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Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to H2020

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ABSTRACT

This study addresses how the institutional impulse developed by the European Union influenced the evolution of the European energy innovation system. Considering the contributing role of innovation systems in the development of new knowledge and technology, it can be stated that the institutional impulse achieved by the European Union through the research framework programmes creates a network of relations between entities and projects. This enables the exchange of information and expertise, which is considered a key element for innovation development. Previous studies have attempted to determine whether institutional impulse is an essential element in understanding the efficiency of innovation systems and their related research policies. However, their investigations have yielded inconclusive results. Using the CORDIS database of the European Commission, this study aims to fill this gap by assessing the European energy innovation system for two periods (2007–2013 and 2014–2020) through two of its research funding programmes—FP7 and H2020—thereby contributing to the literature in the innovation systems field. Social network analysis has been conducted to examine how changes in the institutional impulse, reflected in the new objectives in the research funding programmes, are associated with changes in the structural and topological properties of the innovation systems' underlying networks. The first contribution indicates that the innovation system responds to changes in the goals of funding programmes, as the taxonomy, topology, and structural properties of their underlying networks underwent modifications due to the newly proposed objectives. The second contribution shows that network properties (cohesion and centrality metrics) can explain the efficiency and effectiveness of innovation systems, drawing useful conclusions for policymakers and individual entities. This last contribution also has important policymaking implications, as it provides the basis for understanding how innovation policy goals can be achieved by changing the institutional impulse to direct the innovation system towards these objectives.

1. Introduction

Innovation systems are organisational networks that develop, diffuse, and use innovations (Markard and Truffer, 2008). Recently, innovation systems have been redefined as 'the evolving set of actors, activities, artefacts, institutions, and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors' (Granstrand and Holgersson, 2020). In recent decades, the innovation systems approach has attracted increasing attention from the research community (Badin et al., 2020) as a way to understand and govern the emergence of new technologies, particularly in the context of sustainable development (Wang et al., 2019; Chou et al., 2019; Chen and Lin, 2020; Boyer and Touzard, 2021; Brem and Nylund, 2021; Montenegro et al., 2021;

Abbreviations: CSA, Coordination and Support Action; ERA, European Research Area; EEIS, European Energy Innovation System; EU, European Union; FP, Framework Programme; FP7, Seventh Framework Research Programme; H2020, Horizon 2020; SET-Plan, Strategic Energy Technology Plan; SNA, Social Network Analysis.

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Montenegro et al., 2021, 2021; Zhao et al., 2021).

Nevertheless, one of the main criticisms of the innovation systems framework is the lack of consideration of its evolution (Hekkert et al., 2007). Despite this criticism, some works (Johnson and Jacobsson, 2001; Alkemade et al., 2007; Hekkert et al., 2007; Jacobsson, 2008; Negro et al., 2008; Van Alphen et al., 2008) have assessed the change in innovation systems in various countries, relying on the 'functions' concept—conceived as decisive processes that foster the shaping and development of a technology—that was proposed by Edquist (1997). Within this functional analysis, both endogenous and exogenous structural elements that influence the evolution of innovation systems have been considered (Jacobsson and Bergek, 2011).

In this context, governments and supranational authorities, as endogenous elements, seek to identify ways to strengthen their innovation systems (Chou et al., 2019; De Arroyabe et al., 2021). This urge of these elements is also referred to as institutional impulse. Although institutional impulse was established to support research by funding projects, regulating markets, and/or creating new standards, its role has changed over time. The emphasis has shifted to promoting mechanisms that favour knowledge exchange among participants while achieving broader socio-economic objectives (De Juana-Espinosa and Luján-Mora, 2019; Kashani and Roshani, 2019). Thus, the institutional impulse is key to the evolution of innovation systems, fostering innovation and new technologies, and is a crucial element for the efficacy of innovation policies (Wang et al., 2019; Kapetaniou et al., 2018; Kashani and Roshani, 2019; Arranz et al., 2020). However, despite the relevance of understanding the evolution of innovation systems, more research is needed to understand how context—comprising barriers and driving factors—influences the evolution of innovation systems. In particular, there is a gap in the literature related to the understanding of how changes in institutional impulse, as a driving factor, may affect the evolution of innovation systems (Markard et al., 2015; Weber and Truffer, 2017). Moreover, Brem and Nylund (2021), Bergek et al. (2015), and De Arroyabe et al. (2021) pointed out the pertinence of this topic, as the understanding of the efficiency and effectiveness of the institutional impulse is highly significant for industrial innovation.

Therefore, this study aims to fill this gap in the literature by analysing how innovation systems evolve when a change in institutional impulse occurs. For this purpose, the study focuses on the European Union (EU) as the promoter of the European Innovation System known as the European Research Area (ERA). The EU is promoting the ERA through European framework programmes (FPs) (Amoroso et al., 2018; De Arroyabe et al., 2021) as a key element of EU research and innovation policy (Pinheiro et al., 2016; De Marco et al., 2020). This is relevant, as the EU is investing a significant part of its budget on the promotion of research and innovation. However, according to the findings of De Arroyabe et al. (2021), the outcomes of these policies are limited. Hence, the EU replaced FP—FP7 (2007–2013)—with H2020 (2013–2020) to implement the following three primary changes to their initial programme: more impact-oriented research, more business-centred programmes, and broader knowledge. In summary, H2020 focuses on industry and innovation as well as linking research to the market and society.

Our work examines the energy programme of the two FPs, as this programme is considered the cornerstone of sustainable development and the transition towards a low-carbon economy (Chou et al., 2019; Chen and Lin, 2020; Zhao et al., 2021). For this purpose, we started with the study of Calvo-Gallardo et al. (2021), which assessed the characteristics of the European Energy Innovation System (EEIS) for the period corresponding to FP7 (2007–2013). Our study analysed the period of H2020 (2014–2020) to determine how changes in the institutional impulse developed by the EU through the two FPs affected the EEIS' evolution. Hence, the following research question was formulated for this study:

How did the institutional impulse developed by the EU through its framework programmes affect the evolution of the European Energy Innovation System?

Concerning the operational and instrumental framework for studying the evolution of the EEIS, this study relies on social network analysis (SNA). Considering that FP7 and H2020 energy programme finance projects were developed by groups of at least three entities, the following two networks underlying the promoted innovation system are studied in this paper: (1) the network of entities that collaborate on the same project and (2) the network of projects that share at least one entity. These networks have fostered the development of relationships between industry and research organisations, ultimately aiming to increase the competitiveness in the European industry and create an environment conducive to knowledge exchange (De Juana-Espinosa and Luján-Mora, 2019; Sá et al., 2019).

To analyse the effects of the institutional impulse on the innovation systems' underlying networks as a result of the transition to a new programme, SNA has been used based on two perspectives: (1) to assess the characteristics of the networks as a whole system and (2) to study the role of different nodes within the network by considering them active parts of the network. The consideration of both approaches at the system and actor levels enables a better understanding of the innovation systems (Mignon and Bergek, 2016). This facilitates the assessment of the system's evolution between the two periods—FP7 (2007–2013) and H2020 (2014–2020)—and its relation to the change in the institutional impulse.

This paper is structured as follows. Section 2 presents the conceptual framework, a literature review of the innovation system evolution, and the research model. Further, Section 3 describes the methodology and data used for this empirical study, comparing the network and node properties during the two periods. Subsequently, Section 4 presents the study results, including the correspondence of the network and node changes in properties and the challenges targeted by H2020 as compared to its predecessor FP7. Finally, Section 5 presents a discussion of the results and the conclusions of the study.

2. Conceptual framework and research model

2.1. Innovation systems

The innovation system concept is used to explain how knowledge is commercialised. However, underlying this concept, there is a precise and complex construct where innovation takes place (Hannan et al., 1989; Moore, 1993; Schot, 1998; Oh et al., 2016). Jackson (2011) defined an innovation system as 'the complex relationships that are formed between actors or entities whose functional goal is to enable technology development and innovation'. An innovation system is built as an interactive process that starts from knowledge generation and ends with the successful deployment of innovation in the market (Mytelka and Smith, 2002; Chaminade and Edquist, 2006, 2010). In this framework, the interactions between entities increase industrial performance by improving innovation capabilities (Cheng and Chen, 2013), sharing risks and resources, reducing time to exploitation, and enabling access to new knowledge, technologies, and markets (Enkel et al., 2009; Kumar et al., 2012; Ades et al., 2013; Huang et al., 2013; Parida et al., 2014).

Two main considerations have been adopted in this study. First, our conceptualisation of innovation systems considers both the geographical and institutional scopes. Papaioannou et al. (2009) noted that institutional aspects affect innovation systems. The geographical dimension determines the institutional configuration and public policies that are deployed. Thus, in different geographical contexts, differences might arise in the institutional impulses that affect the efficacy of innovation systems. Dolphin and Nash (2012) highlighted institutional impulse as a key element for the innovative capacity of systems, as it may provide entities with incentives for the cooperation and development of collaborative innovation projects. Second, considering that companies and institutions cooperate within the system, the innovation system approach considers the interaction among the system actors as a key element and analyses their links and relations (Lundvall, 2007). Overall, it can be concluded that there are two key elements in the innovation system approach. On the one hand, the institutional impulse determines the governance of the innovation system. On the other hand, the interactions among the innovation system agents that generate social capital, which, in turn, creates information and knowledge, are crucial elements for the development of innovation projects. The following two sections discuss these two aspects in detail.

2.2. Institutional impulse

Innovation systems operate in specific regional, regulatory, political, social, and economic contexts and are influenced by their operating environment (Esmailzadeh et al., 2020). All these context conditions play a complex yet relevant role in the evolution of innovation systems. They overlap, link, have different weights, and evolve over time (Van der Loos et al., 2021). Previous studies have shown that government support and promotion of research and development (R&D) related to low-carbon technologies can shorten the period needed for innovation systems to bring new technologies to the market (Yin et al., 2019), positing government support for R&D as a significant determinant of innovation efficiency (Li, 2009).

