Journal of Cleaner Production 432 (2023) 139820

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

The role of Horizon (2020) in achieving climate-neutral urban objectives: A study of 14 Spanish cities innovation networks

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Climate-neutral cities
Horizon 2020
Social network analysis
Research networks
Research policy
European missions

ABSTRACT

This study aims to analyse the structure and characteristics of innovation networks from Horizon (2020) projects in fourteen Spanish cities, and to understand how these networks influence a city's success in being selected for the European Mission on Climate-neutral and smart cities by 2030. Utilizing social network analysis, the research uncovers patterns within these urban innovation networks, emphasizing attributes that advance climate neutrality efforts. Results indicate that cities with larger and more interconnected innovation networks, exhibiting balanced participation from diverse stakeholders, and predominantly led by the private sector and research institutions, are more likely to be successfully chosen for the Cities European Mission. This research provides a novel insight into the role of urban innovation systems in the journey towards decarbonization, accentuating the significant influence of European institutional structures in moulding these networks. By focusing on urban networks as a metric for assessing the progress towards climate neutrality, this study offers a fresh perspective that diverges from traditional regional or transnational analyses. The findings have substantial implications for policymakers and urban planners, underscoring the need for fostering robust innovation networks as a strategy to achieve climate neutrality. Additionally, the results pave the way for future research on optimizing resource allocation within urban innovation systems, ultimately contributing to the broader objectives of the European Green Deal.

1. Introduction

Cities have a crucial role in achieving climate neutrality by 2050, as outlined in the European Green Deal (European Commission, 2019). With cities being home to 75% of EU citizens and accounting for more than 70% of global CO_2 emissions (European Commission, 2021a), their contribution to mitigating climate change is essential. To accelerate their green and digital transformation, the European Commission has launched the European Mission on Climate-neutral and smart cities (European Commission, 2021b), from now on referred to as the "Cities Mission". The Cities Mission aims to deliver 100 climate-neutral and smart cities by 2030, with the selected cities acting as innovation and experimentation hubs for others to follow suit (European Commission, 2021c).

To achieve this goal, the European Commission has funded several Horizon 2020 projects, which have created innovation networks in the European cities taking part in these projects. Moreover, this commitment has not ended with H2020, since the European Commission has announced that the Cities Mission will receive €360 million of Horizon Europe funding covering the period 2022–23, to start the innovation paths towards climate neutrality by 2030 (European Commission, 2022a).

In this context, previous research works have addressed how innovation systems can foster environmental sustainability or green technology at national level (Fernandes et al., 2022; Zhang et al., 2022). Similarly, recent studies analyse how innovative networks from living labs created under the auspices of Horizon (2020) projects are able to create societal impact through sustainable transformation, as well as promoting innovation and sustainability (Compagnucci et al., 2021; Kok et al., 2023).

Other studies (Fernandez de Arroyabe et al., 2021) underscored that funding consortia fosters the establishment of innovation systems. These networks interlink all types of entities, facilitating collaboration and

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https://doi.org/10.1016/j.jclepro.2023.139820
Received 11 July 2023; Received in revised form 11 October 2023; Accepted 17 November 2023
Available online 20 November 2023

Abbreviations and acronyms

AVG	Average
CCC	Climate City Contract
Cities Mission	European Mission on Climate-neutral and smart cities
EC	European Commission
EIP-SCC	European Innovation Partnership on Smart Cities and Communities
EU	European Union
ERA	European Research Area
ERDF	European Regional Development Fund
FP	Framework Programme
GHG	Greenhouse gases
H2020	Horizon 2020 Framework Research Programme
HE	Horizon Europe
HES	Higher education establishments entity type
NSC	Cities not selected to take part in the European Mission
OTH	Sector-level organizations entity type
PUB	Public sector entity type
PRC	Private companies entity type
REC	Research organizations entity type
RQ	Research question
SC	Cities selected to take part in the European Mission
SEAP	Sustainable Energy Action Plan
SECAP	Sustainable Energy and Climate Action Plan
SNA	Social Network Analysis

promoting the exchange of knowledge and information (de Juana-Espinosa and Luján-Mora, 2019; Sá and Pinho, 2019). Such interaction has been a key target of recent research policies, which focus on knowledge transfer and project competitiveness (Souzanchi Kashani and Roshani, 2019). Moreover, past studies have assessed the effectiveness of networks formed by these consortia in attaining research policy goals (Calvo-Gallardo et al., 2021; Fernandez de Arroyabe et al., 2021).

Although abundant research exists on the performance of these projects, considering aspects of collaboration and consortia composition (N. Arranz and Fernández de Arroyabe, 2006; Pinheiro et al., 2016), a gap remains in understanding the system of relationships that emerges and its contribution to policy objectives, especially in the context of urban innovation systems (García Muñiz and Cuervo, 2018; Kang and Hwang, 2016), as there is no reference to the performance of innovation systems at city level. Moreover, in recent studies analyzing the key dimensions of cities' engagement in the transition to climate neutrality is stated that the participation of cities in international projects on energy and climate related issues is an under-research aspect (Salvia et al., 2023).

Hence, relevant research (Calvo-Gallardo et al., 2022; Fernandez de Arroyabe et al., 2021; García Muñiz and Cuervo, 2018) underlined the need for exploring the characteristics of inter-consortia relationships to evaluate the efficiency of the emerging innovation systems, considering collaboration, geographic cohesion, and knowledge and technology transfer.

Thus, this study delves into the innovation networks of Spanish cities striving for climate neutrality, particularly those aiming to be part of the European Mission on Climate-neutral and smart cities by 2030. The central objective is to assess how the structure and properties of these networks correlate with their success in achieving climate neutrality goals, using selection for the Cities Mission as a proxy for success.

Drawing from an analysis of fourteen major Spanish cities that were candidates for the Cities European Mission, this research seeks to determine the common characteristics of innovation networks that influenced their selection by the European Commission. Among the cities examined, namely Madrid, Barcelona, Valencia, Sevilla, Zaragoza, Murcia, Valladolid, Gijón, Hospitalet, Vitoria, Pamplona, Santander, Logroño, and Girona, only seven were chosen to participate in the Cities Mission, joining 105 other European cities in this endeavour (European Commission, 2021c). These cities, in their bid for climate neutrality, have anchored their strategies in diverse domains, ranging from sustainable mobility and circular economy to energy efficiency and urban regeneration, considering as well smart and digital infrastructures (European Commission, 2021a).

Grounded in the innovation systems perspective, this research examines the interactions and knowledge diffusion within urban entity networks. Social Network Analysis serves as the methodological backbone, offering insights into the dynamics, roles, and effectiveness of these networks derived from H2020 projects. This methodological approach aims to shed light on strategies for optimizing resource allocation, promoting climate neutrality, and aligning with the European Green Deal's ambitions (European Commission, 2019). Ultimately, the findings are intended to guide the design and execution of innovation policies in cities aiming for climate neutrality.

2. Literature review and conceptual framework

2.1. Innovation systems

Recent studies have advanced from the classical definition of innovation systems towards Technological Innovation Systems, that can be defined as a dynamic network of entities engaged within a distinct economic or industrial domain, operating under a set institutional framework, and actively participating in the creation, spread, and application of technology (Shubbak, 2019), or the more recent and related to this paper Mission-specific Innovation Systems. These last ones are defined as the web of entities and collection of institutions guiding the evolution and spread of novel technological and societal solutions, and reshaping prevailing production and consumption frameworks to fulfill a societal mission (Elzinga et al., 2023; Hekkert et al., 2020).

Innovation systems and networks in cities significantly contribute to advancing the transition towards climate neutrality by fostering collaboration among diverse stakeholders such as businesses, academic institutions, governments, and civil society organizations. These networks, crucial to both the city-wide and the European Mission's climate neutrality objectives, facilitate knowledge sharing, resource allocation, and best practice exchanges, thereby accelerating the development and deployment of innovative climate solutions (EIP-SCC, 2021; Grillitsch et al., 2019).

This research scrutinizes the innovation system embodied by the networks of relationships established by the consortia, which are financially supported by the H2020 projects related to the objectives of the Cities Mission.

2.2. Institutional impulse theory

The institutional theory (Berrone et al., 2013; Gallego-Alvarez et al., 2017; Gao et al., 2019) has been extensively utilized to elucidate how entities within an innovation system conform to common organizational practices and norms. As per this perspective, organizational behaviour is shaped by shared norms, structures, limitations, cognitions, and societal expectations (Ahmad et al., 2023; Berrone et al., 2013). Consequently, the institutional framework propels organizations towards the adoption of shared principles and processes, as recent research has shown for the case of environmental activities in companies (C. F. A. Arranz et al., 2022; C. F. A. Arranz and Arroyabe, 2023).

Therefore, the EU, striving for a competitive innovation landscape within its jurisdiction, has created the European Research Area (ERA) (*European Research Area*, 2023)- envisioned as a harmonious space facilitating the seamless circulation of researchers, scientific knowledge, and technology. During its revitalization process beginning in 2018, the ERA set out 20 concrete actions for the period 2022–2024, including among others to Accelerate the green/digital transition of Europe's key industrial ecosystems and to Support research and innovation investments and reforms (European Commission, 2022b).

In this context, the European Union (EU) has been instrumental in promoting climate action at the city level with initiatives such as the Covenant of Mayors, and the transition from Sustainable Energy Action Plans (SEAPs) to Sustainable Energy and Climate Action Plans (SECAPs). Launched in 2008, the Covenant of Mayors is a voluntary initiative urging cities to commit to greenhouse gas (GHG) emission reductions beyond the EU's minimum targets, and since 2015, it has expanded to include climate adaptation strategies within the SECAPs, which mandate both mitigation and adaptation measures for 2030 emission reduction targets (Covenant of Mayors, 2021).

SECAPs typically encompass an assessment of the city's current energy and emission profile, a set of strategic objectives, and a detailed action plan, and have proven effective in driving local climate action and bolstering city resilience to climate impacts (Salvia et al., 2021). For over a decade, the Covenant of Mayors and SECAPs have provided essential action frameworks, with the EU providing significant support through funding, technical aid, and policy guidance (Bertoldi et al., 2018; European Commission, 2021a; Marchi et al., 2023). As we transition towards sustainability, EU initiatives such as the European Green Deal and the European Mission on Climate-Neutral and Smart Cities will remain pivotal in guiding local authorities in combating climate change and promoting sustainable development (European Commission, 2021c).

The European Mission on Climate-Neutral and Smart Cities, a critical initiative under Horizon Europe, seeks to transform cities into sustainable, climate-resilient territories by enabling the transition towards climate neutrality in at least 100 European cities by 2030, and all EU cities by 2050. In 2023, 112 cities were selected to partake in this initiative, all representing varied urban environments and demonstrating dedication towards climate neutrality and sustainable urban development innovation(European Commission, 2023).

The Implementation Plan for the European Mission on Cities offers concrete actions for these objectives, including governance framework establishment, innovation and collaboration encouragement among cities, and sustainable solutions and green technologies investment promotion. Crucially, Climate City Contracts (CCC), agreements between the European Commission and participating cities, outline specific climate neutrality targets and serve as collaboration platforms for sharing best practices and innovative solutions (European Commission, 2021c). The EU further supports cities with financial aid and technical assistance, including the creation of the Cities Mission Platform (NetZeroCities) to facilitate knowledge exchange and drive investments in sustainable urban development projects (NetZeroCities, 2022). Thus, by setting clear targets, promoting innovation, and fostering collaboration, this initiative provides a comprehensive framework for driving city-level climate action and sustainable development, potentially playing a significant role in helping European cities achieve climate neutrality and construct more resilient, sustainable urban environments.

2.3. Research model

Tackling urban emissions is imperative for climate change mitigation and public health, emphasizing the critical role of cities in achieving global climate targets and maintaining the well-being of urban populations. With the support of the European Union through funding, technical assistance, and policy guidance, strategies such as the European Green Deal and the European Mission on Climate-Neutral and Smart Cities contribute to sustainable development efforts and underline the importance of local authorities in combating climate change.

In this context, innovation networks within cities become vital components in realizing climate neutrality objectives and fostering the Cities Mission's goals, as has been shown in previous research works aiming at a regional or national scale (Frantzeskaki et al., 2014; Grillitsch et al., 2018). By facilitating collaboration, knowledge sharing, and capacity building, these networks enable the development and deployment of innovative climate solutions, expediting the transition towards sustainable and climate-resilient urban environments.

