastructure upgrade • Use of cloud computing for municipal services • Data analysis through AI • Establishment of a climate transition observatory
	Adaptation	• Decarbonization progress monitoring through platform system • Upgrade sensors and devices for data collection to measure air quality
Land Use & Environment	Adaptation	• Create an urban form of low emissions • Pilot projects to limit heat islands, absorb noise, and protect biodiversity

of natural habitats, reforestation initiatives, and wildlife corridors, contribute to maintaining ecosystem services and biodiversity, which are essential for the long-term sustainability and resilience of urban environments.

The inclusion of a mix of mitigation and adaptation projects across sectors such as transport, logistics, and smart city governance underscores the comprehensive approach needed for smart carbon–neutral spatial development. In these sectors, initiatives aim to both reduce greenhouse gas emissions and enhance resilience to climate change impacts, reflecting the interconnectedness of socio-economic and environmental factors in urban development. For instance, transportation projects may include the promotion of public transit, cycling infrastructure, and electric vehicle adoption to mitigate emissions from transportation while also improving mobility and reducing vulnerability to traffic-related disruptions. Additionally, smart city governance projects may leverage technology and data-driven solutions to enhance urban planning, decision-making, and service delivery, contributing to both mitigation and adaptation objectives.

By integrating mitigation and adaptation efforts across sectors, cities can foster sustainable and resilient development pathways that address the complex challenges of climate change while promoting economic prosperity and social equity. This holistic perspective aligns with the systems-innovation approach, emphasizing the interconnectedness of various sectors and the need for innovative solutions to address complex climate challenges in urban settings. By considering the interdependencies between sectors such as energy, transportation, waste management, and urban planning, cities can develop integrated strategies that maximize synergies and minimize trade-offs. Moreover, adopting a systems-innovation approach encourages cities to leverage cutting-edge technologies, collaborative governance structures, and community engagement initiatives to co-create transformative solutions that enhance climate resilience, improve quality of life, and foster inclusive growth (Komninos et al., 2019, 2022).

The convergence of efforts among actions included in the EU Cities Mission underscores a paradigm shift from multi-level governance to a holistic governance-as-a-whole perspective, imperative for driving smart, carbon–neutral development. This means that a holistic approach should be applied not only to the various levels of governance (urban, regional, national, and international), but also to the different sectors interacting in space. Expanding the systems-innovation approach to governance functions suggests that we must embrace flexibility, collaboration, and adaptability as guiding principles. This will enable to trigger and enhance links and interactions among different systemic levers, as the ones presented in Table 2. By integrating diverse stakeholders, including policymakers, urban planners, community representatives, and industry leaders, into decision-making processes, we can foster synergies and co-create innovative solutions that address the complex challenges of smart carbon–neutral development. Moreover, this approach requires reimagining traditional governance structures to be more inclusive and participatory, allowing for bottom-up initiatives and grassroots innovation to thrive. Embracing a governance-as-a-whole perspective acknowledges the interconnectedness of socio-economic, environmental, and technological factors shaping urban development, paving the way for more effective and sustainable solutions.

However, the EU Missions policy framework, while ambitious in its goals for transitioning to a sustainable future by 2030, faces several significant limitations that warrant a critical examination. Firstly, the overly ambitious short-term targets set for the transition may lead to unrealistic expectations and potential failure to meet objectives, undermining public confidence in the initiative. Secondly, the framework suffers from inadequate financial resources allocated to support the scale and complexity of the proposed transformations, raising concerns about the feasibility of implementation. Additionally, challenges associated with the widespread adoption of electromobility, such as infrastructure development and consumer acceptance, present formidable obstacles to achieving transportation sector goals. Moreover, there is a pressing need for greater emphasis on renewable energy sources (RES) storage and network enhancements to ensure reliability and stability in the transition to clean energy. Addressing these limitations is crucial for the EU Missions framework to realize its potential in driving meaningful and sustainable change towards a carbon–neutral future.