Institutional impulse theory explains how entities within an innovation system follow common organisational practices and rules (Scott, 2005; Berrone et al., 2013; Gallego-Alvarez et al., 2017; Gao et al., 2019). Considering that the institutional impulse pushes organisations to adopt common concepts and procedures, the EU is promoting a more competitive innovation system in its geographical area, conceived as the ERA. This system is defined as a unified research area that enables the free circulation of researchers, scientific knowledge, and technologies following the definition of the innovation system proposed by Metcalfe (1995). To drive and promote this innovation system, the EU is funded through FP collaborative research and innovation that addresses the main EU policy objectives (De Arroyabe et al., 2021).

For the last 30 years, the EU has invested numerous resources through its FPs to fund research consortia, in which various sets of entities, including industries and research institutions, collaborate on ambitious innovation projects, sharing goals, knowledge, risks, and resources.

There are several goals of the institutional impulse generated by the EU FPs. First, it tackles the dissemination and collaboration between institutions and companies within the EU, as FPs enable knowledge-sharing among the consortium's partners and also facilitate collaborative research activities (Kuhlmann and Edler, 2003; De Juana-Espinosa and Luján-Mora, 2019; Kashani and Roshani, 2019). This cooperative research allows for the dissemination of knowledge and ideas and provides access to resources, capabilities, and markets (Caloghirou et al., 2004; Arroyabe et al., 2015; Pinheiro et al., 2016; Amoroso et al., 2018; Arranz et al., 2020). Second, FPs aimed to increase competitiveness of the European industry. To that extent, these programmes prioritised several research areas, including, but not limited to, the technology roadmaps established by the European industry within the framework of the European Technology Platforms. Third, the FPs sought to establish cohesion through cooperation between different countries at various levels of development in terms of research and innovation; therefore, the research consortia were expected to involve at least three European countries. Finally, FPs aimed at accomplishing effective technology and knowledge transfer between research consortia and companies. The European Commission (2021) had highlighted the lack of effective technology transfer in the EU as compared to the US and Japan. Therefore, the EU FPs proposed the participation of companies in the research consortium and competition for the best funding through open calls to enhance technology-sharing, thereby addressing this deficit.

2.3. Social capital: Network perspective in the European Innovation System

The social capital approach provides a theoretical framework for understanding the existing and expected resources within a network of relationships (Nahapiet and Ghoshal, 1998; Gatignon et al., 2002; Subramaniam and Youndt, 2005; Mitsuhashi and Min, 2016; Ferraris et al., 2018; Lyu et al., 2019; Arranz et al., 2020). Moran (2005) established that social capital is a valuable asset whose value stems from the access to resources it engenders through an actor's social relationships. Zhang and Guan (2019) pointed out that a network provides specific outcomes for the network participants. Granovetter (1992) and Nahapiet and Ghoshal (1998) relied on the concept of network embeddedness to characterise the structure of one entity's relationships with the rest of the network. Ruef et al. (2003) and Moran (2005) claimed that the network embeddedness of entities impacts their access to information through the relationships among organisations, thereby generating social capital for the participating entities.

As funding research consortia is a key element of the institutional impulse generated by the EU, it is possible to measure the embeddedness of the different entities and partners in the networks of relationships created by these consortia where projects and partners interact. Partners are related as collaborators on the same projects, whereas projects are linked as they share common partners. The specific structure of an organisation's relationships with others creates an innovation network (Echols and Tsai, 2005; Lyu et al., 2019), which is considered a key element in innovation practice (Chesbrough and Crowther, 2006; Koka and Prescott, 2008).

The two networks of relations (among projects and partners) created by the research consortia can be assessed using a two-fold approach. First, the connections and positions of an organisation are determined by its embeddedness in the network, which also determines its level of access to knowledge and information. Gulati (1995) emphasised the value of the structural position of an entity in a network for accessing knowledge, which is also supported by the results of Ferraris et al. (2018). Furthermore, Arranz et al. (2020) demonstrated that different positions in the network afford entities different levels of access to information in terms of quantity, diversity, relevance, and availability, influencing their innovation performance. Second, Newman (2003) established that network topology has a direct impact on network capabilities for knowledge diffusion. This topology can be analysed from a system perspective relying on cohesion attributes, whereas the contribution of each node and its embeddedness properties can be assessed by considering centrality metrics. In general, Newman (2003) highlighted three structural attributes that characterise the topology of social networks—centrality (i.e. which individuals are best connected to others or have the most influence); connectivity (i.e. whether and how individuals are connected through the network); community structure (i.e. how cohesive the network is). Thus, SNA can be considered a powerful tool for measuring the social capital of a network.

2.4. Research model

In this study, the EEIS has been modelled as a two-mode network in which the nodes are represented by either entities or projects. Entities are linked to the projects in which they participate. On the one hand, the entity nodes are characterised by attributes that lead to their heterogeneity in terms of their activity type (companies, research centres, universities, public bodies, or others) and geographical location. On the other hand, the attributes used to characterise the project nodes are related to their research and technology fields, similar between the FP7 and H2020 energy programmes. From this two-mode network, two one-mode networks or nodes were deduced: (i) the nodes comprising partners linked by shared projects; (ii) the nodes comprising projects linked by the common partners.

According to previous studies (Echols and Tsai, 2005; Lyu et al., 2019), the EEIS must be able to fulfil the goals of the EU research and innovation policy. As established previously, the EEIS network topology and structure, as well as its cohesion and centrality metrics, influence the dissemination of knowledge and, thus, the effectiveness of the EEIS (Moran, 2005; Borgatti and Halgin, 2011; Ferraris et al., 2018). Therefore, these network metrics are expected to be responsive to changes in the EU research and innovation policy.

First, Newman (2003) pointed out that collaboration between entities is enabled by cohesive networks, which has been highlighted in the innovation literature as a critical element for the innovation development (Koka and Prescott, 2008; Ferraris et al., 2018). Knowledge exchange has been regarded as a crucial factor in research and innovation development (Kapetaniou et al., 2018). Lyu et al. (2019) noted that cohesive networks enable knowledge acquisition, management, and reassortment. Moreover, research consortia emerging from transnational projects that cover the entire innovation value chain help ensure the heterogeneity among its partners. Therefore, it is expected that *network cohesion* properties have an impact on the achievement of the first objective of the EU R&D policy—promoting diffusion and collaboration between institutions, companies, and countries within the EU's framework.

Second, Wasserman and Faust (1994) pointed out that the central nodes (entities or projects) must be the most active owing to the number of nodes to which they are connected. Moreover, the authors demonstrated that networks create these central nodes because of their higher affinity and similarity in activities, leading to more cohesive research and technology areas. To fulfil the second objective of the EU R&D policy—to promote the competitiveness of companies within the EU—the activities of the network should be aimed at developing priority areas of research in line with the FPs. Therefore, we expect the high *centrality* of the network subgraphs related to each technology to influence the achievement of this objective.

Finally, the EEIS network is characterised by the heterogeneity of its constituent nodes in terms of their activity type, geographical location, or entities. When the heterogeneity of the nodes is considered for the assessment of their connectivity, the position of the different types of nodes in the network influences their level of access to information, which is expected to affect the R&D activity of the node. The last objective of the EU R&D policy is to achieve an effective knowledge transfer among universities, research centres, and companies. Therefore, we can expect the *connectivity* of the entities to impact the transfer of knowledge, thereby influencing the achievement of this objective.

Based on the objective of our research, the following research question has been formulated:

How does the institutional impulse generated by the EU through its framework programmes affect the evolution of the European Energy Innovation System?

Based on this analysis and approach and to thoroughly answer the proposed research question, the authors proposed the following two subquestions, which would lead to a general conclusion:

RQa: How have the properties of the European Energy Innovation System's underlying networks changed between the periods 2007–2013 and 2014–2020?

RQb: Do these changes in the characteristics of the European Energy Innovation Systems between these two periods correspond to the new challenges pursued by the H2020 funding programme compared to its predecessor FP7?

Using SNA modelling, the cohesion, centrality, and connectivity metrics of both periods will be assessed. The results will then be compared to analytically identify the changes in the network cohesion properties between both the FPs. Furthermore, the changes in the roles of different entity types within the networks, owing to their heterogeneity in terms of geographical diversity and main activity (business, university, research centres, etc.), will also be detected. Moreover, the evolution of different energy technologies within the network in consideration of the programmes will be studied. Overall, the properties of the networks of entities and projects underlying the EEIS will be assessed for the periods corresponding to the two programmes (2007–2013 and 2014–2020 for FP7 and H2020, respectively). Subsequently, the results will be compared.

Once the differences in the network properties between the two programmes are identified, the changes resulting from the policy changes pursued by H2020 compared to FP7 will be evaluated. Previous authors (Echols and Tsai, 2005; Lyu et al., 2019) have established that innovation systems must be able to fulfil the objectives of the research and innovation policy. As seen previously, the network properties (cohesion, centrality, and connectivity) influence the access, dissemination of information, and collaboration between entities for technology and knowledge transfer, which are the objectives of EU R&D policy (Moran, 2005; Borgatti and Halgin, 2011; Ferraris et al., 2018). Therefore, the relationship between the changes pursued by the institutional impulse through H2020 as compared to FP7 and the changes in the underlying network properties of the EEIS will be analysed in this paper. This analysis will enable an understanding of how the institutional impulse generated by the EU through the FPs affects the evolution of the EEIS. The conceptual framework is summarised and presented in Fig. 1.

3. Methodology

To answer the research question, the changes in the network properties (topology, cohesion, centrality, and connectivity) of the EEIS between the periods corresponding to FP7 and H2020 will be assessed using SNA and compared to the changes in the institutional impulse generated by the EU between the two funding programmes.

In this section, first, the research design is presented considering two aspects: (i) SNA as a tool for assessing innovation systems; (2) a comparison of FP7 and H2020 to identify their differences and determine how the innovation systems are expected to evolve, particularly in terms of the network properties, owing to the change in the institutional impulse between the two programmes. Second, we present the data used to construct the underlying networks of both innovation systems—FP7 and H2020. Finally, the metrics used to assess network cohesion and node centrality have been explained.

3.1. Research design

The EEISs and their related networks based on FP7 and H2020 are built using data from the European Commission. The institutional impulse is then assessed by identifying the changes in network topology and properties and evaluating the correspondence of these changes to the new goals pursued by H2020 compared to its predecessor FP7. In the following subsections, a discussion of the use of SNA as a tool for evaluating innovation systems and the differences between the characteristics and goals of the two FPs are presented.