These benefits fostered by urban innovation networks are related to the evaluation criteria followed by the expert reviewers in charge of selecting the cities of the Mission. These criteria include cities' level of ambition, preparedness, existing and planned commitment to climate neutrality, plans to involve citizens and stakeholders and the capacity to maximize the impact at national level, together with others like inclusiveness, diversity and geographical balance (European Commission, 2021e).

Thus, given the alignment of the benefits pursued by the urban innovation networks and the Cities Mission evaluation criteria, the subsequent research model in this study applies Social Network Analysis techniques to assess the properties of the networks developed in cities by the H2020 projects funded in a range of topics related to the achievement of climate neutrality. Thanks to this analysis it will be possible to assess if there were a relationship between the cities' networks characteristics and their selection by the European Commission to participate in the mentioned Mission.

To address this assessment, this research model will examine cities' innovation networks as two-mode networks, with nodes representing different types of entities and projects related to the reduction of GHG emissions, being entities linked to the projects in which they participate. The cohesion properties of the cities' networks provide an idea of the structure of this innovation system and the centrality measures of the different categories of nodes provide insights about how each type of entity, depending on their role in the projects, is embedded in the overall network and contribute to its cohesion. In this sense, this study will address the following research questions.

- RQ1: How does the structure of H2020 project-based innovation networks in Spanish cities aiming for climate neutrality, correlate with their climate neutrality success?

Understanding the structure of the cities' innovation networks is pivotal to this research as it provides the foundational groundwork for comprehending the nature of these networks and how they operate to drive climate action. Moreover, by investigating the relationship between network structure and the success of climate neutrality efforts, this question aims to unveil key patterns or characteristics within successful networks. This could potentially help in identifying effective strategies that promote climate neutrality and can be replicated or adapted in different contexts.

- RQ2: How do H2020 project-based innovation networks in these cities differ in network cohesion, node centrality, and attributes, and how do these variations influence their climate neutrality success?

The second research question delves deeper into the specific attributes of the innovation networks. By doing so, it aims to reveal the inner workings of these networks, identifying how different components interact and contribute to the network's function. This could help to identify the key actors within these networks and understand their roles better. Furthermore, exploring how these network attributes correlate with the success of climate neutrality efforts will provide insights into what makes a network more effective in driving climate action. This knowledge could prove invaluable in designing and optimizing networks for greater climate action efficacy.

- RQ3: How can these observations be applied to the design and implementation of innovation policies and programs in other cities and regions aiming to achieve climate neutrality?

Finally, the third research question takes the insights gleaned from the previous questions and looks at how they can be applied to a policy-making context, bringing a practical application aspect to the research. The results could inform strategies for creating and managing innovation networks in different geographical contexts and contribute to broader efforts towards achieving global climate neutrality. This application-oriented approach amplifies the potential impact of the research, making it directly relevant to policymakers, city planners, and other stakeholders involved in climate action at the urban level.

3. Methods

3.1. Data

As this study looks for projects that can be materialized in results for cities and European society in the short or medium-term, only applied research projects from Industrial Leadership and Societal Challenges Pillars have been considered. Concretely, the Research Programmes of the Horizon 2020 Framework Programme considered are the ones shown in Table 25, that can be found in the Appendix section.

In total, these programmes include 8284 projects performed by 27,406 distinct entities, where 9839 of them recurring partners (entities that participate in two or more projects). The total number of participations in the project sample, established as the participation of one entity in one project, rises to 85,055.

3.1.1. Analysed cities

The cities selected for this analysis were those Spanish cities that submitted their candidature to the European Cities Mission on January 31, 2022, which were the following 25: Avilés, Barcelona, Ceutí-Molina de Segura, Elda, Fuenlabrada, Gijón, Girona, Las Rozas de Madrid, L'Hospitalet de Llobregat, Logroño, Madrid, Marbella, Mollet des Vallès, Murcia, Pamplona, Sant Boi de Llobregat, Sant Cugat del Vallès, Santander, Sevilla, Tres Cantos, Valencia, Valladolid, Viladecans, Vitoria-Gasteiz and Zaragoza.

Among these candidates only the following seven cities were finally selected: Madrid, Barcelona, Sevilla, Valencia, Valladolid, Vitoria-Gasteiz and Zaragoza. Nevertheless, to analyse if the properties of the innovation networks of the candidates can be a suitable criterion in future selection processes, also Murcia, Gijón, Hospitalet, Pamplona, Santander, Logroño and Girona have been studied, considering that they count with a relevant amount of Horizon (2020) projects to be assessed and compared (more than 15 projects), and a population higher than 100,000 citizens. For example, Fuenlabrada and Marbella are candidate cities with 192,612 and 149,032 inhabitants respectively, but the first one only counts with two projects located in its area while in the last one there is none.

To enhance readability and ease of tracking throughout the article, a specific formatting choice has been implemented in the presentation of data. In tables where all cities under study are listed, cities chosen for participation in the Cities Mission are highlighted in **bold**. This distinction is intended to provide readers with a clear visual cue, allowing for a more streamlined understanding of which cities are central to the Cities Mission context as the article is navigated.

In Table 1 are shown the main socioeconomic indicators of the analysed cities, also including the R&D expenditure made by the region in which each city is located, as there was no other R&D indicator available at the municipality level. All the figures shown in Table 1 come from the Spanish National Statistical Institute.

Table 1
Socioeconomic and R&D indicators of the analysed cities.

City	Population (2022)	GDP per capita in € (2020)	Regional R&D internal expenditure per capita in € (2021)
Madrid	3,277,451	17,059	670
Barcelona	1,627,559	16,750	532
Valencia	788,842	13,873	267
Sevilla	684,340	12,490	200
Zaragoza	681,430	14,220	294
Murcia	459,778	11,777	231
Valladolid	297,370	14,247	335
Gijón	269,311	13,842	203
Hospitalet	265,003	11,731	532
Vitoria	252,953	15,110	766
Pamplona	203,596	14,264	592
Santander	172,000	14,202	228
Logroño	150,596	13,791	206
Girona	101,648	14,750	532

As can be seen, the seven cities selected were bigger in terms of population except for Murcia, Gijón and Hospitalet. Indeed, some of the not selected cities for the European Mission count with higher figures in both GDP per capita and regional R&D expenditure than some of the cities participating in the Mission, such as Girona, Pamplona or Santander.

3.1.2. Research project types in the analysed cities

The data used for developing this study has been collected from the Horizon 2020 Research program of the European Commission database (accessible at the following url: https://data.europa.eu/data/datasets/cordish2020projects?locale=es, accessed on March 15, 2023). The entities based on the fourteen cities studied are identified relying on their postal code, as included in their addresses, when each of them registered its Participant Identification Code.

To process and prepare the data for analysis, several steps were undertaken.

- Data Cleaning: After initial extraction, the data underwent rigorous cleaning to remove any redundancies, inconsistencies, or inaccuracies. This included verifying the validity of postal codes, ensuring consistent formatting, and cross-referencing with other databases when necessary. For instance, to ascertain the accuracy of the postal codes, the dataset was cross-referenced with the national postal databases of the respective analysed cities. Moreover, to ensure the correctness of the Participant Identification Code (PIC), a cross-reference was carried out with the Unique Registration Facility (URF) database maintained by the European Commission. Such cross-referencing helped in identifying and rectifying any discrepancies, thus enhancing the accuracy and completeness of our dataset.
- Network Construction: Based on the cleaned dataset, a network was constructed, representing entities as nodes and their collaborative ties as edges. This network formed the foundation for subsequent Social Network Analysis.
- Attribute Assignment: To each node (entity), relevant attributes were assigned, such as the type of entity (e.g., research institution, private company) and its primary focus within the scope of the H2020 projects. These attributes allowed for a more nuanced analysis of the roles and significance of different entities in the network.
- Data Validation: To ensure the integrity and accuracy of the constructed network, random samples were cross-checked with the original database, and any discrepancies were addressed promptly.

Through these meticulous steps, the data was made ready for in-depth analysis, ensuring that the insights derived are both accurate and meaningful in the context of urban innovation networks and their role in driving climate neutrality.

The decision to use data from the Horizon 2020 Research program database is directly aligned with RQ1. By focusing on entities based in the fourteen cities of interest and examining their innovation networks, it is aimed to understand the structure of these networks and its relationship with their climate neutrality success.

In Table 18, Tables 19 and 20 of the Appendix are shown the number of projects considered in the study located in each of the analysed cities, divided by the research programme to which these projects belong.

Additionally, in Table 21 (see appendix), the distribution of the number of projects within the different research programmes is compared, considering the projects with entities from the analysed cities and the distribution of all the projects executed in the research programmes. In this sense, it is significant that the cities analysed participated in more projects than the average in research programmes addressing ICTs or agro-bio-based issues, while on the other hand, the analysed cities were less present in projects addressing sustainable transport challenges, which, according to the European Commission (European Commission, 2021d), represent almost a quarter of Europe's greenhouse gases emissions and is the main cause of air pollution in cities.

3.1.3. Entity types and roles in the project

Participating entities are categorized based on their nature and primary activities into the following types: public sector (PUB), higher education establishments (HES), research organizations (REC), private companies (PRC), and others (OTH).

The public sector (PUB) primarily consists of national, regional, and local public authorities, as well as energy agencies. Higher education establishments (HES) predominantly encompass universities. The research organizations (REC) category comprises two main types of stakeholders: publicly funded national research centres and research and technology organizations, which are predominantly private, non-profit entities. Private companies (PRC) include both large enterprises and small and medium-sized companies. Lastly, the other (OTH) category encompasses sector-level associations, which may also include some research institutes that are legally constituted as associations.

Moreover, regarding the entities' roles, it is also relevant to mention that each consortium is led by one entity that acts as a 'coordinator', while the remaining consortium partners are considered as 'participants' when they are independent, or 'third parties' if they have a legal and/or a capital link to another beneficiary. Nevertheless, the presence of third parties is almost negligible and thus will not be considered in this study.

In this context, and to answer the first research question, an exhaustive analysis of the different actors composing the innovation networks of the fourteen candidate municipalities for the Cities Mission has been carried out.

Table 2
Participants analysis per entity type.

	PUB	HES	REC	PRC	OTH
H2020 Energy	8.00%	13.00%	9.00%	63.00%	8.00%
Madrid	6.58%	2.06%	5.56%	71.60%	14.20%
Barcelona	7.99%	2.88%	7.67%	70.93%	10.54%
Valencia	10.08%	1.68%	10.08%	71.43%	6.72%
Sevilla	11.11%	2.22%	11.11%	67.78%	7.78%
Zaragoza	5.56%	3.33%	8.89%	76.67%	5.56%
Murcia	18.42%	5.26%	5.26%	60.53%	10.53%
Valladolid	11.63%	2.33%	13.95%	60.47%	11.63%
Gijón	4.76%	0.00%	9.52%	85.71%	0.00%
Hospitalet	10.00%	0.00%	10.00%	80.00%	0.00%
Vitoria	21.05%	0.00%	5.26%	65.79%	7.89%
Pamplona	11.54%	7.69%	3.85%	69.23%	7.69%
Santander	5.56%	5.56%	11.11%	72.22%	5.56%
Logroño	0.00%	0.00%	5.56%	94.44%	0.00%
Girona	15.38%	7.69%	7.69%	61.54%	7.69%
AVG cities	**9.98%**	**2.91%**	**8.25%**	**72.02%**	**6.84%**
AVG SC	**10.57%**	**2.07%**	**8.93%**	**69.24%**	**9.19%**
AVG NSC	**9.38%**	**3.74%**	**7.57%**	**74.81%**	**4.50%**

In Table 2 are presented the entities participating in H2020 projects based on the studied cities, categorized by their activity type while in Table 3 is shown the percentage of the entities assuming the role of coordinators at least in one project. In both tables are also included the average (AVG) percentage of participation and coordination among the different entity types, as obtained by the work carried out in previous studies addressing H2020 energy programme data (Calvo-Gallardo et al., 2022).

In Table 2 it is relevant to note that the average participation of HES entities is almost five times lower than the H2020 Energy programme average, while PUB and PRC types participation are higher, probably thanks to the presence of local authorities and companies linked to the different municipalities. Moreover, when analysing the entities type participants in the selected cities by the Cities Mission (AVG SC), it results that PUB, REC and OTH types participation is higher while PRC and HES participations are lower than in the non-selected cities by the Cities Mission (AVG NSC).

As can be seen in Table 3, the average coordination percentage in the analysed cities is almost three times higher than the average of the Energy Programme of H2020, which has been considered a representative one in terms of addressing climate neutrality. It is particularly remarkable the case of the cities not selected for the European Mission, as they triple the average degree of coordination, which may imply that the entities from these municipalities need to take a lead role to be able to participate in this kind of projects.