5. Conclusions

Societal challenges, like climate change, are emblematic of the intricate web of complexities humanity faces. In addressing such multifaceted challenges, it is crucial to recognize that the policy design process exceeds a simple aggregation of its individual components; instead, it frequently embodies a larger, interconnected whole. Thus, embracing a holistic perspective in policy design becomes paramount in addressing climate change challenges and achieving smart carbon–neutral development.

A holistic approach, rooted in systems-innovation, offers a promising avenue for addressing the multifaceted challenges of smart carbon–neutral development. Unlike traditional approaches that treat policy actions as isolated occurrences, a holistic perspective acknowledges the interconnectedness and complexity inherent in socio-ecological systems. This entails recognizing that policy interventions are influenced not only by immediate factors but also by broader path-dependence and self-organization dynamics. Moreover, governance must be viewed through a comprehensive lens, capturing various spatial levels from local to international, along with the diverse actors and systems operating within them. In this framework, each policy action and governance model emerges as the result of an evolutionary process, shaped by a multitude of interacting factors such as socio-cultural contexts, technological advancements, and economic drivers. Consequently, a complexity arises when attempting to align policy actions, derived from local contexts, with governance frameworks sourced from different paths and scales—be it regional, national, or international. Embracing reflexive governance, as proposed by the EU Cities Mission, acknowledges this inherent complexity and emphasizes continuous learning, adaptation, and collaboration among stakeholders to navigate uncertainty and foster effective implementation of policy.

Furthermore, the uniqueness of the holistic approach compared to systemic levers lies in its ability to integrate these levers more effectively. By recognizing the interdependencies and complementarities among different sectors—such as energy, transportation, waste management, and urban planning—a holistic strategy can ensure that policy design, implementation, and outcomes are more aligned with the overarching goals of carbon–neutral development. This integrated approach allows for a more nuanced understanding of how interventions in one sector may impact others, thus minimizing unintended consequences and maximizing synergies. Additionally, reflexive governance practices enable ongoing assessment and adjustment of policies based on feedback loops and evaluation mechanisms, ensuring that interventions remain responsive to evolving socio-environmental dynamics. In this way, a holistic approach transcends traditional siloed thinking and fosters a more coherent and adaptive approach to addressing the complex challenges of sustainability and resilience in spatial development.

Navigating this complexity necessitates a shift in our approach. Rather than viewing actions and governance as separate entities that need to be linked and/or combined, policy design should be perceived as a convolution process—a merging of functions—of actions and governance models. This entails synthesizing actions and governance into a cohesive framework that acknowledges both their individual trajectories and their intertwined nature. By adopting a systems perspective, policy designers can meaningfully amalgamate diverse actions and governance mechanisms towards this direction. This process of convolution not only yields a comprehensive understanding of the issue but also facilitates the creation of innovative solutions that transcend traditional silos.

In the context of smart carbon–neutral development, several challenges arise from the complexities outlined above. One significant challenge lies in the integration of disparate elements into a cohesive framework. Despite the necessity for a holistic perspective in policy design, achieving this unity proves intimidating amidst the multiple spatial levels, actors, and systems involved. The inherent path-dependence and self-organization dynamics further complicate matters, as policies and initiatives evolve independently, shaped by diverse factors. Aligning these evolving elements with overarching governance frameworks becomes a huge task, fostering uncertainty in effectively coordinating actions towards carbon neutrality goals. Moreover, the convolution process itself, aimed at merging actions and governance models, encounters resistance due to deep-rooted siloed thinking and institutional barriers. Harmonizing divergent policies demands a nuanced understanding of their individual trajectories and intersections within the broader context of carbon–neutral development. Additionally, the effective implementation of policies across varying spatial scales presents a difficult challenge, necessitating innovative solutions that transcend conventional approaches.

Overall, addressing the complexity of climate change requires a paradigm shift—one that embraces convolution and multi-scale governance as a means of integrating policies and actions into a unified framework. Only through such holistic approaches can societies hope to effectively combat the multifaceted climate challenges that lie ahead.

CRediT authorship contribution statement

Nicos Komninos: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Anastasia Panori:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

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.

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Data availability

No data was used for the research described in the article.

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