3.1.1. Social network analysis for assessing the evolution of innovation systems

Different methods have been proposed in the literature to define and evaluate the functions of innovation systems for assessing their evolution. SNA has been proven to be a powerful tool for assessing how an innovation system, as a structure of interacting entities in common projects, may contribute to the diffusion of innovation. This tool allows for the characterisation of innovation systems and their related research networks, providing insights into their operations and enabling the identification of dysfunctions and strengths (Van Rijnsoever et al., 2015; Kofler et al., 2018; Decourt, 2019; Li et al., 2019; Porto-Gomez et al., 2019).

In this context, van Alphen et al. (2010) studied the network of actors related to Carbon Capture and Storage technologies in the US for two

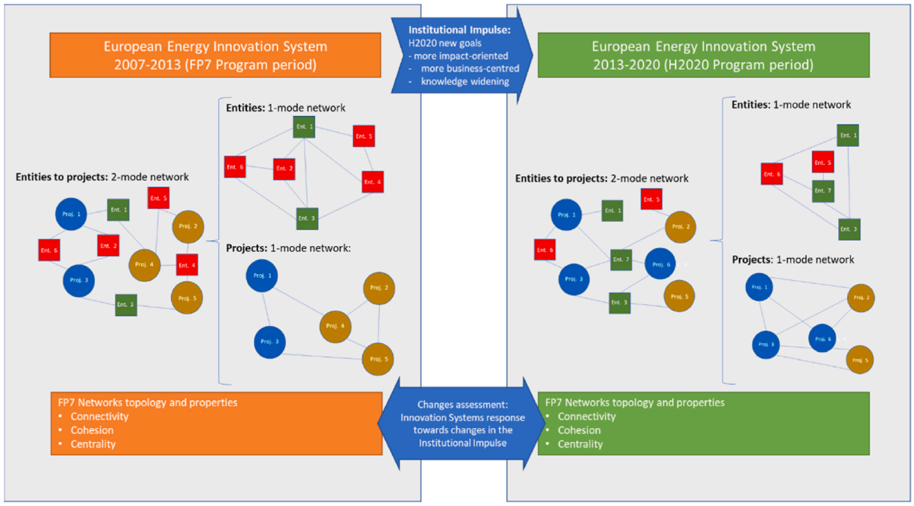

Fig. 1. Overview of the conceptual framework.

periods—2003–2005 and 2006–2008—mainly in terms of growth and connectivity. Nevertheless, although there was a clear increase in investment during these two periods, the innovation systems were not driven by a single public research funding programme having clear policy goals that targeted changes in the innovation system. Therefore, it was not possible to assess the effects of the institutional impulse. Furthermore, although the network of actors is assessed at both the network and node levels, the characteristics of the network of projects were not considered, and the technological trajectories within the innovation system could not be evaluated.

Following the recent work of Calvo-Gallardo et al. (2021), we have used SNA in this study to compare the results corresponding to H2020 and FP7. SNA was applied using the UCINET software (Borgatti et al., 2002). The two-mode network composed of the projects and entities in H2020 is, therefore, decomposed into two one-mode networks, one for entities and the other for projects, whose properties are assessed and compared to those determined in the FP7 study.

The analysis is performed at the network and node levels. The properties analysed at the network level are the average degree, average distance, density, components, average tie strength between groups, and H-index. For the node-level dyadic analysis, the following properties are assessed: degree, closeness, eigenvector, and betweenness.

3.1.2. *From FP7 to H2020: Energy research policies and programmes*

Energy plays a central role in achieving the EU's climate-neutrality goal by 2050 and is currently responsible for 75% of the EU's greenhouse gas emissions. To achieve this objective, the European Commission has highlighted the need to decarbonise at least six times faster than anything achieved globally, increasing the share of renewable energy and clean energy carriers and improving energy efficiency. In this context, research and innovation, as well as novel and disruptive renewable technologies, are critical to delivering solutions and system transformations. The research and innovation actions related to energy in the EU are governed by the Strategic Energy Technology Plan (SET-Plan), whose research and innovation initiatives are financially supported at the EU level, mainly by the FPs. The eighth FP, called Horizon 2020 (H2020), ran from 2014 to 2020, with a budget of EUR 79 billion, and was the successor of the seventh Framework Programme (FP7).

H2020 brought together all existing EU research and innovation funding, including the FP for research, the innovation-related activities of the Competitiveness and Innovation Framework Programme, and the European Institute of Innovation and Technology. It focuses on the multidisciplinary societal challenges that European citizens face. Apart from the differences related to administrative and financial aspects, there are three key areas pursued by H2020 compared to FP7: (1) H2020 seeks impact-oriented rather than knowledge-oriented research; (2) H2020 is more business-centred rather than academia-centred; (3) H2020 aims at widening knowledge rather than deepening it. In summary, H2020 focuses on industry and innovation and linking research to the market and society.

'Secure, Clean, and Efficient Energy' is the Societal Challenge specified in Pillar III of H2020. In this challenge, energy research and innovation are the focus, with a total budget of 5931 million euros for 2014–2020.

The energy challenge is structured around seven specific objectives and research areas: (1) reducing energy consumption and carbon footprint; (2) low-cost, low-carbon electricity supply; (3) alternative fuels and mobile energy sources; (4) a single smart European electricity grid; (5) new knowledge and technologies; (6) robust decision-making and public engagement; (7) market uptake of energy innovation—building on Intelligent Energy Europe. The energy programme has been built around these objectives. The main purpose of each objective has been discussed in detail in Table 1.

The H2020 objectives mostly involve all the research activities covered within the FP7 programme but are structured differently. However, the last objective is new and integrates the activities of the IEE programme to consider the market uptake of energy innovation. Furthermore, the FP7 activities of 'Energy efficiency and savings' and 'Renewables for heating and cooling' are integrated into the H2020 objective of 'Reducing energy consumption and carbon footprint by smart and sustainable use'. Moreover, FP7 activities related to 'CO2 capture and storage', 'Clean coal technologies', and 'Renewable electricity generation' are integrated into the 'Low-cost, low-carbon electricity supply' objective.

3.2. *Data collection*

This study aims to assess the evolution of the innovation system developed under FP7 during 2007–2013 to the system in 2013–2020 under H2020 and determine whether the changes in the properties of its underlying networks are related to the policy goal changes pursued by H2020. Therefore, the data considered are restricted to the projects and consortia funded under H2020's Societal Challenge of 'Secure, Clean, and Efficient Energy'. All the comparisons will be made against the results of a previous FP7 study by Calvo-Gallardo et al. (2021). Therefore, to ensure the coherence of the comparison, this study does not consider the projects funded under coordination and support action (CSA) schemes, in which research and innovation activities were not performed. Data are obtained from the CORDIS database (European Commission, 2021).

Table 1
Research objectives funded under H2020's Secure, Clean, and Efficient Energy challenge.

Objective	Main purpose
Reducing energy consumption and carbon footprint by smart and sustainable use	The activities shall focus on research and full-scale testing of new concepts, non-technological solutions, and more efficient, socially acceptable, and affordable technology components and systems with in-built intelligence. The purpose is to allow real-time energy management for new and existing near-zero-emission, near-zero-energy, and positive energy buildings, retrofitted buildings, cities and districts, renewable heating and cooling, and highly efficient industries, and mass take-up of energy-efficient and energy-saving solutions and services by companies, individuals, communities, and cities.
Low-cost, low-carbon electricity supply	The activities shall focus on research, development, and full-scale demonstration of innovative renewables, efficient, flexible, and low-carbon emission fossil power plants and carbon capture and storage, or CO2 re-use technologies, offering larger-scale, lower-cost, and environmentally safe technologies with a higher conversion efficiency and availability to different market and operating environments.
Alternative fuels and mobile energy sources	The activities shall focus on research, development, and full-scale demonstration of technologies and value chains to make bio-energy and other alternative fuels more competitive and sustainable. The aim is to generate power and heat and enable surface, maritime, and air transport, with the potential for more efficient energy conversion, to reduce time to market for hydrogen and fuel cells and bring new options exhibiting long-term potential for maturity.
A single, smart European electricity grid	The activities shall focus on research, development, and full-scale demonstration of new smart energy grid technologies and backup and balancing technologies that enable higher flexibility and efficiency, including conventional power plants, flexible energy storage systems, and market designs. The aim is to plan, monitor, control, and safely operate interoperable networks, including standardisation issues, in an open, decarbonised, environmentally sustainable, climate-resilient, and competitive market under normal or emergency conditions.
New knowledge and technologies	The activities shall focus on multidisciplinary research on clean, safe, and sustainable energy technologies (including visionary actions) and joint implementation of pan-European research programmes and world-class facilities.
Robust decision-making and public engagement	The activities shall focus on the development of tools, methods, models, and forward-looking and perspective scenarios for robust and transparent policy support. These include activities related to public engagement, user involvement, environmental impact, and sustainability assessment to improve the understanding of energy-related socio-economic trends and prospects.
Market uptake of energy innovation—building on Intelligent Energy Europe	The activities shall build upon and further enhance the initiatives undertaken within the Intelligent Energy Europe (IEE) programme. They shall focus on applied innovation and the promotion of standards to facilitate the market uptake of energy technologies and services, address non-technological barriers, and accelerate the cost-effective implementation of the EU's energy policies. Attention will also be given to innovation for the smart and sustainable use of the existing technologies.

The project sample includes collaborative research and innovation projects funded under the H2020 energy programme. It comprises 523 projects performed by 3546 distinct entities, of which 1052 are recurring partners (entities that participated in two or more projects). The total number of participants in the project sample—defined as the participation of one entity in one project—rises to 7176.

From this first data, it can be seen how, although the total budget of H2020 is 2.5 times that of FP7 (rising from 2300 to 5931 million euros at the current value), the number of projects and the number of participating entities increases 1.7 times (from 311 to 523 and from 2061 to 3546, respectively). The number of recurring partners increases by double (from 516 to 1052). Thus, it is expected that attractiveness and adherence to the programme are higher in H2020 as compared to FP7, considering that the share of recurring partners among the participating entities is proportionally higher.