It is significant as well that the degree of coordination in PRC entities located in the analysed cities is five times higher than the H2020 Energy Programme average, while the coordination percentage of REC entities in the analysed cities is half the one in the H2020 Energy Programme. This may suppose that for private entities is more strategic to participate in projects linked to the municipality in which their headquarters or main activities are based. Finally, when comparing the selected and non-selected cities by the Cities Mission coordination ratio, it is shown that OTH types are the only ones with a higher coordination ratio in the average selected cities.

The 1323 entities from the 14 cities analysed account for 4996 participations, implying that, on average, each entity is involved in 3.78 projects. However, this varies significantly between cities, as in Madrid or Santander each entity is involved in 4.50 and 4.56 projects respectively, while in Logroño or Hospitalet this ratio decreases to 1.28 and 1.60 respectively.

In Table 4 are presented the number of participations of each entity type to quantify their activity. In terms of participations, the average figures of the cities analysed are in line with previous studies addressing H2020 energy programme data (Calvo-Gallardo et al., 2022), except for public entities, that double their presence in the projects of the analysed cities, at the expense of the HES entities which decrease its participations in almost 6%. In this case, when analysing the entities type participations in the selected cities by the Cities Mission (AVG SC), it results that REC and OTH types participation is higher while HES participation is lower than in the non-selected cities by the Cities Mission (AVG NSC). The case of REC participations in the selected cities is relevant as it is more than two times higher than in non-selected cities.

Regarding the coordination ratio of the different entities' participations per type that is shown in Table 5, again, the average coordination percentage in the analysed cities is more than two times the average of the Energy Programme of H2020. It is especially relevant in the case of public entities and private companies, which ratios are more than two times and four times respectively higher than the average of the Energy Programme of H2020. Moreover, it is significant that REC entities coordinate almost half the percentage of projects in the analysed cities than in the average H2020 Energy Programme.

Finally, when comparing the selected and non-selected cities by the Cities Mission coordination ratio, in this case, it is shown that HES and OTH types are the ones with a higher coordination ratio in the average selected cities.

Table 3
Participant's coordination percentage per entity type.

	PUB	HES	REC	PRC	OTH	AVG Coord.
H2020 Energy	3.00%	18.90%	22.00%	5.30%	2.60%	8.20%
Madrid	3.13%	20.00%	3.70%	22.70%	4.35%	17.70%
Barcelona	0.00%	11.11%	0.00%	26.13%	6.06%	19.49%
Valencia	0.00%	0.00%	16.67%	21.18%	0.00%	16.81%
Sevilla	10.00%	50.00%	0.00%	18.03%	0.00%	14.44%
Zaragoza	0.00%	0.00%	25.00%	26.09%	0.00%	22.22%
Murcia	0.00%	50.00%	50.00%	30.43%	0.00%	23.68%
Valladolid	0.00%	0.00%	16.67%	19.23%	20.00%	16.28%
Gijón	0.00%	0.00%	0.00%	50.00%	0.00%	42.86%
Hospitalet	0.00%	0.00%	0.00%	12.50%	0.00%	10.00%
Vitoria	25.00%	0.00%	0.00%	8.00%	0.00%	10.53%
Pamplona	0.00%	0.00%	0.00%	38.89%	0.00%	26.92%
Santander	0.00%	0.00%	50.00%	30.77%	0.00%	27.78%
Logroño	0.00%	0.00%	0.00%	29.41%	0.00%	27.78%
Girona	50.00%	100.00%	0.00%	25.00%	0.00%	30.77%
AVG cities	**6.29%**	**16.51%**	**11.57%**	**25.60%**	**2.17%**	**21.95%**
AVG SC	**5.45%**	**11.59%**	**8.86%**	**20.19%**	**4.34%**	**16.78%**
AVG NSC	**7.14%**	**21.43%**	**14.29%**	**31.00%**	**0.00%**	**27.11%**

Table 4
Participations analysis per entity type.

	PUB	HES	REC	PRC	OTH
H2020 Energy	4.00%	21.00%	19.00%	49.00%	6.00%
Madrid	10.89%	11.89%	19.72%	48.67%	8.83%
Barcelona	7.36%	19.48%	19.94%	46.51%	6.71%
Valencia	4.18%	26.69%	25.30%	39.64%	4.18%
Sevilla	7.89%	14.14%	21.71%	51.32%	4.93%
Zaragoza	5.49%	14.74%	41.33%	36.13%	2.31%
Murcia	21.33%	22.67%	5.33%	40.00%	10.67%
Valladolid	7.83%	7.23%	54.82%	24.10%	6.02%
Gijón	2.22%	0.00%	42.22%	55.56%	0.00%
Hospitalet	12.50%	0.00%	6.25%	81.25%	0.00%
Vitoria	23.75%	0.00%	7.50%	62.50%	6.25%
Pamplona	20.00%	15.56%	4.44%	48.89%	11.11%
Santander	15.85%	39.02%	2.44%	34.15%	8.54%
Logroño	0.00%	0.00%	4.35%	95.65%	0.00%
Girona	7.55%	47.17%	16.98%	24.53%	3.77%
AVG cities	**10.49%**	**15.61%**	**19.45%**	**49.21%**	**5.24%**
AVG SC	**9.63%**	**13.45%**	**27.19%**	**44.12%**	**5.61%**
AVG NSC	**11.35%**	**17.77%**	**11.72%**	**54.29%**	**4.87%**

As an additional analysis, it is also relevant to look at the total contribution or funding received by the European Commission in the analysed projects by entity type, as well as the total budget invested by them, which are shown in Tables 27 and 28. When looking at the total budget invested by the entities participating from each city, the first seven cities in descendent order coincide with the cities selected to participate in the Mission. However, when assessing the total grant received, Santander is ahead of Vitoria, although both cities, together with Girona, are in the same range of EC contribution received. Nevertheless, it is relevant that Valladolid and Valencia hold the tenth and twelfth positions when the total investment made by public entities from entities located in each city is analysed, meaning that in other cities like Pamplona or Murcia, their public entities had to make bigger investments to dynamize their innovation networks. Indeed, it is relevant that in Vitoria (65,26% of investment versus 23.75% of participations) and Girona (12,51% of investment versus 7,55% of participations) the public entities account for significantly bigger investments than what should be expected due to their participations rates.

Finally, it is also worth mentioning that cities with higher-than-average socioeconomic aspects like population or regional R&D internal expenditure per capita, as it is the case of Hospitalet and Logroño, made such a low investment in H2020 projects. On the other hand, Pamplona, the next city in terms of low project's budget after these two, invested four and three times more than them respectively.

3.2. Methodology

Numerous studies have explored the use of SNA to assess innovation system performance (Abreu and Nunes, 2020; Calvo-Gallardo et al., 2022; Calvo-Gallardo et al., 2021; Fernandez de Arroyabe et al., 2021; Franco-Bermúdez and Ruiz-Castañeda, 2019; Morisson et al., 2020);

Table 5
Participations coordination percentage per entity type.

	PUB	HES	REC	PRC	OTH	AVG Coord.
H2020 Energy	3.00%	18.90%	22.00%	5.30%	2.60%	8.20%
Madrid	3.36%	7.31%	0.70%	16.73%	5.18%	9.97%
Barcelona	0.00%	53.11%	0.00%	15.03%	4.17%	17.61%
Valencia	0.00%	0.00%	11.02%	18.09%	0.00%	9.96%
Sevilla	16.67%	95.35%	0.00%	12.82%	0.00%	21.38%
Zaragoza	0.00%	0.00%	39.16%	24.00%	0.00%	24.86%
Murcia	0.00%	5.88%	75.00%	23.33%	0.00%	14.67%
Valladolid	0.00%	0.00%	14.29%	15.00%	30.00%	13.25%
Gijón	0.00%	0.00%	0.00%	52.00%	0.00%	28.89%
Hospitalet	0.00%	0.00%	0.00%	7.69%	0.00%	6.25%
Vitoria	21.05%	0.00%	0.00%	4.00%	0.00%	7.50%
Pamplona	0.00%	0.00%	0.00%	40.91%	0.00%	20.00%
Santander	0.00%	0.00%	50.00%	28.57%	0.00%	10.98%
Logroño	0.00%	0.00%	0.00%	22.73%	0.00%	21.74%
Girona	75.00%	100.00%	0.00%	15.38%	0.00%	56.60%
AVG cities	**8.29%**	**18.69%**	**13.58%**	**21.16%**	**2.81%**	**18.83%**
AVG SC	**5.87%**	**22.25%**	**9.31%**	**15.10%**	**5.62%**	**14.93%**
AVG NSC	**10.71%**	**15.13%**	**17.86%**	**27.23%**	**0.00%**	**22.73%**

however, none have specifically focused on Horizon 2020 research and innovation projects related to emissions reduction in cities. Conclusions drawn from other fields demonstrate a positive link between innovation system performance and the connectivity of related networks, illustrating the efficiency of networks as mechanisms for knowledge diffusion and creation (Altuntas and Gök, 2020; M. Li et al., 2019).

A well-integrated and interconnected network that includes all different actors in the innovation value chain and connects all related projects is critical for the high performance of a research program (Kolleck, 2013). Research networks facilitate information exchange and experience sharing, helping to avoid overlapping actions and fragmentation of activities, which are crucial challenges for enhancing the EU's R&D performance (European Commission, 2010). Increasing the integration of energy research networks will expedite the delivery and deployment of R&D results that cities require to achieve their climate neutrality targets.

In this sense, SNA is pivotal for RQ2 as it provides metrics on network cohesion and centrality. By analysing these metrics, it can be understood the variations in network structures across cities and how these variations might correlate with their climate neutrality success. The insights derived from SNA will shed light on the characteristics of effective innovation networks.

This study utilizes UCINET software (S. Borgatti et al., 2002) to examine the relationship between the H2020 project city networks' characteristics and their selection by the European Commission to participate in the mentioned Mission. UCINET is a widely recognized software package for the analysis of social network data. Developed by Borgatti, Everett, and Freeman, it is tailored for analysing sociometric data, enabling researchers to study complex relational structures and their patterns. Common applications of UCINET encompass a variety of network metrics, including centrality measures, subgroup identification, and role analysis, among. In this study, UCINET was employed to process and analyse the relational data drawn from our selected cities' innovation networks. Specifically, its robust tools were used to quantify network cohesion, identify central actors and project, and discern patterns of interaction that underpin the innovation dynamics in the context of environmental sustainability. By leveraging UCINET's comprehensive suite of analytical tools, it is ensured a systematic and in-depth exploration of the innovation networks analysed in this research.

The analysis results may be used by the European Commission, the Mission Platform (NetZeroCities, 2022), and other platforms related to the Member State level when selecting future cities or evaluating the convenience of retaining the 112 selected ones within the Mission. Furthermore, municipalities and other city-based entities participating in FPs can benefit from the SNA insights to enhance their position and embeddedness within the networks. As a result, participants can identify opportunities to establish new connections with other entities or projects to improve their access to and transfer of new knowledge.

Moreover, the conclusions and insights drawn from the SNA will serve as a foundation for RQ3, as understanding the characteristics of successful innovation networks, recommendations for other cities and regions can be provided. This knowledge will be invaluable for crafting effective innovation policies and programs aiming to achieve climate neutrality.

The innovation system constructed by the H2020 projects related to the objectives of the Cities Mission is understood as a 2-mode network, in which entities are tied to projects. From this 2-mode network, two 1-mode networks can be deducted: one of the projects linked by shared entities and one of the entities tied by common partners. Fig. 1 illustrates an example of these networks.

Within the entity network, nodes represent the participating entities. An edge connects two entities (nodes) if they are involved in the same project. The network is weighted, considering that a connection between two entities is as strong as the number of projects they both participate in.

In the project network, nodes represent the projects themselves. Two projects (nodes) are connected by an edge if an entity participates in both projects. The network is weighted, considering that the connection between two projects is as strong as the number of entities involved in both projects.

The process of constructing a network representing entities as nodes and their collaborative ties as edges is foundational for both RQ1 and RQ2. By visualizing and analyzing these networks, their structure and characteristics will be understood, and subsequently how these factors might be influencing the cities' success in achieving climate neutrality will be determined.

Moreover, attributes characterize the nodes. For the entity network, these attributes include the entity type (HES, REC, PRC, and OTH), the entity's country, and the entity's role within a project (coordinator or participant). The assignment of attributes to each node is primarily aimed at addressing RQ2. By categorizing entities in can be analysed how these different attributes influence the network's dynamics, cohesion, centrality, and overall effectiveness in driving climate neutrality initiatives.

Two distinct analyses are performed for both 1-mode networks: (1) a network-level analysis to identify the network's global cohesion metrics, and (2) a node-level analysis to compute various centrality metrics for each node.

Concerning the network analysis, cohesion and centrality metrics were analysed (S. P. Borgatti et al., 2023; Wasserman and Faust, 1994). Network cohesion metrics offer insights into the overall interconnectedness of the network. For example, a higher density implies a more closely-knit network, suggesting efficient knowledge diffusion and collaborative potential. The average degree, on the other hand, indicates the average number of direct connections an entity has, reflecting its active engagement within the network. For the purpose of this study, understanding network cohesion is crucial as it indicates the potential of a city's innovation network to collaboratively drive climate neutrality efforts. In this sense, the following cohesion metrics have been analysed.

- Average degree: computed as the mean degree for all nodes, where the degree refers to the count of connections for a specific node. This measure represents the network's level of activity.
- Average distance: the average length between all reachable node pairs, where the distance between two connected nodes is the shortest path's length, defined by the number of edges it includes. This metric indicates the network's compactness or dispersion.

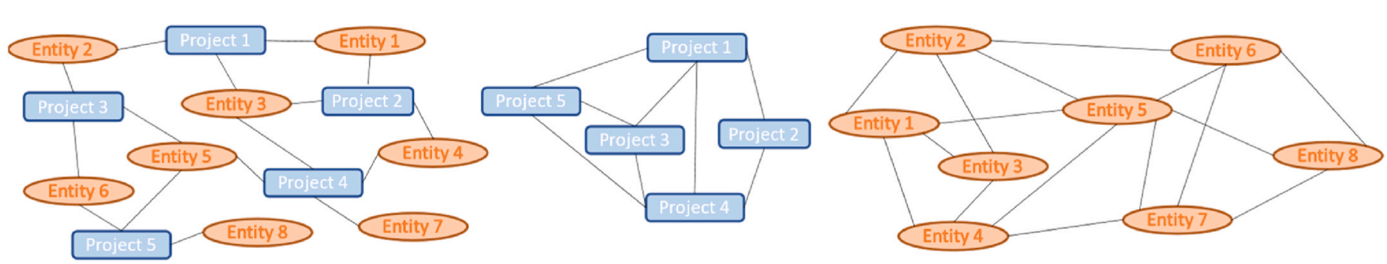

Fig. 1. Illustrative example of a 2-mode network of entities and projects and its associated 1-mode network of projects and 1-mode network of entities.

- H-Index: the maximum number of nodes with an equal or greater number of connections to other nodes. This measure of network cohesion mitigates the impact of outliers.
- Density: the sum of all ties divided by the possible total number of ties. In a weighted network, like those in this study, it is the total of all values divided by the possible number of ties.
- Connectedness: the degree to which nodes within a network are directly or indirectly linked. It represents the average number of steps between any two nodes. High connectedness generally correlates with efficient knowledge sharing and collaboration in the network.
- Transitivity/Closure: the propensity of nodes in a network to form complete triads. A complete triad occurs when three nodes connect in such a way that if node A links to node B, and node B connects to node C, then node A also connects to node C.
- Diameter: the longest geodesic distance (the shortest distance between two nodes) among connected nodes in the network, representing the network's extent.
- Average tie strength between groups: the mean of the weighted connections between nodes with differing attributes, signifying the connection strength between other node types in the network.

Regarding centrality metrics, delve deeper into the influence and reach of individual entities. These metrics are pivotal in this research, as they help identify key players and potential bottlenecks in the innovation networks, guiding strategies for optimizing resource allocation and stakeholder engagement. In this sense, the following centrality metrics were considered.

- Degree: Determined as the number of nodes linked to a specific node. In the case of weighted networks, it consists of the sum of the tie values. This metric provides a measure of the immediate probability for a node to receive whatever flows through the network, in this case, knowledge and expertise.
- Closeness: Calculated for a given node as the average of the shortest path lengths to every other node in the network. This metric is a measure of a node's proximity to all other nodes.
- Eigenvector: Assesses a node's influence within a network, functioning as a prestige score. For this purpose, relative scores are assigned to all nodes in the network, with connections to high-scoring nodes contributing more to the considered node's score than equal connections to low-scoring nodes.
- Betweenness: Quantifies the frequency with which a specific node serves as a bridge in the shortest paths between two other nodes. This metric measures a given node's control over communications between all other nodes in a network.

With the analysis of these metrics in the context of urban innovation systems and climate neutrality, this research aims to provide a granular understanding of how different cities, through their innovation networks, are positioned to contribute to the broader objectives of the European Green Deal.

4. Analysis and results

Considering the previous methodology, and to answer the second research question, an analysis to identify key metrics shared by the urban innovation networks selected to be part of the Cities Mission is reported in the present section.

4.1. Urban networks of entities

4.1.1. Network-level analysis: cohesion

Following the presented methodology, the fourteen networks of entities, one for each Spanish city analysed, have been developed. Table 6 and Table 7 present different cohesion metrics considered for the fourteen networks of entities.

The most significant information that impacts the observer at first sight is the existence of three cities whose networks of entities count with very small or null values in number of ties, H-index or diameter among others.

The first city of this set, Logroño, appears to have a very low number of nodes (18), and ties (2) which shows a low level of interconnectivity among entities. With an average degree of 0.111, it indicates that there is very little connection between nodes within the network. The H-index of 1 is also low, indicating that only one node in the network has at least one tie. The density of 0.00654 and connectedness of 0.007 are also quite low, indicating a lack of cohesiveness and interaction in the network. The closure is not reported which might be due to the lack of ties between nodes. Also, the diameter of 1 suggests a lack of depth in the network. These metrics suggest that its network of entities is not well developed and lacks the level of interconnectivity necessary for innovation networks.

The second one, Hospitalet, has the lowest number of nodes (10) and no ties at all. This suggests that there is no interconnection or collaboration between entities in this city. This is confirmed by the null values of the average degree and an H-index. The density, connectedness, closure, and diameter are also not reported, which is likely due to the absence of ties.

The third one of this group, Gijón, has a slightly higher number of nodes (21) compared to Logroño and Hospitalet but still has a very low number of ties (6), indicating very limited interaction between nodes. The average degree of 0.286 and an H-index of 1 shows a low level of interconnectivity. The density of 0.01429 is low, and the connectedness of 0.014 is also low, indicating a lack of cohesion in the network. Closure is null due to the low number of ties. The diameter of 1 suggests a lack of depth in the network.

Considering this analysis, the networks of entities in Logroño, Hospitalet, and Gijón are weak and lack interconnectivity, as evidenced by the low average degree, H-index, density, and connectedness values. Furthermore, the absence or low number of ties in these cities indicates a lack of collaboration or interaction among entities, which is a key component of innovation networks. Therefore, these cities may not be suitable for further analysis in studies addressing average tie strength between entity types or centrality metrics of its nodes.

After disregarding the three mentioned cities in the cohesion analysis, it is observed that the most populated cities have a higher number of nodes as well, although this expected trend is broken by Murcia for the number of nodes (38), as it is lower o equal to less populated cities like Valladolid (43) or Vitoria (38). This also happens with regard to the number of ties, as Murcia (74) and Pamplona (66), which were not selected to participate in the Cities Mission, have a higher number of ties than Valladolid (52) and Vitoria (40), which are among the chosen ones. Something similar happens when the H-Index is analysed, as Pamplona has the fourth highest number (7) and Murcia the fifth (6), although this

Table 6
Project networks of Entities in the cities: cohesion metrics (1/2).

City	Number of nodes	Number of ties	Avg. Degree	H-Index
Madrid	486	1584	3.259	13
Barcelona	313	568	1.815	10
Valencia	119	322	2.706	9
Sevilla	90	128	1.422	5
Zaragoza	90	140	1.556	5
Murcia	38	74	1.947	6
Valladolid	43	52	1.209	3
Gijón	21	6	0.286	1
Hospitalet	10	0	0.000	0
Vitoria	38	40	1.053	3
Pamplona	26	66	2.538	7
Santander	18	28	1.556	2
Logroño	18	2	0.111	1
Girona	13	14	1.077	2

Table 7
Project networks of Entities in the cities: cohesion metrics (2/2).

City	Density	Connectedness	Closure	Diameter
Madrid	0.00672	0.394	0.187	8
Barcelona	0.00582	0.217	0.292	9
Valencia	0.02293	0.364	0.294	5
Sevilla	0.01598	0.175	0.219	8
Zaragoza	0.01748	0.248	0.176	6
Murcia	0.05263	0.131	0.750	4
Valladolid	0.02879	0.193	0.180	4
Gijón	0.01429	0.014	–	1
Hospitalet	–	–	–	–
Vitoria	0.02845	0.038	0.800	3
Pamplona	0.10154	0.172	0.891	3
Santander	0.09150	0.359	0.235	3
Logroño	0.00654	0.007		1
Girona	0.08974	0.269	0.214	3

does not necessarily indicate a higher network quality, as H-Index is not always correlated directly with the general network effectiveness.

When assessing the average degree, Pamplona and Murcia are again placed among the top positions for non-selected cities, specifically the third and fourth positions, with a value of 2.538 and 1.947 respectively, and also Santander is in sixth place with 1.556, ahead of most populated cities selected by the European Commission for its Cities Mission like Valladolid (1.209) or Vitoria (1.053).

Moreover, when connectedness is analysed, Santander (0.359) and Girona (0.269) are placed in third and fourth position respectively, probably because their networks have a lesser number of ties. It is also significant that three of the non-selected cities are among the first seven when the closure is assessed, with Pamplona having the highest value (0.891). This means that the networks of these cities, which have a smaller number of nodes, form well-connected closed triads.

Nevertheless, the selected cities' order is maintained when density is assessed, as non-selected cities are the ones with a higher network density, which is logical since they have fewer nodes. This suggests that the networks in these cities could be more efficient in terms of communication and cooperation, despite having fewer nodes and ties. Something similar happens with the diameter, as selected cities with a higher number of nodes have a higher network diameter, with the exception of Murcia, with a diameter of 4 ahead of Vitoria with 3. This could indicate a greater diversity and reach in the cities with a higher number of nodes, although it may also present challenges in terms of coordination and collaboration among the network actors.

As a summary, higher cohesion and interconnectedness in innovation networks can be advantageous for cities aiming for decarbonization. A tightly knit network can foster rapid knowledge sharing, pooling of resources, and collaborative problem-solving. However, cities with larger networks must ensure that while they benefit from diverse entities, they don't lose out on the advantages of close collaboration. Conversely, cities with smaller but highly cohesive networks might be better positioned to implement and iterate on innovations quickly. However, they might face challenges in scaling or diversifying their innovation efforts due to fewer entities.

Another relevant cohesion measure is the average tie strength, that in this study has been calculated considering the different activity types of the entities shaping each city network. Thus, a particular table has been generated considering the average tie strength between each entity activity type (PUB, HES, REC, PRC and OTH) with other types in each city.

This way, in Table 24 (see appendix) is shown the average tie strength values between PUB entities and all the entity types in each city network. The data in this table shows that the strongest collaborations involving public entities are seen with Higher Education establishments (HES), like happens in Santander, Valladolid or Valencia and with Research entities, as can be seen in Girona, Murcia or Zaragoza. This could imply a strong policy focus on education and research in these cities. When looking at the average of the selected cities (AVG SC), it shows a strong collaboration of public entities with HES and REC types very close in figures (0.1334 and 0.1244 respectively), being higher 2.3750 and 0.3214 respectively) in the average data of the non-selected cities.

Table 25 (see appendix) shows the average tie strength values between HES entities and all the entity types in each city network. These entities display strong internal ties in Valencia, Barcelona and Madrid, suggesting a robust academic community. However, Santander shows an unusually high tie strength between HES and Public entities, indicating a strong collaboration between the local authorities and the public University of the region. When considering the average values of the selected cities for the Mission, the strongest collaboration is with the REC type being relevant that in non-selected cities there is no collaboration between HES types with themselves.

In Table 26 (see appendix) are presented the same values with REC entities as reference. The data shows that internal tie strengths are high in Murcia, Zaragoza and Valladolid, which could reflect a strong focus on research in these cities. Santander and Zaragoza show substantial ties with public entities and higher education establishments, indicating a collaborative research ecosystem. When looking at the average of the non-selected cities (AVG NSC), it is relevant that there is almost no collaboration of REC type entities with private companies (PRC).