3.2.1. Entity types and roles in the project

The participating entities were categorised based on their nature and main activity into the following types: public sector (PUB), higher education establishments (HES), research organisations (REC), private companies (PRC), and others (OTH). Notably, each consortium is led by one entity that acts as the 'coordinator', while the rest of the partners are considered 'participants'.

The PUB category consists primarily of national, regional, and local public authorities, as well as energy agencies. HES mainly comprises universities. REC is composed of two main types of stakeholders: national research centres with a public nature and research and technology organisations that are mostly private and non-profit organisations. PRC includes large, small, and medium companies. Finally, the OTH category comprises sector-level associations that include a few research institutes legally recognised as associations.

A comparison of entities and participation per entity type and role between FP7 and H2020 is presented in Table 2. The share of participating entities in terms of their type doubled from 4% in FP7 to 8% in H2020 for both PUB and OTH but decreased from 16% to 12% in FP7 to 13% and 9% in H2020 for HES and REC, respectively. Nevertheless, when the number of participations per entity type is considered, these trends remain but are smoother. The share of participations for PUB and OTH increases from 3% to 4% and from 3% to 6% between Fp7 and H2020, respectively; the share for PRC increases from 48% to 49%. Finally, HES and REC decreased their participations from 23% to 21% and 19%, respectively.

The average number of participations per entity increased by 9.1%, indicating an increase in adherence to H2020. Except for PUB and OTH, all the remaining entity types increased their adherence: HES, REC, and PRC increased their average participation per entity by 21%, 17%, and 15%, respectively, in H2020 compared to FP7.

Regarding participation as a coordinator, the main difference can be observed in an increase in HES that comes from a decrease in REC. Furthermore, the overall rate of entities acting as at least one coordinator decreases from 9.6% in Fp7 to 8.2% in H2020.

The taxonomies of FP7 and H2020 comprising newcomers, those that stopped their participation, and those that continued to participate are presented in Tables 3 and 4, respectively. When the rotation of entities within the innovation systems is assessed, we note that out of the 3546 entities that participated in the H2020 energy programme, 2879 did not participate in its predecessor FP7. Therefore, there are 81% newcomers. Further, of the 2061 entities that participated in FP7, 1394 discontinued their participation in H2020, while the remaining 667 proceeded to participate in H2020.

Regarding coordination, while 81% of all participants were newcomers, this rate decreased to 48% for the coordinators. The coordinators mainly belonged to the HES and REC groups. Thus, the innovation system stability between the two periods is mainly given by the coordinators belonging to HES and REC; the stopping rates for both of these groups between the FPs are the lowest in the FP7 programme (20% and 27%, respectively, compared to 68% for the entire programme). This trend is confirmed by the low rate of newcomers acting as coordinators from HES and REC in H2020 (30% and 33%, respectively, compared to 81% of the entire programme). Contrary to HES and REC,

Table 2
Comparison of the total number of entities and participations by entity type and role between the FP7 and H2020 energy programmes.

Entity type	Number of participating entities	Total number of participations	Average participations per entity	Entities acting as coordinators at least once	Share of entities acting as coordinators at least once	Participations acting as a coordinator
H2020						
PUB	268 (8%)	315 (4%)	1.18	8	3.0%	8 (2%)
HES	465 (13%)	1513 (21%)	3.25	88	18.9%	144 (28%)
REC	327 (9%)	1376 (19%)	4.21	72	22.0%	191 (37%)
PRC	2219 (63%)	3536 (49%)	1.59	117	5.3%	167 (32%)
OTH	267 (8%)	436 (6%)	1.63	7	2.6%	13 (2%)
Total	3546	7176	2.02	292	8.2%	523
FP7						
PUB	87 (4%)	105 (3%)	1.21	4	4.6%	4 (1%)
HES	326 (16%)	874 (23%)	2.68	54	16.6%	76 (24%)
REC	243 (12%)	874 (23%)	3.60	56	23.,0%	123 (40%)
PRC	1323 (64%)	1827 (48%)	1.38	80	6.0%	101 (32%)
OTH	82 (4%)	136 (3%)	1.66	4	4.9%	7 (2%)
Total	2061	3816	1.85	198	9.6%	311

PRC has the highest stopping rate (78%), with a significantly lower stopping rate for coordinators (54%) than participants (80%). Further, PRC in H2020 had the highest rate of newcomers among coordinators (69%). Thus, PRC are entities that provide more dynamics to the innovation system in terms of participation and involvement.

3.2.2. *Countries and roles in the project*

Upon assessing for the largest participating countries, it is found that the top ten list of countries for H2020 differs from that for FP7 regarding only one position: while Greece entered the list for H2020, Switzerland, included in the list for FP7, exited. These ten countries account for 70% of the total number of participants in H2020, which is less than the percentage in FP7 (73%). The participation details of the top ten countries are presented in Table 5. The share of involvement as coordinators increased for all ten countries, except for Germany (declining from 8.1% to 7.9%), with the highest increases for Sweden (from 5.6% to 8.4%), the Netherlands (from 6% to 8.3%), and France (from 7.2% to 9.6%). Nevertheless, the coordination rates increased moderately for Spain (from 11.5% to 11.7%) and Italy (from 9.0% to 11.5%).

Similar to in FP7, Central and Eastern European countries continue not to be present in the list of top-ten countries in H2020. This list has not been presented to evaluate the performance of each country—that would require new country normalised metrics to consider the differences in country sizes. However, it signals that the innovation system with H2020 has still not been able to involve, to a great extent, the entities from the last countries entering in the EU, as it already happened in FP7.

Table 3
Evolution of entity participation from FP7 to H2020 by type and role in the projects.

FP7 – Energy theme entity type and role of the participants	Total number of entities	Continued their participation in H2020	Stopped their participation	Percentage of entities stopping participation
PUB	87	26	61	70%
Coordinator	4	2	2	50%
Participant	83	24	59	71%
HES	326	200	126	39%
Coordinator	54	43	11	20%
Participant	272	157	115	42%
REC	243	113	130	53%
Coordinator	56	41	15	27%
Participant	187	72	115	61%
PRC	1323	289	1034	78%
Coordinator	80	37	43	54%
Participant	1243	252	991	80%
OTH	82	39	43	52%
Coordinator	4	2	2	50%
Participant	78	37	41	53%
Total	2061	667	1394	68%

Table 4
Composition of entities participating in H2020 in relation to their previous participation in FP7 by type and role in the projects.

H2020 - Energy entity type and role of the participants	Total number of entities	Experienced	Newcomers	Share of newcomers
PUB	268	26	242	90%
Coordinator	8	3	5	63%
Participant	260	23	237	91%
HES	465	203	262	56%
Coordinator	88	62	26	30%
Participant	377	141	236	63%
REC	327	116	211	65%
Coordinator	72	48	24	33%
Participant	255	68	187	73%
PRC	2219	288	1931	87%
Coordinator	117	36	81	69%
Participant	2102	252	1850	88%
OTH	267	34	233	87%
Coordinator	7	4	3	43%
Participant	260	30	230	88%
Total	3546	667	2879	81%

The share of newcomers is assessed and presented in Table 6 for the ten countries with the highest share to determine the rotation rate per country. Nine out of the ten countries with the highest share of newcomers also belong to the top ten countries with the highest participation rates, indicating a possible relationship between the rotation rate and participation volume. This may also be a consequence of a more dynamic country-level innovation system.

3.2.3. *Project types, research areas, and consortia composition*

The sample of projects comprises those funded as research and innovation actions in the Clean, Secure, and Efficient Energy Programme of H2020. This programme comprises the objectives summarised in Table 1. The average duration of the projects (3.72 years) was almost the same as in FP7 (3.73). Therefore, the first projects started in 2014, and the last ones will end around 2024 and 2025.

The project distribution per starting year and objective is presented in Table 7. Regarding the distribution across objectives, no project appears under the objective of ‘Market uptake of energy innovation—building on Intelligent Energy Europe’. This is because the projects targeting this objective were mainly funded under the CSA scheme and, as such, did not perform research or innovation. Therefore, these projects were not considered in this study. Furthermore, any project classified under the objective of ‘New knowledge and technologies’ was classified under at least two objectives. Thus, to enable a comparison between FP7 and H2020, such projects were presented under the other objective class instead of ‘New knowledge and

Table 5
Top ten countries by share of participation and roles in the H2020 energy programme.

Country	Position in H2020	Prior position in FP7	Total number of participations	Involvement as coordinator	Involvement as participant	Share of involvement as coordinator
ES – Spain	1	2	907	104	803	11%
DE – Germany	2	1	811	66	745	8%
IT – Italy	3	4	680	61	619	9%
FR – France	4	5	554	40	514	7%
UK – United Kingdom	5	3	509	34	475	7%
NL – Netherlands	6	6	436	26	410	6%
BE – Belgium	7	7	352	27	325	8%
EL – Greece	8	N/A	301	27	274	9%
DK – Denmark	9	8	234	18	216	8%
SE – Sweden	10	9	234	13	221	6%

Table 6
Top ten countries with the highest share of newcomers in the H2020 energy programme.

Country	Position in the top-ten participation in H2020	Total number of participating entities	Experienced	Newcomers	Share of newcomers
EL – Greece	8	115	16	99	86%
ES – Spain	1	418	71	347	83%
DK – Denmark	9	102	18	84	82%
NL – Netherlands	6	207	41	166	80%
SE – Sweden	10	125	25	100	80%
DE – Germany	2	384	77	307	80%
FR – France	4	278	56	222	80%
BE – Belgium	7	165	37	128	78%
IT – Italy	3	305	69	236	77%
CH – Switzerland	N/A	97	22	75	77%
UK – United Kingdom	5	259	61	198	76%

technologies' (see Table 8).