In Table 27 (see appendix) is shown the average tie strength values between PRC entities and all the entity types in each city network. For PRC higher collaboration rate is established with HES type, followed by far for the rest. Interestingly, Pamplona and Santander show strong ties with public entities, suggesting public-private partnerships could be a focus in these cities. Finally, it is relevant to highlight that although the highest values are in the collaboration of private companies with HES type, there is almost no collaboration between PRC and REC types in non-selected cities while REC is the second main collaborator of PRC entities in the selected ones.

Finally, Table 28 (see appendix) shows the same data with OTH entities as a reference. In this case, Valencia shows the highest internal tie strength, followed by Madrid. Girona shows strong ties with Higher Education and Research organizations, indicating a collaborative ecosystem involving various entity types. It is also relevant to mention that there is no collaboration between OTH entities in non-selected cities.

In summary, each city displays a unique pattern of collaboration between different types of entities, likely influenced by local policies, economic contexts, and the nature of the entities present in each.

4.1.2. Node-(entity) level analysis: centrality measures

This section collects the centrality metrics of the eleven networks of entities created in the analysed cities, considering the role performed by these entities. In this sense, Table 8 shows the centrality metrics of each network of entities when these are acting as coordinators, while Table 9 shows the same metrics when the entities shaping those networks are

Table 8
Network of entities by the role played in the projects: coordinators' centrality measures.

City	Number of entities	Average Degree	Average Eigenvector	Average Betweenness	Average Closeness
Madrid	86	2.314	0.0002	96.221	3827.83
Barcelona	61	0.902	0.0164	76.669	3016.54
Valencia	20	3.989	0.0182	43.295	547.22
Sevilla	13	3.000	0.0783	53.308	712.38
Zaragoza	20	1.968	0.0200	18.486	516.00
Murcia	9	0.444	0.0000	1.222	180.78
Valladolid	7	0.286	0.0026	2.429	202.71
Vitoria	4	1.000	0.0000	0.000	143.50
Pamplona	7	0.000	0.0000	0.000	100.00
Santander	5	0.000	0.0000	0.000	68.00
Girona	4	1.750	0.2465	3.000	43.75

acting as participants.

In the coordinator networks, Valencia has the highest average degree, suggesting that, on average, entities in Valencia are more connected than those in other cities. This is interesting, especially considering that Madrid and Barcelona have more entities but a lower average degree. Regarding the average eigenvector, Sevilla stands out with the highest value, indicating that entities in Sevilla, though fewer in number, are influential in the network due to their connections to other influential entities. In this measure it is relevant as well that Girona counts with the highest value (0.2465), suggesting that even if there only four entities with the role of coordinators in this city network, they are key in the connection between the city entities.

On the other hand, Madrid, with the largest network, unsurprisingly has the highest average betweenness, suggesting that the entities in its network often act as bridges, controlling the flow of information. Also Madrid leads again the average closeness, indicating that its entities can quickly interact with all other entities in the overall network.

It is also relevant to mention that in general, the decreasing order of the values coincides with the selected cities to participate in the Mission, but for Girona in the case of average degree and eigenvector, and Murcia in the case of closeness. This happens mainly because a chosen city like Vitoria has particularly low values in several centrality measures, as Pamplona or Santander, indicating a peripheral role in the overall network.

In the participant networks, Madrid leads in average degree (5.936), suggesting that its entities are, on average, more connected than those in other cities. Interestingly, Santander (5.182), despite having a smaller network, also has a high average degree, indicating significant interconnectivity among its entities. Pamplona and Santander stand out with the highest average eigenvector centrality, indicating influential entities within their networks. It's worth noting Vitoria has a negative value, which is unusual and might warrant further investigation into the network structure or the relationships between entities. As happened with the coordinators' networks, Madrid leads the average betweenness and closeness ranking.

Among the other cities, Valencia, Sevilla, and Zaragoza have moderate average degree, eigenvector, betweenness, and closeness centrality measures, indicating moderately interconnected participant networks. Santander has a relatively high average degree (5.182) and betweenness centrality (4.182) compared to its number of entities, suggesting that its participants network is more interconnected with a higher proportion of participants serving as bridges or intermediaries.

In this case, the decreasing order of the values coincides with the selected cities to participate in the Mission in the values of betweenness and closeness, but for Murcia that is again ahead of Vitoria, which counts with particularly low values in several centrality measures.

Once the differences between the centrality properties of the networks of entities in the cities has been analysed by entity role, it is also relevant to look at these measures differentiated by activity type of each entity.

Table 10 shows the average degree values by entities activity type in each city. Madrid, as the capital, presents the highest degree of centrality across all entity types, with the most interconnected entities being higher education establishments (HES) with an average degree of 27.300. This suggests that universities in Madrid are particularly well connected within the network, which could be due to collaborations or partnerships with other organizations.

Barcelona, Sevilla and Valladolid exhibit a similar pattern, albeit with lower average degrees, with HES being the most interconnected entities. Valencia shows a unique pattern where higher education establishments have a significantly high average degree of 38.500. This indicates a particularly strong interconnectedness of universities within Valencia, overcoming even that of Madrid and Barcelona.

Zaragoza shows a more balanced distribution across different types of entities, with HES and Research Organizations (REC) with higher average degree values. In Vitoria, the most interconnected entities are the other entities (OTH) like associations and NGOs suggesting a strong influence of these entities in the network.

Interestingly, in Pamplona, public sector entities (PUB) have a high average degree of 8.333, suggesting a strong interconnection within this sector. Santander shows an exceptionally high average degree for public sector entities (PUB) and higher education establishments (HES), with values of 15.000 and 26.000 respectively, indicating strong ties within these sectors. Girona, Vitoria and Murcia show relatively low degrees of centrality across all entity types.

In Table 11 are displayed the average eigenvector values by entities activity type in each city. As can be seen Madrid. Barcelona and Vitoria, shows a very low Eigenvector centrality across entity types. However, Santander, Girona and Valencia, show high Eigenvector centrality for HES entities, suggesting that universities in these cities are well connected and linked to other influential nodes within their respective networks.

Sevilla (0.0058) and Valencia (0.0045) lead in PRC type, which might suggest influential private companies actively participating in the network, while Zaragoza and Valladolid show a high value of eigenvector for Research Organizations (REC), with scores of 0.1323 and 0.1721, respectively. This might indicate a significant presence and influence of entities like Technology Centres in these cities.

Vitoria stands out with negative eigenvector centrality for Private Companies (PRC). This unusual circumstance might be due to the data structure, with certain entities perhaps isolated or poorly connected. Finally, Pamplona, Santander, and Girona display very high Eigenvector centrality for Public Sector (PUB) and Higher Education Establishments (HES).

Table 12 shows the average betweenness values by entity activity type in each city. Madrid shows high betweenness for HES and REC organizations, with scores of 2503.198 and 766.313 respectively, suggesting that these entities act as key connectors or brokers within the Madrid network, linking different groups of entities. Similarly, Barcelona, Zaragoza and Valladolid have high betweenness centrality for HES

Table 9
Network of entities by role played in the projects: participants' centrality measures.

City	Number of entities	Average Degree	Average Eigenvector	Average Betweenness	Average Closeness
Madrid	346	5.936	0.0044	274.204	3209.81
Barcelona	225	2.547	0.0021	119.728	2667.19
Valencia	89	3.100	0.0041	0.825	518.90
Sevilla	65	1.585	0.0104	12.892	714.65
Zaragoza	63	2.429	0.0044	23.281	495.43
Murcia	24	2.542	0.0451	2.583	165.71
Valladolid	32	1.781	0.0383	6.594	186.84
Vitoria	24	1.000	−0.0433	0.208	144.88
Pamplona	14	3.286	0.1385	1.786	86.93
Santander	11	5.182	0.1442	4.182	50.27
Girona	9	1.222	0.0376	0.556	39.67

Table 10
Network of entities by activity type: average Degree centrality measure.

City	PUB	HES	REC	PRC	OTH
Madrid	12.000	27.300	11.222	3.816	2.812
Barcelona	3.800	8.889	5.792	1.653	1.424
Valencia	3.000	38.500	7.250	1.953	4.750
Sevilla	1.400	14.000	3.100	1.377	0.714
Zaragoza	3.200	8.667	7.250	0.884	1.400
Murcia	3.286	1.000	3.500	1.478	2.500
Valladolid	2.600	10.000	4.000	0.692	0.600
Vitoria	1.750	0.000	3.000	0.760	2.333
Pamplona	8.333	3.500	2.000	1.444	5.000
Santander	15.000	26.000	1.000	1.231	7.000
Girona	0.500	7.000	4.000	0.500	2.000

Table 11
Network of entities by activity type: average Eigenvector centrality measure.

City	PUB	HES	REC	PRC	OTH
Madrid	0.0037	0.0109	0.0384	0.0007	0.0011
Barcelona	0.0015	0.1098	0.0099	0.0012	0.0004
Valencia	0.0035	0.5022	0.0170	0.0045	0.0077
Sevilla	0.0001	0.4676	0.0434	0.0058	0.0000
Zaragoza	0.0099	0.0209	0.1323	0.0024	0.0030
Murcia	0.0000	0.4974	0.0000	0.0033	0.0191
Valladolid	0.0133	0.0540	0.1721	0.0031	0.0092
Vitoria	0.0000	0.0000	0.0000	−0.0540	0.0000
Pamplona	0.3959	0.1321	0.0000	0.0523	0.2036
Santander	0.3514	0.9046	0.0172	0.0254	0.1799
Girona	0.0025	0.9862	0.1223	0.0205	0.0471

Table 12
Network of entities by activity type: average Betweenness centrality measure.

City	PUB	HES	REC	PRC	OTH
Madrid	225.328	2503.198	766.313	129.057	131.685
Barcelona	196.053	1103.171	401.888	32.766	54.505
Valencia	15.235	946.129	116.941	2.948	43.878
Sevilla	0.700	231.250	18.350	14.410	9.714
Zaragoza	9.627	193.294	119.900	2.912	6.567
Murcia	4.714	1.500	5.500	0.913	1.250
Valladolid	3.900	62.000	24.417	0.000	0.000
Vitoria	0.000	0.000	0.000	0.240	0.667
Pamplona	8.333	0.000	0.000	0.000	0.000
Santander	10.500	35.500	0.000	0.000	0.000
Girona	0.000	12.000	5.000	0.000	0.000

and REC.

Valencia and Sevilla, show high betweenness centrality for HES, suggesting that higher education establishments in these cities are central in connecting different groups within the network.

Murcia, Vitoria, Pamplona, Santander, and Girona show relatively low betweenness centrality scores across all entity types. This could imply a less hierarchical structure in these cities' networks, with no single type of entity dominating the brokerage role.

Finally, in Table 13 are shown the average closeness values by entities activity type in each city, thus depicting the average length of the shortest paths to access all other entities in the network. In this sense, Madrid shows high average closeness centrality across all types of entities, with Private Companies (PRC) at the top (3326.03), closely followed by Others (OTH) at 3300.84. This suggests that these types of entities can reach others in fewer steps, indicating a more central role in the network. Barcelona shows a similar pattern, with PRC and OTH showing the highest average closeness centrality values, though these are lower than those in Madrid. This suggests that these entities are less central in the Barcelona network than in Madrid.

In Valencia, we see a much lower range of average closeness centrality, with the highest value for Private Companies at 583.54. Sevilla, Zaragoza, and Valladolid also have relatively lower closeness centrality

Table 13
Network of entities by activity type: average Closeness centrality measure.

City	PUB	HES	REC	PRC	OTH
Madrid	2960.81	2827.20	3132.19	3326.03	3300.84
Barcelona	2532.96	2366.44	2529.54	2773.04	2778.64
Valencia	543.50	405.00	478.08	583.54	519.00
Sevilla	714.50	613.00	681.30	713.33	770.43
Zaragoza	437.00	426.67	447.63	552.80	519.00
Murcia	165.71	178.00	147.50	171.70	170.00
Valladolid	180.00	153.00	175.00	193.81	190.40
Vitoria	141.50	0.00	138.00	145.84	141.33
Pamplona	72.00	86.50	97.00	92.11	85.00
Santander	43.00	39.00	57.00	57.15	47.00
Girona	43.00	31.00	33.00	43.50	34.00

values, which suggest a less efficient communication structure among entities in these cities. Murcia and Vitoria count with average values with the exception that Vitoria shows a unique case where the average closeness centrality for Higher Education Establishments (HES) is zero, suggesting these entities are isolated or disconnected from the rest of the network.

Finally, Pamplona, Santander, and Girona have the lowest average closeness centrality measures among the cities. This could imply that the entities in these cities are less centrally located in the network and may need more steps to reach other entities.

It is also worth mentioning that the descendent order in values of both average betweenness and average closeness of the five entity types coincides with the cities selected by the European Commission to take part in the Cities Mission, except for Vitoria.

In summarizing the entity-level centrality metrics of the cities' innovation networks, distinct patterns emerge that reveal the nature of connectivity and influence within each city. Cities like Madrid and Barcelona, while having more entities, exhibit varied degrees of interconnectedness based on the role and type of the entity. Valencia stands out with its higher education establishments, showcasing a degree of connectivity surpassing even larger cities. The significance of entities as coordinators or participants in the network also sheds light on their influence, with cities like Sevilla and Girona displaying prominent entities pivotal to their respective innovation networks. Closeness metrics further corroborate the central role some entities play in fostering quick and efficient communication across the network. Interestingly, despite the prominence of certain candidates in their selection for the Cities Mission, metrics like betweenness and closeness centrality reveal that many non-selected cities possess networks with robust connectivity patterns. The data underscores the importance of not just the number but the quality of connections, emphasizing that even smaller networks can have potent collaborative structures vital for innovation and progress.

4.2. Network of projects analysis

4.2.1. Network-level analysis: cohesion

Once the networks of entities have been analysed, a similar analysis for the fourteen networks of projects is presented within this section, beginning with the cohesion metrics of the network. Thus, in Table 14 and Table 15 are shown the main cohesion properties of the projects networks in the fourteen cities analysed.

From the obtained data, Madrid exhibits a significantly large project network, with 1427 nodes and 132,816 ties, which is the largest network among the cities listed. The high average degree of 93.074 and H-index of 268 further solidify the city's network's robustness. The city also showcases a moderate level of network density and connectedness, a high level of closure, and a considerable network diameter.

On the other end of the spectrum, Logroño and Hospitalet have the

Table 14
Networks of projects in the cities: cohesion metrics (1/2).

City	Number of nodes	Number of ties	Avg. Degree	H-Index
Madrid	1427	132,816	93.074	268
Barcelona	815	24,822	30.456	110
Valencia	376	16,048	42.681	107
Sevilla	238	3262	13.706	40
Zaragoza	280	8212	29.329	72
Murcia	55	340	6.182	15
Valladolid	137	4838	35.314	66
Gijón	40	226	5.650	14
Hospitalet	16	18	1.125	3
Vitoria	63	218	3.460	10
Pamplona	32	78	2.438	5
Santander	54	1160	21.481	31
Logroño	22	14	0.636	2
Girona	45	698	15.511	24

Table 15
Networks of projects in the cities: cohesion metrics (2/2).

City	Density	Connectedness	Closure	Diameter
Madrid	0.06527	0.730	0.905	8
Barcelona	0.03742	0.504	0.914	9
Valencia	0.11382	0.658	0.928	6
Sevilla	0.05783	0.336	0.880	9
Zaragoza	0.10512	0.590	0.943	7
Murcia	0.11448	0.170	0.965	3
Valladolid	0.25966	0.578	0.976	5
Gijón	0.14487	0.164	0.989	2
Hospitalet	0.07500	0.075	1.000	1
Vitoria	0.05581	0.087	0.918	3
Pamplona	0.07863	0.113	0.894	3
Santander	0.40531	0.638	0.913	3
Logroño	0.03030	0.030	1.000	1
Girona	0.35253	0.546	0.953	2

smallest networks with only 22 and 16 nodes and 14 and 18 ties respectively. They have a very low average degree (0.636 and 1.125) and the lowest H-index of 2 and 3. Their density, connectedness, and closure metrics are also the lowest among the cities, reflecting less cohesive and less interconnected networks.

Several cities, like Barcelona and Valencia, demonstrate a balance between the two extremes. Barcelona, with an H-index of 110 and an average degree of 30.456, has a moderate-sized and well-connected network. Valencia, while having a fewer number of nodes (376), shows a high average degree of 42.681 and an H-index of 107.

When looking at the closure metric, most cities are close to or at a value of 1, indicating that most of the possible ties that could exist in the network do, suggesting strong mutual connectivity among nodes. This result implies a high level of collaboration and interaction among projects within each city.

The diameter metrics also provide insight into the reachability within each network. A smaller diameter, as seen in Gijón, Logroño, Hospitalet and Girona, could suggest easier communication and collaboration among the projects within the network, as information can be disseminated quickly from one end of the network to the other.

From a general perspective of the selected cities by the European Mission, it can be observed that when considering a decreasing order in the number of nodes and diameter, the list of the first seven cities coincides with the ones selected for participating in the Cities Mission. However, when the number of ties, average degree, and connectedness are considered in decreasing order Santander and Girona are in the list of the first seven cities, instead of Vitoria in the main part of the cases. Finally, Santander, Girona and Murcia are ahead Vitoria again when H-Index is analysed in decreasing order.

Considering all the above, the data reveals a range of cohesion within these project networks, with some cities demonstrating high levels of interconnectivity and robustness, such as Madrid, while others have smaller, less interconnected networks, like Logroño and Hospitalet.

4.2.2. Node- (project) level analysis: centrality measures

Finally, Table 16 shows the average centrality metrics obtained from the analysis of the networks of projects belonging to the fourteen studies cities.

As can be observed, Madrid stands out with the highest number of projects (1,427) and the highest average degree (99.083), suggesting that each project in Madrid's network is connected to many others. In general, Madrid consistently leads across all centrality measures, highlighting its central and influential role in the broader network of projects. On its side, Barcelona, while having fewer projects than Madrid, also plays a significant role with its projects being well-connected and acting as bridges within the network.

Valencia, Sevilla, and Zaragoza have a moderate number of projects, but their centrality measures vary. While Valencia's projects are interconnected, Sevilla's projects are more central in the network, and Zaragoza's projects act as bridges. The negative eigenvector centrality value for Murcia is unusual, although the importance of a node in the network is indicated by the magnitude of its eigenvector centrality score, regardless of the sign, so it can be considered as an absolute value.

Table 16
Network of projects centrality measures by city.

City	Number of projects	Average Degree	Average Closeness	Average EigenVector	Average Betweenness
Madrid	1427	99.083	6268	0.012	879.75
Barcelona	815	30.886	5436	0.014	492.49
Valencia	376	43.027	1457	0.029	156.59
Sevilla	238	14.101	1805	0.029	76.22
Zaragoza	280	29.457	1318	0.032	119.04
Murcia	55	6.218	192	−0.073	1.80
Valladolid	137	35.474	481	0.061	29.06
Gijón	40	7.100	105	0.093	0.38
Hospitalet	16	1.125	29	0.125	0.00
Vitoria	63	3.587	234	0.053	1.13
Pamplona	32	2.563	115	0.070	0.72
Santander	54	23.630	124	0.110	6.67
Logroño	22	0.636	41	0.078	0.00
Girona	45	15.600	92	0.115	4.27

Gijón, Hospitalet, and Logroño have low centrality measures across the board, suggesting their projects play more peripheral roles in the broader network. Finally, Vitoria, Pamplona, and Girona also have lower centrality values, indicating potential areas to enhance the connectivity and influence of their projects within the network.

It is also relevant to mention that when considering a decreasing order in the number of projects and average closeness, the list of the first seven cities coincides with the ones selected for participating in the Cities Mission. The same happens with the average eigenvector in increasing order. Finally, when average degree and average betweenness are considered in decreasing order Santander and Girona, for the first variable, and Santander again for the second one are in the list of the first seven cities.

In summary, the centrality metrics reveal that larger cities tend to have more interconnected and central project networks, while smaller cities may have less connected networks with a higher proportion of projects serving as bridges or intermediaries.

5. Discussion

This paper analyses the urban innovation networks from fourteen Spanish municipalities thriving for climate neutrality by 2030. More concretely, the objective of the study is to analyse the structure and properties of these innovation networks and their relationship with the success of climate neutrality efforts in the Spanish cities analysed, understanding as success to have been selected among the 112 cities composing the European Mission on Climate-neutral and smart cities. This hypothesis is made in base of recent research suggesting that the lack of consistency in municipal carbon accounting methods and emission scopes make cities carbon neutrality goals incomparable (Huovila et al., 2022).

For this purpose, and in line with previous works (Calvo-Gallardo et al., 2022; Calvo-Gallardo et al., 2022; Calvo-Gallardo et al., 2021; Fernandez de Arroyabe et al., 2021), this study considers that these urban innovation systems are generated by the H2020-funded projects and consortia, addressing the objectives of the Cities Mission. The mentioned networks are generated by entities linked by joint projects and projects linked by common partners. It is assumed that funding these consortia is the mechanism that the EU uses for the development of its research and sustainability policy, that fosters, among other objectives, to achieve climate neutrality in the localities selected by the Cities Mission. This hypothesis is consistent with previous works that also consider the participation of the Mission candidate cities in international projects as a key dimension to achieve a smart and sustainable transition (Salvia et al., 2023).

Regarding the theoretical implications addressed, first, our results show that European institutional impulse plays a relevant role in the evolution of city innovation systems. It is considered that the Institutional Impulse of the EU through the framework programs and Mission-oriented innovation policy creates a network of relationships between stakeholders, fostering the exchange of information and aligning them around a shared goal, which is in line with previous research (Wiarda et al., 2023). Moreover, this study complements previous ones addressing the challenge of cities decarbonization from the perspective of SECAPs and the action of institutional networks of cities (Heikkinen et al., 2020; Marchi et al., 2023; Reckien et al., 2019), by analysing the innovation networks derived from the H2020 projects located in the studied cities. This line of research also tries to provide another view to previous research stating that transnational municipal networks are not yet representative, ambitious and transparent players (Bansard et al., 2017).

Furthermore, following similar works (Calvo-Gallardo et al., 2022; Kang and Hwang, 2016), the structural characteristics of the urban innovation networks have been assessed. From the study results, it can be concluded that, in line with previous studies (N. Arranz et al., 2020; Calvo-Gallardo et al., 2021; Fernandez de Arroyabe et al., 2021) the centrality and cohesion metrics provide information to consider the suitability of municipal innovation networks to achieve policy-based objectives like climate neutrality.

In this context, regarding the first research question (RQ1), an exhaustive analysis of the different actors (mainly their type and role in the projects) composing the innovation networks of the fourteen candidate municipalities to the Cities Mission has been carried out, following previous studies (N. Arranz et al., 2020; Calvo-Gallardo et al., 2021; Fernandez de Arroyabe et al., 2021).

In exploring the structural variations between the innovation networks of participants in the selected and non-selected cities, there appears to be increased participation from public authorities (PUB), research entities (REC), and associations (OTH) entity types in the networks of selected cities, comparatively lessening the involvement of higher education institutions (HES) and private companies (PRC), that fall to 2.07% and 69.24% respectively. In comparison with the average of the Horizon 2020 Energy Programme projects, the urban innovation networks of the selected cities count with higher participation of public entities, private companies and associations, with research organizations in the same levels and HES type falling from 13% to the mentioned 2.07%. This pattern may suggest that REC types are potentially more effective than HES in bridging the interests of local authorities and private companies in innovation projects. Furthermore, the presence of OTH types, which encapsulate the interests of civil society and sectorial associations, may stimulate increased citizen engagement in decarbonization projects. When scrutinizing the different entities' number of participations in projects within the selected cities, the more relevant figures are the higher participation of REC entities (27.19% in selected cities against 11.72% in non-selected ones), together with lesser participation of PRC and HES types with more than 10% and 4% of difference respectively.

Regarding the coordination rates of the participants analysis, it is relevant that private companies coordinate four times more initiatives in the selected cities projects than in the H2020 Energy programme average, while for PUB and OTH types the increase is around 1.5 times, in detriment of HES and REC entities, that assume the coordination role in around half the times. On the other hand, when analysing the entities' participations, PUB and OTH keep coordinating 1.5 times more than in the average energy programme projects, while PRC coordinates 3 times more initiatives in detriment of REC entities that again coordinate half initiatives while in this case, HES entities rise their coordination rate by almost 4%.

Upon analysing the average tie strength values of selected cities to take part in the Cities Mission, it becomes apparent that the strongest collaboration of public entities (PUB) is set with higher education institutions (HES) closely followed by research organizations (REC). On the other hand, when analysing the same values for the non-selected cities, all of them share a lack of collaboration between HES and OTH entities between themselves within their networks, together with a neglectable collaboration between private companies (PRC) and research organizations (REC).