Considering that the total number of projects increases from 315 in FP7 to 523 in H2020 (66%), the following main conclusions can be drawn by assessing the representation of each objective in the whole programme:

1. Suppose the number of projects addressing the H2020 objective of 'Reducing energy consumption and carbon footprint by smart and sustainable use' is compared to the number of those targeting the FP7 goals of 'Energy efficiency and savings' and 'Renewables for heating and cooling'. Subsequently, an increase can be observed from 50 projects in FP7 to 103 projects in H2020, accounting for a 100.1% increase, considerably above the average of 66%.
2. Suppose the number of projects addressing the H2020 objective of 'Low-cost, low-carbon electricity supply' is compared to that of projects targeting the FP7 goals of 'CO2 capture and storage', 'Clean coal technologies', and 'Renewable electricity generation'. Subsequently, an increase can be found from 137 projects to 183 projects, indicating a 33.5% increase, which is below the average of 66%.
3. The number of projects addressing the H2020 objective of 'Alternative fuels and mobile energy sources' increased to 50 as compared to 37 for the FP7 objective of 'Renewable fuel production', indicating a 35% increase, which is above the average of 66%.
4. The number of projects addressing the H2020 objective of 'A single, smart European electricity grid' rose to 141 compared to 43 in the FP7 objective of 'Smart energy networks', resulting in an increase of 227%, which is significantly higher than the average of 66%.

In summary, the number of projects addressing the reduction of energy use and its associated footprint, as well as the electricity grid, shows a clear increase at the expense of projects addressing low-carbon electricity supply.

Regarding consortium composition concerning the number of partners, the average number of partners per consortium reaches 13.7 in H2020–11.4% higher than in FP7 (12,3). There is a high dispersion of data over the years, even larger than in FP7, as can be seen in the coefficient of variation of the sample in terms of the number of partners in the consortia, which rank between 33% and 75% throughout the years. Therefore, the number of partners differed significantly across different consortia.

Table 7
Number of projects funded per year at each activity within the H2020 energy programme.

Starting year	Number of projects	Reducing energy consumption and carbon footprint by smart and sustainable use	Low-cost, low-carbon energy supply	Alternative fuels and mobile energy sources	A single, smart European electricity grid	New knowledge and technologies	Robust decision-making and public engagement
2014	2	2					
2015	73	19	23	4	16	5	6
2016	102	26	41	5	20	3	7
2017	62	11	13	7	30	1	
2018	63	3	33	11	10	4	2
2019	78	12	30	4	23	3	6
2020	99	29	28	9	30		3
2021	44	1	15	10	12		6
Total	**523**	**103**	**183**	**50**	**141**	**16**	**30**

Table 8
Consortia composition characteristics within the H2020 energy programme.

Starting year	Total	2014	2015	2016	2017	2018	2019	2020	2021
Average number of partners	13.7	14.0	11.6	13.8	14.3	13.98	14.9	14.4	12.4
Minimum number of partners	4	9	4	5	5	6	5	4	5
Maximum number of partners	83	19	40	41	46	35	47	83	21
Standard deviation	7.8	7.1	5.6	7.7	8.5	6.1	7.6	10.8	4.2
Coefficient of variation	57%	51%	49%	56%	59%	43%	51%	75%	33%

3.3. Network cohesion and node centrality metrics

To assess the main topological and structural features of the EEIS networks, as well as the role of the nodes, a nominalist approach has been used to construct the graphs of the entities and projects. For this purpose, an affiliation matrix is constructed by assigning attributes to different nodes—an approach usually adopted in similar research works (e.g. Wasserman and Faust, 1994). Two perspectives are considered in this analysis: a node-level approach, in which the embeddedness of the nodes is measured through centrality metrics, and a whole network perspective, in which network cohesion is assessed.

Addressing the node-level approach, also known as dyadic analysis, Gulati (1995) pointed out that network embeddedness reveals the informational value of a node's structural position in the network. However, Arranz et al. (2020) and Grewal et al. (2006) highlighted that the node position provides differential access to information. The network embeddedness of the nodes was measured in this study using the following centrality metrics:

- Degree: It measures the number of nodes connected to a given node. In the case of weighted networks, as in this study, the sum of the tie values is calculated. It assesses the opportunities of a node to obtain information and knowledge circulating around the network.
- Closeness: It calculates the average distance of the shortest paths between a particular node and every other node of the network. It assesses the closeness of a node to all the other nodes.
- Eigenvector: It assesses the influence of a node in the network, which is similar to a prestige rating. To assess this metric, relative ratings are given to all nodes in the network, where the connections to high-rating nodes contribute more to the score for the considered node than the equal connections of the node to low-rating nodes.
- Betweenness: It calculates the number of times a given node is positioned in the shortest path between two other nodes. It assesses the level of control of a particular node on the knowledge flow between all other nodes in the network.

Regarding the network approach, the following cohesion metrics are considered in this work:

- Average degree: It calculates the average degree of all nodes, which is an assessment of the network activity.
- Average distance: It is determined by the average distance between all reachable pairs of nodes—the distance between two connected nodes is the length of the shortest path, which is calculated as the number of edges it contains. It assesses how compact or dispersed a network is.
- Diameter: It is calculated as the longest geodesic distance (minimum distance between two nodes) between connected nodes within the network—the longest length of the shortest paths of all the reachable nodes. It assesses the extent of the network.
- Density: It is determined as the total number of ties divided by the total number of possible ties. For a weighted network, similar to those considered in this study, it is the total of all values divided by the number of possible ties.
- Components: They are defined as the sets of connected nodes not linked to the rest of the network. It represents the number of non-connected subnetworks.
- Average tie strength between groups: It denotes the average of the weighted connections of the links between nodes with different attributes. It indicates the strength of the connection between the other types of nodes within the network.
- H-Index: It corresponds to the maximum number of nodes having at least the same number of connections with other nodes. It is a measure of network cohesion that prevents the effects of outliers.

4. Results from the analysis of innovation systems' underlying networks

4.1. Network of projects analysis

4.1.1. Network-level analysis: Cohesion

The network of projects comprises 523 nodes (projects) and 42402 ties (connections between two projects through a shared partner). The average degree of the H2020 energy programme network is 81.07, an increase of 54% compared to that of FP7, which is 52.66. The network has an H-degree of 115, which is also higher than that of FP7 (75). There is only one project, GAIA, that is not connected to the rest of the projects, resulting in the existence of two components, as in FP7.

The density of the network is 0.16, which is slightly lower than that in FP7 (0.17). The diameter is 4, which is lower than that in FP7 (5). This indicates that the longest connection between the two projects is reduced by one in H2020. The average distance between projects is 1.885, which is also lower than that in FP7 (1.942).

From the above values, it can be said that the network is even better meshed in H2020 than in FP7. Furthermore, if the projects are clustered by objective and sub-objective (see Table 9), the density increases above the average density of 0.16.

The lowest density appears in the sub-objective of bringing to market energy-efficient technologies (0.109), which was also the lowest in FP7 (0.186). The biggest difference between H2020 and FP7 is the decrease in the density of wind, CO_2 capture and storage, and smart energy networks, from 0.971, 0.856, and 0.864 in FP7 to 0.498, 0.542, and 0.551 in H2020, respectively. This may be caused by a higher maturity of the associated technologies, a reduction in entry barriers, or an increasing interest in the industrial sector—the lack of a significant hub of recurring partners from HES and REC joining all the projects.

4.1.2. Node- (project) level analysis: Centrality measures

Table 10 presents the 20 projects scoring the highest values for the four centrality metrics considered in the analysis (degree, closeness, eigenvector, and betweenness).

The degree metric is, on average, higher and within a more limited range: it ranks between 219 and 389 in H2020, while in FP7, it ranks between 152 and 405. The median degree for the 20 top-ranking projects has risen from 178 in FP7 to 244 in H2020, thereby indicating how this small number of projects may have played a more significant role in connecting the whole network. The closeness metric is between 774 and 833 in H2020, while it is significantly lower in FP7, between 417 and 520; thus, in H2020, the projects have become more separate. The range of the eigenvector is comparable between the two FPs. Finally, the

Table 9
Number of projects and density of the subgraph per objective and sub-objective within the H2020 energy programme.

Objectives and sub-objectives	Number of projects	Density
Reducing energy consumption and carbon footprint through smart and sustainable use	**103**	**0.202**
Bring technologies and services to the mass market for smart and efficient energy use	35	0.109
Unlock the potential of efficient and renewable heating-cooling systems	34	0.226
Foster European smart cities and communities	34	0.394
Low-cost, low-carbon energy supply	**183**	**0.256**
Develop the full potential of wind energy	23	0.498
Develop efficient, reliable, and cost-competitive solar energy systems	51	0.482
Develop competitive and environmentally safe technologies for CO2 capture, transport, storage, and re-use	31	0.542
Develop geothermal, hydro, marine, and other renewable energy options	78	0.253
Alternative fuels and mobile energy sources	**50**	**0.318**
Make bio-energy more competitive and sustainable	32	0.333
New alternative fuels	18	0.340
A single, smart European electricity grid	**141**	**0.306**
Pan-European market, achieve a massive increase in renewable energy sources; manage interactions between millions of suppliers and customers, including owners of electrical vehicles, novel energy storage, synergies between smart grids, ICT, and telecommunication networks	44	0.224
Test large-scale demonstration projects and validate solutions and assess the benefits for the system and individual stakeholders, before deploying them across Europe	41	0.551
Establish connections between the electricity, gas, and heat networks	11	0.218
Put consumer at the centre of the energy system and attain demand response	45	0.259
New knowledge and technologies	**16**	**0.467**
Robust decision-making and public engagement	**30**	**0.331**
Obtain extensive knowledge of energy technologies and services, infrastructure, markets, and consumer behaviour for providing policymakers with robust analyses	25	0.330
Take advantage of the possibilities offered by web and social technologies; consumer behaviour, including that of vulnerable consumers such as persons with disabilities, and behavioural changes will be studied in open innovation platforms such as the Living Labs and large-scale demonstrators for service innovation	5	0.300

betweenness metric is higher, ranging from 2668 to 810 in H2020, while it ranges between 2224 and 430 in FP7. Therefore, these projects have a more effective role in intermediating between other projects.

4.2. Network of partner analysis

4.2.1. Network-level analysis: Cohesion

The network comprises 3546 nodes (entities) and 114654 ties (connections between entities that collaborate on the same project). The average degree of the network is 32.33, 1.32 times higher than that in FP7 (24.52). Thus, the entities in H2020 have, on average, a larger network of collaborating partners than those in FP7. The network in H2o20 has an H-index of 121, which is also higher than that of FP7 (85). There are two components, as the partners working on the GAIA project do not collaborate with any other participating entities.