Taken together, these findings indicate a notable divergence in network structure and collaboration patterns between cities selected and not selected to take part in the Cities Mission. The data suggests that an urban innovation network with entities type share of 45% for private companies, 25% for research organizations, 15% for higher education institutions, 10% for public entities and 5% for associations, together with a coordination coming from a company or a University and with the presence of more than one HES and OTH entities, might be associated with more successful climate neutrality efforts in the context of Horizon (2020) projects in Spanish cities.

These findings are in line with studies suggesting that is necessary to count on stakeholders with non-market-based interests and previous experience in eco-innovations, including universities and research centres, to non-market or non-profit goals such as achieving a successful development of eco-innovations like climate neutrality (N. Arranz et al., 2021; Ozdemir et al., 2023).

Regarding the second research question (RQ2), the application of social network analysis allowed the identification of key metrics shared by the urban innovation networks selected to be part of the Cities Mission.

Examining the cohesion within networks of entities, three cities, Logroño, Hospitalet, and Gijon, have been omitted from further analyses due to their lowest values in terms of the number of nodes and ties, average degree, H-Index, closure, and diameter. Notably, if the analysis had focused primarily on the number of ties, H-Index, and average degree, Murcia, Pamplona or even Santander would have been among the selected cities. However, the decision for selection seems to give more weight to properties such as the number of nodes, as the descendent order based on this attribute aligns with the list of selected cities in the European Mission.

Concerning centrality within the network of entities, the properties analysed depending on the entities' role, show that the selection order in the participants' network aligns with the descendent order in the number of entities and average closeness variables, although Murcia is slightly ahead of Vitoria regarding closeness. The same pattern is observed in the coordinators' network, but only in terms of average closeness. The centrality properties analysed depending on the entity type also reveal an intriguing pattern where the descendent order in values of average closeness for the five entity types matches the list of cities selected by the European Commission to participate in the Cities Mission, again except for Murcia slightly ahead of Vitoria.

Observing the cohesion within the network of projects from a general perspective, when considering a decreasing order in the number of nodes and diameter, the list of the first seven cities selected for participation in the Cities Mission coincides. However, considering the number of ties, average degree, and connectedness in decreasing order introduces Santander and Girona into the list of the first seven cities, replacing Vitoria in most cases. Furthermore, an analysis of the H-Index in decreasing order positions Santander ahead of Vitoria.

Regarding the centrality within the network of projects, when considering a decreasing order in the number of projects and average closeness, the list of the first seven cities aligns with the selected participants in the Cities Mission. The same pattern is evident with the average eigenvector in increasing order. However, when average degree and average betweenness are considered in decreasing order, Santander and Girona are featured for the first variable, and Santander alone for the second variable, among the first seven cities.

The observed patterns indicate that the cohesion properties with higher relevance in both entities and projects networks have been the number of nodes and the network diameter. On the other hand, regarding centrality properties, the number of nodes and average closeness were the key measures shared by the selected cities among the analysed ones.

A higher number of nodes means a bigger network with more projects and participating entities in the urban innovation network. However, a network with both a high diameter and high closeness is quite paradoxical. If there is a high degree of closeness (meaning nodes are generally close to one another), it would be unusual to also have a high network diameter (implying some nodes are far apart). Nevertheless, it might be possible in complex or irregular networks with certain structural quirks. For example, a network might be tightly interconnected (high closeness) but also contain a few nodes that are very distant from the rest, thereby inflating the diameter. These might be outliers or anomalies in the network structure (Brandes et al., 2016).

Considering these results, it appears probable that the evaluators of Cities Mission may have prioritized cities with larger innovation networks (high number of nodes) and higher closeness values. The prioritization of such attributes ensures rapid dissemination of information across all network nodes, thereby fostering an environment where all entities are kept abreast of the latest updates of the network's research activities. Consequently, all entities are equipped to contribute their optimum efforts, bolstering the synergic momentum of the innovation network (Chen et al., 2023; Kim, 2019; Wegner et al., 2023).

These results are in line and go beyond the findings of previous studies addressing that city size is the strongest predictor for carbon neutrality, whilst climate network(s) membership, also plays a role (Heikkinen et al., 2020; Salvia et al., 2021), as a large city size often implies larger innovation networks and being part of a climate network of cities enhance the diffusion of know-how among the urban innovation network members. Moreover, the participation in international projects is one of the key dimensions to consider a high engagement in the transition to climate neutrality in cities following already mentioned papers focused on the Mission Cities candidates (Salvia et al., 2023), while other studies confirmed that the smartness agendas resulting from Horizon (2020) city related projects increase the levels of ambition in energy sustainability targets (Haarstad and Wathne, 2019).

In addressing the initial two research questions, we derive findings that equip us to propose guidelines for the design and implementation of innovative policies and initiatives in cities that strive towards climate neutrality, thereby providing an answer to the third research question.

First, it is important to remark that some non-selected cities outperformed selected ones in terms of socioeconomic indicators like GDP per capita and regional R&D expenditure. This discrepancy suggests that factors beyond the scope of socioeconomic and R&D indicators may be influencing the selection process, in line with recent research for both European and Chinese cities (Genta et al., 2022; Z. Li et al., 2022; Patel et al., 2022), and also with the previous findings of this study. Moreover, as related literature states, cities' actions to mitigate climate change are heavily dependent on other levels of governance, i.e. regional or national (Abu-Rayash and Dincer, 2023; Franzén, 2013; Shu et al., 2023).

In this context, when considering innovation programs, our study of urban innovation networks suggests a formula for success when elaborating consortia. These consortia ideally should comprise a balance of around half of private sector enterprises and one-third of academic institutions. Interestingly, the composition of academic entities should lean heavily towards research institutions, outnumbering higher education counterparts two-to-one. Furthermore, the inclusion of at least one local governmental body is critical, as is the involvement of no less than two non-profit organizations, each either representing specific sectoral interests or those of the broader citizenry. These considerations are suggested in previous studies, stating that multi-stakeholder engagement groups are key for the energy transition process and that multi-actor partnerships adopt different approaches to co-innovation which is beneficial when facing contextual contingencies (Escario-Chust et al., 2023; Fieldsend et al., 2022).

Coordination of such consortia seems to be most successful when it lies in the hands of either private businesses or academic institutions. This choice is probably depending on the maturity level of each project's expected results with respect to the market.

Further, for European cities with an ambition to join the Cities Mission initiative, it might be beneficial to broaden their project portfolio under the Horizon Europe umbrella, specifically, those projects addressing urban decarbonization. It is also recommended to maintain a core group of partners who consistently participate in these projects. This strategy could potentially facilitate quicker dissemination of innovative outcomes throughout the network, enhancing the overall impact of these initiatives, and fostering capacity building across multiple domains as those points are key to turn commitments into factual contributions to climate neutrality as stated in previous analysis (Bulkeley et al., 2014; Ulpiani et al., 2023).

Lastly, it is recommended that the network's projects comprehensively cover all domains related to climate neutrality. Avoiding gaps in these areas is key, as shown by the fourteen cities studied here, which demonstrated a significant 5% difference in the Smart, Green and Integrated Transport program. This suggests that the breadth of issues addressed by a city's innovation initiatives is crucial to its overall success in achieving climate neutrality (Liakou, 2022).

6. Conclusions

This study applies social network analysis to understand the properties of the urban innovation networks generated by the H2020 projects located in fourteen Spanish municipalities submitting their expressions of interest to participate in the European Mission on Climate-neutral and smart cities by 2030.

The findings propose several theoretical and practical contributions. From the theoretical perspective, this study extends the literature on innovation systems analyses by addressing them from an urban-level point of view, as previous research articles were focused on regional or transnational networks, and by tackling the comprehensive field of decarbonization in cities, since previous works addressed more specific themes like energy, information and communication technologies or agri-food programmes. In this sense, as this study analyses the city networks shaped considering all the H2020 projects related to all the aspects needed to reach climate neutrality, all the stakeholders involved in this purpose has been characterized and thus, the main efforts made by both the European Commission and the city players have been considered, following a rigorous methodology based in networks cohesion and centrality measures for the first time in this topic.

Moreover, this work proposes a new perspective to assess the intermediate success of a city thriving to climate neutrality, by trusting the selection process carried out by the European Commission to choose the 112 cities taking part in the first instance in the Cities Mission. This hypothesis is considered a premise valid for this study as previous works suggest a lack of consistency in municipal carbon accounting methods that makes it difficult to compare cities' emissions inventories.

Regarding further theoretical contributions, this study underscores the vital role of the European institutional impulse in shaping urban innovation systems towards sustainability. It supports the idea of setting sustainability objectives for cities that the European Commission has fostered via SECAPs and city related funded calls, and shows that the creation of relationships between stakeholders through EU's framework programs and Mission-oriented innovation policy fosters information exchange and alignment towards shared goals. These findings align with prior research, affirming the importance of the institutional context in facilitating urban innovation for climate neutrality.

Concerning practical contributions, through social network analysis, a robust methodological approach rarely used in such contexts, the study identifies key metrics shared by the selected urban innovation networks. The findings suggests that network cohesion and centrality measures played significant roles, with larger innovation networks (higher number of nodes) and higher closeness values being preferred to reach the desired objectives. These findings suggests that more interconnected networks are more likely to facilitate proper information dissemination, efficiency in coordination due to the existence of shorter paths between key entities and enables an effective influence of the most successful projects, thereby fostering better collective research efforts.

On the policy recommendations side, the research implies that beyond socioeconomic indicators and R&D expenditure, other factors are influencing the selection process. In this sense, cities striving for climate neutrality should prioritize multi-stakeholder engagement to ensure alignment with city-wide decarbonization goals. This can be achieved through workshops, roundtables, and dedicated innovation hubs that bring together diverse actors.

Furthermore, city planners should seek a balanced composition of actors in their innovation networks, which should include a mix in which private sector and academic institutions (prioritizing research institutions over higher education establishments) suppose around 85% of the consortium members, being completed by governmental bodies and more than one non-profit organizations. This way, it is recommended to prioritize partnerships with research institutions, given their pivotal role in driving innovation. Simultaneously, collaborations with private sector entities can facilitate the practical implementation of research-driven solutions.

Additionally, municipalities aiming to join the Cities Mission initiative should broaden their project portfolio related to urban decarbonization and maintain a consistent group of partners to facilitate the rapid dissemination of innovative outcomes. Establishing platforms for seamless information exchange within the innovation network is encouraged to ensure that breakthroughs, best practices, and challenges are shared in real-time, fostering collective problem-solving.

Moreover, the coverage of the projects should be comprehensive to avoid gaps in issues related to climate neutrality, considering the many aspects addressed by sustainability challenges. In this sense, it is also relevant to ensure that local policies are conducive to the objectives of the innovation network, providing incentives for sustainable innovations and facilitating collaborations across sectors.

By strategically curating their innovation networks and fostering a culture of collaboration and knowledge-sharing, cities can accelerate their journey towards achieving climate neutrality, setting a precedent for sustainable urban development globally.

Finally, it is worth mentioning some of the limitations inherent to this study. Firstly, the scope of the study was limited to candidate cities. However, the analysis could have been extended to encompass other Spanish cities of significant socioeconomic relevance, such as Málaga, Murcia, Palma de Mallorca, or Bilbao. These cities have a larger population than some of the cities analysed, such as Valladolid or Vitoria, but did not participate in the Cities Mission call. This limitation may have affected the comprehensiveness of our understanding of innovation networks across Spain.

Secondly, the empirical focus of this study was primarily on projects funded under the Horizon 2020 framework. It would be beneficial for future studies to expand the scope to include projects funded under the Seventh Framework Programme (FP7), the predecessor of Horizon (2020), as well as Horizon Europe, its successor. Inclusion of other innovation projects funded through the European Regional Development Fund (ERDF), or national calls could provide a more comprehensive analysis of the innovation landscape.

Lastly, this study only considered Spanish municipalities that were candidates for the European Cities Mission. Therefore, the results obtained may contain national biases. To avoid these potential biases and to gain a more holistic understanding, future studies could extend the analysis to incorporate candidate cities from other countries participating in the European Mission. This would provide a more balanced and diverse perspective on the cohesion and centrality properties of innovation projects networks.

CRediT authorship contribution statement

David Rodríguez Ochoa: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Project administration, Funding acquisition, Writing – original draft. **Nieves Arranz:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Juan Carlos Fernandez de Arroyabe:** Conceptualization, Methodology, Supervision, Validation, 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

All the data used for this research is public and available

Acknowledgements

This research has been funded by the Horizon Europe project Neutralpath with GA number 101096753.

Appendix

Some of this study tables have been moved to this appendix in order to make Data section easy to follow for the reader.

Table 17
H2020 Research Programmes selected for this study

Programme legal basis	Description
H2020-EU.2.1.	INDUSTRIAL LEADERSHIP - Leadership in enabling industrial technologies
H2020-EU.2.1.1.	INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Information and Communication Technologies (ICT)
H2020-EU.2.1.2.	INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies – Nanotechnologies
H2020-EU.2.1.3.	INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Advanced materials
H2020-EU.2.1.4.	INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies – Biotechnology
H2020-EU.2.1.5.	INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Advanced manufacturing and processing
H2020-EU.3.2.	SOCIETAL CHALLENGES - Food security, sustainable agriculture and forestry, marine, maritime and inland water research, and the bioeconomy
H2020-EU.3.3.	SOCIETAL CHALLENGES - Secure, clean and efficient energy
H2020-EU.3.4.	SOCIETAL CHALLENGES - Smart, Green and Integrated Transport
H2020-EU.3.5.	SOCIETAL CHALLENGES - Climate action, Environment, Resource Efficiency and Raw Materials
H2020-EU.3.6.	SOCIETAL CHALLENGES - Europe in a Changing World - Inclusive, Innovative and Reflective Societies

Table 18
Number of projects involving each city per research programme analysed (1/3)

	Madrid	Barcelona	Valencia	Sevilla	Zaragoza
H2020-EU.2.1.	0	0	1	0	0
H2020-EU.2.1.1.	352	256	132	33	42
H2020-EU.2.1.2.	21	16	5	4	4
H2020-EU.2.1.3.	56	22	13	9	17
H2020-EU.2.1.4.	25	11	10	7	3
H2020-EU.2.1.5.	63	34	19	9	21
H2020-EU.3.2.	200	63	48	46	47
H2020-EU.3.3.	271	118	61	46	79
H2020-EU.3.4.	241	145	48	41	39
H2020-EU.3.5.	142	87	32	39	17
H2020-EU.3.6.	56	63	7	4	11

Table 19
Number of projects involving each city per research programme analysed (2/3)

	Murcia	Valladolid	Gijón	Hospitalet	Vitoria
H2020-EU.2.1.	0	0	0	0	0
H2020-EU.2.1.1.	13	12	5	2	4
H2020-EU.2.1.2.	0	3	4	0	2
H2020-EU.2.1.3.	1	5	5	1	8
H2020-EU.2.1.4.	1	2	0	0	1
H2020-EU.2.1.5.	1	24	9	1	10
H2020-EU.3.2.	16	16	3	2	6
H2020-EU.3.3.	11	38	7	6	16
H2020-EU.3.4.	2	12	6	2	10
H2020-EU.3.5.	7	22	0	2	4
H2020-EU.3.6.	3	3	1	0	2

Table 20
Number of projects involving each city per research programme analysed (3/3)

	Pamplona	Santander	Logroño	Girona
H2020-EU.2.1.	0	0	0	0
H2020-EU.2.1.1.	8	26	11	2
H2020-EU.2.1.2.	1	0	0	0
H2020-EU.2.1.3.	0	0	0	0
H2020-EU.2.1.4.	1	0	0	2
H2020-EU.2.1.5.	1	0	1	2
H2020-EU.3.2.	6	3	2	2
H2020-EU.3.3.	11	9	6	12
H2020-EU.3.4.	1	6	0	7
H2020-EU.3.5.	3	7	2	14
H2020-EU.3.6.	0	3	0	4

Table 21
Research programme projects distribution

Research Programme	Number of projects in the analysed cities	Cities' projects distribution	Total number of projects	All projects distribution
H2020-EU.2.1.	1	0%	2	0%
H2020-EU.2.1.1.	898	25%	1921	23%
H2020-EU.2.1.2.	60	2%	386	5%
H2020-EU.2.1.3.	137	4%	184	2%
H2020-EU.2.1.4.	63	2%	130	2%
H2020-EU.2.1.5.	195	5%	290	4%
H2020-EU.3.2.	460	13%	926	11%
H2020-EU.3.3.	691	19%	1476	18%
H2020-EU.3.4.	560	16%	1765	21%
H2020-EU.3.5.	378	10%	747	9%
H2020-EU.3.6.	157	4%	457	6%
Total values	**3600**	**100%**	**8284**	**100%**

Table 22
Total EC Contribution received by entity type in million euro

City	PUB	HES	REC	PRC	OTH	TOTAL
Madrid	45.81	67.08	65.59	365.54	26.84	570.87
Barcelona	17.28	43.99	73.89	138.09	22.21	295.45
Valencia	2.64	34.86	52.56	57.20	3.74	151.00
Sevilla	4.38	18.27	13.24	46.92	2.48	85.29
Zaragoza	5.28	7.75	57.77	28.85	0.71	100.36
Murcia	2.46	2.16	0.90	6.45	1.34	13.29
Valladolid	1.01	4.06	14.52	7.22	2.30	29.11
Gijón	0.15	0.00	7.73	11.47	0.00	19.35
Hospitalet	0.23	0.00	0.13	2.74	0.00	3.09
Vitoria	16.02	0.00	0.23	5.25	2.20	23.70
Pamplona	2.97	3.42	0.51	2.96	2.87	12.73
Santander	0.93	16.10	0.55	7.78	0.00	25.37
Logroño	0.00	0.00	0.41	4.34	0.00	4.74
Girona	2.88	11.37	3.50	5.66	0.22	23.62

Table 23
Total budget invested by entity type in million euro

City	PUB	HES	REC	PRC	OTH	TOTAL
Madrid	80.97	67.08	65.80	484.70	27.71	726.27
Barcelona	18.65	43.99	74.57	194.18	24.82	356.20
Valencia	2.74	34.86	52.77	80.63	3.74	174.75
Sevilla	4.77	18.50	13.81	58.71	2.51	98.30
Zaragoza	5.28	7.76	58.55	42.42	0.94	114.95
Murcia	2.61	2.16	0.96	8.92	1.34	15.98
Valladolid	1.09	4.06	14.53	9.78	2.32	31.79
Gijón	0.15	0.00	7.73	17.74	0.00	25.62
Hospitalet	0.23	0.00	0.19	3.56	0.00	3.97
Vitoria	22.74	0.00	0.40	8.51	3.20	34.85
Pamplona	3.05	3.42	0.51	4.28	2.89	14.14
Santander	0.93	16.10	0.57	10.68	1.42	29.70
Logroño	0.00	0.00	0.41	6.38	0.00	6.79
Girona	3.19	11.37	3.50	7.20	0.22	25.47

Table 24
Average tie strengths between PUB entities and the different entity types

City	PUB	HES	REC	PRC	OTH
Madrid	0.1472	0.0812	0.0880	0.0108	0.0072
Barcelona	0.0200	0.0444	0.0350	0.0072	0.0145
Valencia	0.0152	0.2083	0.0694	0.0127	0.0625
Sevilla	0.0444	0.0000	0.0200	0.0115	0.0143
Zaragoza	0.0000	0.2000	0.2750	0.0058	0.0000
Murcia	0.1429	0.0000	0.2857	0.0621	0.1071
Valladolid	0.1000	0.4000	0.1333	0.0385	0.0000
Vitoria	0.0714	0.0000	0.2500	0.0150	0.1250
Pamplona	1.0000	0.5000	0.0000	0.2222	0.6667
Santander	0.0000	9.0000	0.5000	0.3846	0.0000
Girona	0.0000	0.0000	0.5000	0.0000	0.0000
AVG SC	**0.0569**	**0.1334**	**0.1244**	**0.0145**	**0.0319**
AVG NSC	**0.2857**	**2.3750**	**0.3214**	**0.1672**	**0.1935**

Table 25
Average tie strengths between HES entities and the different entity types

City	PUB	HES	REC	PRC	OTH
Madrid	0.0812	0.1333	0.1333	0.0506	0.0333
Barcelona	0.0444	0.1389	0.0972	0.0170	0.0168
Valencia	0.2083	1.0000	0.9583	0.2353	0.4375
Sevilla	0.0000	0.0000	0.6500	0.1230	0.0000
Zaragoza	0.2000	0.0000	0.3333	0.0580	0.2000
Murcia	0.0000	0.0000	0.0000	0.0217	0.1250
Valladolid	0.4000	0.0000	1.0000	0.0769	0.0000
Vitoria	0.0000	0.0000	0.0000	0.0000	0.0000

(*continued on next page*)

Table 25 (*continued*)

City	PUB	HES	REC	PRC	OTH
Pamplona	0.5000	0.0000	0.0000	0.0833	0.2500
Santander	9.0000	0.0000	0.5000	0.7692	6.0000
Girona	0.0000	0.0000	2.0000	0.5000	1.0000
AVG SC	**0.1334**	**0.1817**	**0.4532**	**0.0801**	**0.0982**
AVG NSC	**2.3750**	**0.0000**	**0.6250**	**0.3436**	**1.8438**

Table 26
Average tie strengths between REC entities and the different entity types

City	PUB	HES	REC	PRC	OTH
Madrid	0.0880	0.1333	0.0399	0.0142	0.0161
Barcelona	0.0350	0.0972	0.0543	0.0103	0.0152
Valencia	0.0694	0.9583	0.0909	0.0373	0.0417
Sevilla	0.0200	0.6500	0.0444	0.0197	0.0000
Zaragoza	0.2750	0.3333	0.1786	0.0471	0.0750
Murcia	0.2857	0.0000	1.0000	0.0217	0.0000
Valladolid	0.1333	1.0000	0.1333	0.0449	0.1000
Vitoria	0.2500	0.0000	0.0000	0.0200	0.1667
Pamplona	0.0000	0.0000	0.0000	0.0000	1.0000
Santander	0.5000	0.5000	0.0000	0.0000	0.0000
Girona	0.5000	2.0000	0.0000	0.0000	1.0000
AVG SC	**0.1244**	**0.4532**	**0.0774**	**0.0276**	**0.0592**
AVG NSC	**0.3214**	**0.6250**	**0.2500**	**0.0054**	**0.5000**

Table 27
Average tie strengths between PRC entities and the different entity types

City	PUB	HES	REC	PRC	OTH
Madrid	0.0108	0.0506	0.0142	0.0066	0.0042
Barcelona	0.0072	0.0170	0.0103	0.0045	0.0022
Valencia	0.0127	0.2353	0.0373	0.0084	0.0221
Sevilla	0.0115	0.1230	0.0197	0.0126	0.0094
Zaragoza	0.0058	0.0580	0.0471	0.0043	0.0029
Murcia	0.0621	0.0217	0.0217	0.0316	0.0652
Valladolid	0.0385	0.0769	0.0449	0.0062	0.0000
Vitoria	0.0150	0.0000	0.0200	0.0200	0.0400
Pamplona	0.2222	0.0833	0.0000	0.0261	0.0833
Santander	0.3846	0.7692	0.0000	0.0000	0.0769
Girona	0.0000	0.5000	0.0000	0.0000	0.0000
AVG SC	**0.0145**	**0.0801**	**0.0276**	**0.0089**	**0.0115**
AVG NSC	**0.1672**	**0.3436**	**0.0054**	**0.0144**	**0.0564**

Table 28
Average tie strengths between OTH entities and the different entity types

City	PUB	HES	REC	PRC	OTH
Madrid	0.0072	0.0333	0.0161	0.0042	0.0051
Barcelona	0.0145	0.0168	0.0152	0.0022	0.0019
Valencia	0.0625	0.4375	0.0417	0.0221	0.1071
Sevilla	0.0143	0.0000	0.0000	0.0094	0.0000
Zaragoza	0.0000	0.2000	0.0750	0.0029	0.0000
Murcia	0.1071	0.1250	0.0000	0.0652	0.0000
Valladolid	0.0000	0.0000	0.1000	0.0000	0.0000
Vitoria	0.1250	0.0000	0.1667	0.0400	0.0000
Pamplona	0.6667	0.2500	1.0000	0.0833	0.0000
Santander	0.0000	6.0000	0.0000	0.0769	0.0000
Girona	0.0000	1.0000	1.0000	0.0000	0.0000
AVG SC	**0.0319**	**0.0982**	**0.0592**	**0.0115**	**0.0163**
AVG NSC	**0.1935**	**1.8438**	**0.5000**	**0.0564**	**0.0000**

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