The density of the H2020 energy network is 0.009, which is lower than that of FP7 (0.012). The diameter of the network is 5 μm, which is lower than that of FP7 (6 μm). The average distance between entities in H2020 is lower than that in FP7, achieving a value of 2.678 in H2020 compared to 2.801 in FP7.

Summarising the cohesion parameters of the whole network of partners, we find a larger network with 1.72 times more nodes in H2020 than in FP7, where the partners are more connected and closer, despite a reduced density.

Table 11 presents the calculated values of tie strengths between the different entity types for H2020. The table shows that the only tie strength that has increased from Fp7 to H2020 is that of HES with PUB, which is 1.19 times higher; this may be linked to the higher participation of PUB that may enter the programme by joining HES. Although all the reflexive tie strengths (within the same type of entities) are less in H2020 as compared to FP7, HES and PRC present comparable values of the strength of their internal collaboration (0.94 and 0.91 times that in FP7, respectively). The values for REC, PUB, and OTH are clearly lower (0.63, 0.59, and 0.52 times the FP7 values, respectively). Except for OTH, whose all values were reduced by almost half, the values for the rest of the connections range between 0.79 and 0.85 times their corresponding values for FP7.

When density is calculated considering their role in the project, the coordinators' density reaches 11.1% in H2020, which is close to the value in FP7 (12%). This value is 12 times larger than the density of the overall network of partners; in FP7, it is 10 times larger. Thus, the active contribution of project coordinators in FP7 shows an increasing trend in H2020.

Regarding the average tie strength between entities from different countries, as presented in Table 12, the highest values appear between entities from the same country, being particularly high in Denmark, Greece, Sweden, and The Netherlands. Thus, the high internal collaboration observed in FP7 persists in H2020. The average internal collaboration rate in FP7 is 0.035, whereas that in H2020 is 0.025. The average collaboration rate with other countries in FP7 is 0.015, whereas, in H2020, it is 0.009. This shows a minor trend between programmes to collaborate more with entities from the same country than those from other countries, as the rate of internal collaboration is 2.33 times the external collaboration in FP7 and 2.78 times that in H2020. Denmark (0.0460), Ireland (0.0384), and Sweden (0.0361) have the highest internal collaboration rates. The lowest internal collaboration rates are found in Germany (0.0133), Spain (0.0179), and Belgium (0.0179).

Regarding the collaboration rates between different countries, Table 13 presents the average tie strength between the ten largest participant countries. They were divided into three groups depending on the tie strength (strong, medium, and weak).

Comparing the results of this analysis for H2020 with those for FP7, we can find that the UK, which was present three times in the list of countries having strong ties with DK, NL, and BE and two times in the list of medium ties with FR and IT in FP7, witnesses a significant reduction in the strength of its collaboration; the tie strengths get dispersed, and no clear links can be seen. In H2020, the UK appears six times in the list of pairs with the weakest ties, as well as two times in the medium-tie list (EL and ES) and once in the strongest-tie list (IT). This may have occurred due to the Brexit situation and the perceived uncertainty regarding participation changes for UK entities in H2020.

Four pairs of countries remain in the list of the strongest ties: ES-BE, FR-BE, ES-IT, and IT-BE. The strong relationship between these four countries (ES, BE, FR, and IT) is maintained between FP7 and H2020. EL, a newcomer in the top-ten participant countries, also presents a clear collaboration with these four countries.

There is another group of countries with a clear preference for collaboration in FP7, which is composed of NL, SE, and DK. Nevertheless, these two strong collaboration groups are tied by countries such as BE or ES, which also have strong ties with some of the countries in these groups.

Regarding those countries with no clear collaboration links (weakest ties), we find that, in addition to the UK, Germany appears five times in this list and is absent in the list of countries with the strongest ties. The lack of clear preference in the collaboration of DE with other countries, which is also true in the case of FP7, has been highlighted in H2020, and DE is one of the largest participants. Denmark also appears five times on

Table 10
Centrality measures of the FP7 energy theme network of projects; selection of the 20 highest values for degree, closeness, eigenvector, and betweenness.

Degree		Closeness		Eigenvector		Between	
Top 20 projects	Value	Top 20 projects	Value	Top 20 projects	Value	Top 20 projects	Value
INSHIP	389	INSHIP	774	LEAP-RE	0.225	INSHIP	2668
OneNet	359	LEAP-RE	812	OneNet	0.219	LEAP-RE	2098
LEAP-RE	336	Open ENTRANCE	813	INSHIP	0.151	OneNet	1762
EU-SysFlex	308	EU-SysFlex	832	EU-SysFlex	0.143	Open ENTRANCE	1470
Open ENTRANCE	295	OneNet	841	POCITYF	0.131	POCITYF	1151
POCITYF	279	POCITYF	842	RESPONSE	0.112	EU-SysFlex	1128
SmartNet	260	GreenDiamond	848	Open ENTRANCE	0.108	NOBEL GRID	1071
GreenDiamond	248	ATELIER	848	ATELIER	0.108	RESPONSE	1055
HighLite	245	SmartNet	860	HighLite	0.105	CL-Windcon	1033
ATELIER	244	MAtchUP	862	IANOS	0.102	ATELIER	983
CL-Windcon	232	HighLite	866	MAtchUP	0.100	SET-Nav	948
MAtchUP	230	IANOS	873	GreenDiamond	0.096	SmartNet	924
NextBase	229	ECEMF	873	SmartNet	0.095	DESOLINATION	910
GEMex	228	EPC RECAST	873	SERENDI-PV	0.091	GEMex	898
RESPONSE	227	SERENDI-PV	874	NextBase	0.090	GOLD	885
IANOS	227	SET-Nav	875	AMPERE	0.090	CO2OLHEAT	856
FLEXnCONFU	226	BALANCE	878	GEMex	0.090	IANOS	842
TIGON	223	GRETA	879	INTERRFACE	0.090	PROMOTION	841
INSULAE	222	CL-Windcon	880	ECEMF	0.088	GreenDiamond	836
AMPERE	219	FLEXnCONFU	883	NOBEL GRID	0.085	INSULAE	810

Table 11
Average tie strengths between the different types of partners in the H2020 energy programme.

	Public sector	Higher education	Research organisations	Private companies	Others
Public sector	0.018	0.010	0.014	0.006	0.011
Higher education	0.010	0.028	0.031	0.010	0.012
Research organisations	0.014	0.031	0.043	0.013	0.016
Private companies	0.006	0.010	0.013	0.007	0.006
Others	0.011	0.012	0.016	0.006	0.009

Table 12
Average tie strength between the partner countries in the H2020 energy programme.

Country	BE	DE	DK	EL	ES	FR	IT	NL	SE	UK
BE	0.0179	0.0083	0.0077	0.0136	0.0108	0.0100	0.0102	0.0090	0.0089	0.0075
DE	0.0083	0.0133	0.0084	0.0082	0.0088	0.0099	0.0093	0.0084	0.0084	0.0074
DK	0.0077	0.0084	0.0460	0.0111	0.0111	0.0051	0.0078	0.0117	0.0100	0.0070
EL	0.0136	0.0082	0.0111	0.0384	0.0134	0.0089	0.0133	0.0103	0.0098	0.0090
ES	0.0108	0.0088	0.0111	0.0134	0.0179	0.0088	0.0118	0.0079	0.0090	0.0086
FR	0.0100	0.0099	0.0051	0.0089	0.0088	0.0202	0.0095	0.0089	0.0105	0.0077
IT	0.0102	0.0093	0.0078	0.0133	0.0118	0.0095	0.0197	0.0104	0.0063	0.0106
NL	0.0090	0.0084	0.0117	0.0103	0.0079	0.0089	0.0104	0.0286	0.0140	0.0084
SE	0.0089	0.0084	0.0100	0.0098	0.0090	0.0105	0.0063	0.0140	0.0361	0.0072
UK	0.0075	0.0074	0.0070	0.0090	0.0086	0.0077	0.0106	0.0084	0.0072	0.0172

Table 13
Average tie strength between the different pairs of partner countries in the H2020 energy programme.

Pairs of countries with the strongest ties			Pairs of countries with medium ties			Pairs of countries with the weakest ties		
Country 1	Country 2	Tie Strength	Country 1	Country 2	Tie Strength	Country 1	Country 2	Tie Strength
SE	NL	0.0140	SE	DK	0.0100	UK	NL	0.0084
EL	BE	0.0136	FR	DE	0.0099	DK	DE	0.0084
ES	EL	0.0134	SE	EL	0.0098	NL	DE	0.0084
IT	EL	0.0133	IT	FR	0.0095	DE	BE	0.0083
IT	ES	0.0118	IT	DE	0.0093	EL	DE	0.0082
NL	DK	0.0117	UK	EL	0.0090	NL	ES	0.0079
ES	DK	0.0111	NL	BE	0.0090	IT	DK	0.0078
EL	DK	0.0111	SE	ES	0.0090	UK	FR	0.0077
ES	BE	0.0108	SE	BE	0.0089	DK	BE	0.0077
UK	IT	0.0106	NL	FR	0.0089	UK	BE	0.0075
SE	FR	0.0105	FR	EL	0.0089	UK	DE	0.0074
NL	IT	0.0104	FR	ES	0.0088	UK	SE	0.0072
NL	EL	0.0103	ES	DE	0.0088	UK	DK	0.0070
IT	BE	0.0102	UK	ES	0.0086	SE	IT	0.0063
FR	BE	0.0100	SE	DE	0.0084	FR	DK	0.0051

the list of the weakest tie strengths, indicating a non-clear preference for collaborating.

4.2.2. Node- (entity) level analysis: Centrality measures

The centrality metrics of degree, closeness, eigenvector, and betweenness are presented in Table 14 for the 20 entities with the highest values for each metric.

The four lists continue to be dominated by REC and HES, with only two PRC: Electricité de France, also present in FP7, and Rina Consulting, which appears in the four lists in H2020. No OTH or PUB is present in these lists. Fraunhofer continues to be the first entity in the four ranks of centrality metrics, as in FP7.

Compared to the same analysis for FP7, we can define four clusters of entities by considering the evolution of their centrality metrics: (1) extremely relevant entities in both programmes (those present in all the four top-20 centrality metrics lists for both programmes); (2) even more relevant entities (those already present in some of the four lists in FP7 as well as in the four lists in H2020); (3) considerably new and extremely relevant entities (those that are not present in any of the four lists in FP7, although most of them were FP7 participants, but present in the four metrics' lists of H2020); (4) less relevant entities (those present in one or more lists in FP7 but do not appear in any list of H2020). The composition of these clusters is provided in Table 15. The entities are presented in alphabetical order, along with information pertaining to their activity type, country, and role in the projects. All the 17 entities comprising the first three lists are coordinators in H2020—11 REC, 4 HES, and 2 PRC. The fourth list includes 15 entities—9 REC and 6 HES. There is a slight trend of REC and PRC being more prominent in the network. Regarding the countries, the first three lists represent the largest participant countries, while in the fourth list, remarkably, there are four entities from NO out of the 15.

To assess the centrality of the partners in terms of their country, the average of the four normalised centrality measures for all entities belonging to the ten countries with the highest number of projects (Table 5) is presented in Table 16. Compared to the same analysis for FP7, the strong position of Greece, the newcomer country in the list of ten most prominent participants in H2020, is remarkable; Greek's entities rank in the first position in three of the four metrics.

The average of the four centrality measures is presented in Table 17 to assess the centrality of different types of partners. REC has the highest values in all four of the centrality measures, followed by HES, thereby confirming their prominent role in the programme, which has been already established for FP7.

Regarding the centrality of the participants depending on their role in the projects, the average centrality metrics of coordinators (those entities that have coordinated at least one project) and participants (entities that have never coordinated a project) are presented in Table 18. The significant differences detected in FP7 between coordinators and participants has become even more prominent in H2020. On average, compared to participants, coordinators in H2020 have 4.12 times more connections (degree), are 1.11 times closer to other entities (closeness), influence the whole system 5.09 times more (eigenvector), and serve to connect other entities 33.18 more times (betweenness).

5. Discussion

This study analyses the evolution of the EEIS between two periods—2007–2013 and 2014–2020—corresponding to two different EU research and innovation FPs, FP7 and H2020, respectively, to assess how the innovation system evolution corresponds to the changes in the policy goals and challenges set forth by newer programme H2020. In line with previous studies (Esmailzadeh et al., 2020; Calvo-Gallardo et al., 2021; De Arroyabe et al., 2021; Van der Loos et al., 2021), it was found that these conditions—changes in the institutional impulse—played a relevant and complex role in the evolution of the innovation systems. They overlap, link, have different weights, and evolve over time (Van der Loos et al., 2021). It is considered that the institutional impulse generated by the EU through the FPs created a network of relationships between actors that enabled the exchange of knowledge and information, which, according to Enkel et al. (2009) and Huang et al. (2013), is a crucial element in innovation and technology development. Thus, following Kang and Hwang (2016) and Muñiz and Cuervo (2018), the topological and structural characteristics of the EEIS were assessed using SNA. The results indicate that, contrary to previous studies (e.g. Hekkert et al., 2007; Papaioannou et al., 2009), the centrality metrics provided information pertaining to the efficiency and efficacy of the innovation systems.

From the analysis of the EEIS′ evolution from FP7 to H2020, we found a few characteristics related to its inertia and dynamics. Previous studies have found that a balance between inertia and dynamics is crucial for achieving performant innovation systems (Janssen, 2019). Based on this statement, we see that the EEIS, which is responsible for the prominent position of European countries in low-carbon innovation (Bonnet et al., 2019), exhibits the following properties. First, the innovation system's inertia is indicated by the overall stability of its cohesion property. It can be understood by the recurring partners in H2020, which are already big players in FP7, and mostly represented by REC and HES that acted as project coordinators. Second, the dynamics, primarily detected in the innovation system growth and high rate of newcomers, are provided mainly by PRC, PUB, and OTH, which have a more prominent role in H2020 than in FP7. Finally, regarding the different energy technologies, although a change was sought by H2020 (as the share of projects funded per technology presents high variations between both programmes), the cohesion property of each technology did not vary much compared to FP7, only achieving a smoother trend of FP7.

Regarding the first research question that addressed the changes in the properties of the EEIS between the two periods, we identified relevant differences. The characteristics of the underlying networks of the innovation system evolved according to the objectives of H2020, indicating a high dynamism due to an elevated rate of rotation of entities while maintaining some core partners to achieve inertia and continuity in the technology trajectories. Therefore, in line with Janssen (2019), there is a positive evolution of the topological properties of the EEIS towards the expected performance. In more detail, our results show that the three main changes proposed by H2020 compared to FP7 are adopted by the EEIS. Thus, it can be said that the properties of the underlying networks promoted by H2020 suggest that the innovation system has evolved to fulfil these proposed goals. First, the focus on project impacts rather than on knowledge generation may be supported by an increase in the participation of PRC, PUB, and OTH, which are responsible for both the market delivery and removal of non-technical barriers. Second, this change in the participants' taxonomy also supports the objective of having a more business-centred program rather than an academia-centred one. This is a relevant aspect highlighted in the literature that suggests the relevance of linking companies, universities, and research centres for effective knowledge transfer, from universities to the market (Arroyabe et al., 2015; Karaulova et al., 2017; Amoroso et al., 2018; Arranz et al., 2020), as well as an increase in the applicability of the FPs (Pinheiro et al., 2016; Amoroso et al., 2018)[1]. Moreover, our results show the consequence of knowledge widening rather than its deepening—the reduction of the differences between the intrinsic densities at each technology field and the overall density supports the idea that the innovation system has adopted this objective. Therefore, in line with Calvo-Gallardo et al. (2021), we confirm the relevance of the network density in the achievement of the research and innovation policy goals. Additionally, we identify how the assessment of

[1] A drawback was identified in the European technology policy compared to Japan and the US related to the difficulties in transforming inventions into innovations (Pinheiro et al., 2016; Amoroso et al., 2018).

Table 14
Centrality measures of the network of entities within the H2020 energy programme with the 20 highest values for degree, closeness, eigenvector, and betweenness.

Degree		Closeness		Eigenvector		Betweenness	
Top 20 entities	Value	Top 20 entities	Value	Top 20 entities	Value	Top 20 entities	Value
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	1134	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	0.562	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	0.442	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	757305
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	804	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	0.535	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	0.237	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	360021
FUNDACION TECNALIA RESEARCH & INNOVATION	743	FUNDACION TECNALIA RESEARCH & INNOVATION	0.533	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	0.236	FUNDACION TECNALIA RESEARCH & INNOVATION	353816
ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	680	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	0.531	FUNDACION TECNALIA RESEARCH & INNOVATION	0.210	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	284659
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	670	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	0.528	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	0.170	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	266755
RINA CONSULTING SPA	659	RINA CONSULTING SPA	0.525	RINA CONSULTING SPA	0.164	AALBORG UNIVERSITET	254218
TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	642	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	0.521	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	0.161	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	248954
AALBORG UNIVERSITET	508	DANMARKS TEKNISKE UNIVERSITET	0.518	DANMARKS TEKNISKE UNIVERSITET	0.150	RINA CONSULTING SPA	247905
DANMARKS TEKNISKE UNIVERSITET	488	AALBORG UNIVERSITET	0.516	ELECTRICITE DE FRANCE	0.118	DANMARKS TEKNISKE UNIVERSITET	216621
CONSIGLIO NAZIONALE DELLE RICERCHE	488	CONSIGLIO NAZIONALE DELLE RICERCHE	0.514	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	0.115	CONSIGLIO NAZIONALE DELLE RICERCHE	163823
POLITECNICO DI MILANO	475	POLITECNICO DI MILANO	0.513	POLITECNICO DI MILANO	0.114	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	160451
RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN	461	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN	0.513	CONSIGLIO NAZIONALE DELLE RICERCHE	0.114	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN	149416
FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	455	ELECTRICITE DE FRANCE	0.511	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	0.109	POLITECNICO DI MILANO	148597
ELECTRICITE DE FRANCE	441	FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	0.508	FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	0.106	FUNDACION CARTIF	148493
FUNDACION CARTIF	430	FUNDACION CARTIF	0.508	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN	0.106	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	139457
AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	412	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	0.507	AALBORG UNIVERSITET	0.100	FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	129230
VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	397	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	0.504	FUNDACION CARTIF	0.096	ELECTRICITE DE FRANCE	129136
ENGINEERING - INGEGNERIA INFORMATICA SPA	362	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	0.503	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	0.093	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	113150
DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	328	TECHNISCHE UNIVERSITEIT DELFT	0.502	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	0.092	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	111953
NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	321	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	0.500	TECHNISCHE UNIVERSITEIT DELFT	0.091	TECHNISCHE UNIVERSITAET MUENCHEN	109072

Table 15
Clusters of entities related to the evolution of their centrality metrics between FP7 and H2020

Extremely relevant entities in both programmes	Considerably new and extremely relevant entities
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (REC, FR, Coordinator) - DANMARKS TEKNISKE UNIVERSITET (HES, DK, Coordinator) - FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V. (REC, DE, Coordinator) - FUNDACION TECNALIA RESEARCH & INNOVATION (REC, ES, Coordinator) - NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO (REC, NL, Coordinator) - TEKNOLOGIAN TUTKIMUSKESKUS VTT OY (REC, FI, Coordinator)	- AALBORG UNIVERSITET (HES, DK, Coordinator) - AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH (REC, AT, Coordinator) - FUNDACION CARTIF (REC, ES, Coordinator) - FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS (REC, ES, Coordinator) - POLITECNICO DI MILANO (HES, IT, Coordinator) - RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN (HES, DE, Coordinator) - RINA CONSULTING SPA (PRC, IT, Coordinator) - VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N. V. (REC, BE, Coordinator)
Even more relevant entities	**Less relevant entities**
- CONSIGLIO NAZIONALE DELLE RICERCHE (REC, IT, Coordinator) - ELECTRICITE DE FRANCE (PRC, FR, Coordinator) - ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS (REC, EL, Coordinator)	- AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE (REC, IT, Coordinator) - CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION (REC, EL, Coordinator) - CENTRO DE INVESTIGACIONES ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS-CIEMAT (REC, ES, No coordinator) - EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH, (HES, CH, Coordinator) - FUNDACION CENER (REC, ES, Coordinator) - IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE (HES, UK, No coordinator) - JRC -JOINT RESEARCH CENTRE-EUROPEAN COMMISSION (REC, BE, No coordinator) - NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU (HES, NO, Coordinator) - RICERCA SUL SISTEMA ENERGETICO - RSE SPA (REC, IT, Coordinator) - SINTEF ENERGI AS (REC, NO, Coordinator) - SOFIA UNIVERSITY ST KLIMENT OHRIDSKI (HES, BG, N/A) - STICHTING ENERGIEONDERZOEK CENTRUM NEDERLAND (REC, NL, No coordinator) - STIFTELSEN SINTEF (REC, NO, No coordinator) - UNIVERSITAET STUTTGART (HES, DE, No coordinator) - UNIVERSITY OF STRATHCLYDE (HES, UK, Coordinator)

the network structure enables the evaluation of the competitiveness of different areas in the FPs (De Arroyabe et al., 2021).

Regarding the second question, our results facilitate an understanding of how changes in the characteristics of the EEIS between the two periods correspond to the new challenges pursued by H2020, the new FP, compared to its predecessor FP7. Thus, we have derived the following results from the comparative analysis of the two periods corresponding to the two FPs driving the EEIS. First, the innovation system has a larger number of players, of which 88% are newcomers, indicating a higher participation recurrence compared to the average number of connections, along with a lower share of entities that acted as coordinators. Van Rijnsoever et al. (2015) and Zhang and Guan (2019) pointed out that although network size is a relevant property in terms of information diffusion and collaboration, partners' connectivity is a critical element in influencing network efficiency (Lyu et al., 2019; Arranz et al., 2020; De Arroyabe et al., 2021). Second, despite the reduction in the share of REC and HES in the taxonomy and participation, these entities continue to hold a prominent position, especially those that acted as coordinators, with the biggest influence on network cohesion and, consequently, on the innovation system performance. Lyu et al. (2019) highlighted that the participation of HES and REC in innovation systems is controversial. They identified a positive aspect of the integration of HES and REC, as they have relevant research backgrounds. However, these authors also considered that the excessive presence of HES and REC limits the role of industries and, thus, possible future innovations. Third, the countries' participation seems to be uniform across the FPs; however, political aspects such as Brexit or the delay in the negotiation of Switzerland participation have strongly reduced the position of the countries' entities in the innovation system. Furthermore, EL notably improved its participation in H2020 compared to FP7. Therefore, the goal of geographical cohesion is achieved in terms of technology policy in the EU, indicating that cohesion metrics are relevant indicators for assessing this objective (e.g. De Arroyabe et al., 2021). Fourth, entities continue to be more prone to collaborate with partners from the same country. Nevertheless, some linked clusters of collaborating countries have emerged. Arroyabe et al. (2015) highlighted that the affinity between partners to collaborate on a project due to geographical proximity, as well as previous collaboration experiences, is a key element for developing collaboration agreements. Therefore, the EU should consider implementing measures to address this bias. Fifth, the network of partners, despite a small reduction in its density driven by the growth of the innovation system, is better meshed and more compact in H2020 than in FP7. In line with De Arroyabe et al. (2021), this study shows how network cohesion is an indicator of the effectiveness of innovation systems. Sixth, although more budget has been assigned proportionally to energy efficiency-related projects, as compared to low-carbon electricity or fuel production, this field continues to be the less cohesive one. Seventh, although some technologies, such as wind, CO_2 capture and storage, and smart energy networks, present less restricted environments, including the emergence of new players, they still possess a high but not too extreme density, which may lead to a higher maturity of the associated technologies, a reduction of entry barriers, or a growing interest in the industrial sector. Finally, there are still a few projects and partners with considerably high centrality metrics compared to the entire population. Nevertheless, a balance between the partners that stayed in their group, from FP7 to H2020, and those that changed their participation status has been identified. De Arroyabe et al. (2021) pointed out that the high centrality driven by the high participation of a limited number of organisations in a high number of projects allows for technology transfer and cohesion among partners.

6. Conclusions

This study's *first theoretical contribution* extends previous works in the innovation literature, particularly regarding the understanding of how innovation systems contribute to the industrial eco-innovative capacity related to low-carbon technologies (Porto-Gomez et al., 2019; Dahesh et al., 2020; Musiolik et al., 2020). In this sense, our study contributes to the understanding of the responsive capacities of innovation systems towards changes, particularly towards changes resulting from the

Table 16
Average normalised centrality measures for the countries with the highest participation in the H2020 energy programme.

Degree		Closeness		Eigenvector		Betweenness	
Country	Value	Country	Value	Country	Value	Country	Value
EL	1,21E-02	NL	3,78E-01	EL	8,33E-03	EL	8,46E-04
IT	1,08E-02	FR	3,75E-01	IT	7,78E-03	DK	8,36E-04
ES	1,02E-02	BE	3,75E-01	NL	7,72E-03	DE	6,87E-04
FR	9,96E-03	DE	3,75E-01	FR	7,48E-03	IT	6,27E-04
NL	9,94E-03	ES	3,75E-01	DE	7,35E-03	ES	5,93E-04
BE	9,56E-03	DK	3,75E-01	BE	7,25E-03	NL	5,37E-04
DK	9,43E-03	IT	3,74E-01	ES	7,09E-03	FR	4,41E-04
DE	9,13E-03	EL	3,71E-01	DK	6,81E-03	SE	4,26E-04
SE	9,02E-03	UK	3,69E-01	UK	5,52E-03	BE	3,72E-04
UK	8,42E-03	SE	3,69E-01	SE	5,39E-03	UK	3,54E-04

Table 17
Average centrality measures for the different types of entities in the network in the H2020 energy programme (PUB, HES, REC, PRC, and OTH).

Entity type	Average degree	Average closeness	Average eigenvector	Average betweenness
PUB	8,89E-03	3,75E-01	5,30E-03	4,10E-05
HES	1,47E-02	3,86E-01	1,08E-02	1,17E-03
REC	1,86E-02	3,89E-01	1,62E-02	2,19E-03
PRC	7,76E-03	3,70E-01	5,33E-03	1,58E-04
OTH	8,58E-03	3,73E-01	5,68E-03	1,91E-04
Total	9,82E-03	3,74E-01	7,07E-03	4,71E-04

Table 18
Average centrality measures for entities acting as coordinators and participants in the H2020 energy project.

Role	Average degree	Average closeness	Average eigenvector	Average betweenness
Coordinators	3,22E-02	4,13E-01	2,69E-02	4,28E-03
Participants	7,81E-03	3,71E-01	5,29E-03	1,29E-04
Total	9,82E-03	3,74E-01	7,07E-03	4,71E-04

institutional impulse generated by research and innovation funding programmes. First, it provides empirical evidence of how the composition (*node heterogeneity*) and structure of the network *(cohesion, centrality, and connectivity)* of entities and relationships underlying the innovation system evolved between two FPs based on the goals pursued by each programme. Second, this study contributes to extending knowledge in the field of innovation system evolution and dynamics. Thus, the comparison between the two periods corresponding to the two FPs allows for an analysis of innovation system dynamics using SNA based on the evolution of the network properties. This indicates that the whole system properties, which were evaluated using cohesion metrics, evolved in a smoother way, driven by the sharper changes in the properties of the nodes, which were assessed by centrality metrics. Third, this study contributes to assessing the effectiveness of innovation systems by considering the relevance of partners' heterogeneity in terms of activity type and geographical location. Thus, the identification and characterisation of the evolution of these entities that increase the cohesion of the whole system, relying on centrality metrics and their attributes, enable the consideration of the nodes as an active part of the network. This can provide the dynamics and changes in the cohesion properties of the whole system and, consequently, in its overall performance. Finally, in line with previous studies, SNA has been proven to be a powerful tool for assessing the evolution of complex innovation systems and evaluating the overall dynamics without losing the entity perspective, and providing complementary insights from the system and node perspectives, thereby enabling the complex and elaborate drawing of conclusions.

Our *second theoretical contribution* is situated within the institutional theory (Scott, 2005; Gao et al., 2019). Our work extends the existing literature by providing insights into how the institutional impulse of public funding research programmes impacts the development of low-carbon technologies (e.g. Zhao et al., 2021). Contrary to previous studies that have considered only the direct impact of the institutional impulse, our work shows that the network of relations developed through the institutional impulse has a relevant impact on the low-carbon innovative development of companies. Therefore, it can be concluded that, in addition to the direct impact on companies, it generates a spillover impact that materialises as a network of relations, thereby indicating the efficiency of the FPs in driving industrial innovation.

Our *third theoretical contribution* is framed within the context of the EU FPs, in which there has been an asymmetrical development of different research areas. Therefore, the assessment and comparison of the cohesion and centrality metrics of each technology subgraph enable the evaluation of the effectiveness of the technology trajectories and research areas.

Furthermore, this last contribution has important *policymaking implications*, as it provides the basis for understanding how innovation policy goals may be achieved by changes in the institutional impulse capable of driving the innovation system towards the achievement of these objectives. First, the evaluation of existing network topologies and their structural properties, followed by a design where changes would be more convenient for policy goal achievement, may provide a good basis for policymaking. Second, the involvement of the more influential entities in contributing to the foreseen changes may foster the innovation system's movement towards the achievement of new goals. Thus, continuous monitoring of the entities that have the strongest influence in the network and closely working with them may pave the way for the successful implementation of policy changes. Third, changes in the institutional impulse and funding programmes are effective in managing the evolution of different technologies. Although energy efficiency and savings continue to be one of the key challenges, some improvements in the cohesion of its related networks have been achieved, along with the achievement of openness in some technologies that were previously closed and restricted to a few entities. Moreover, from the participant entities' perspective, the results from monitoring the dynamics of innovation systems provide valuable insights into the evaluation of technology-related trends, identification of key players, and consideration of policy goals and context. This information is useful for the assessment of investments, technology choices, and alliance development.

This study has some limitations. Empirical research focuses on the energy field, which is a regulated sector; therefore, some of its particularities may hamper the replication of the results in other sectors. Thus, further research is needed to tackle more and different sectors or research programmes. Moreover, a larger number of studies covering additional fields are needed to pave the way towards determining a more convenient balance between the inertia and dynamics in the topology and properties of the innovation systems' underlying networks to achieve more performant innovation systems.

CRediT authorship contribution statement

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

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