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Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives

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ABSTRACT

This study analyses the properties of the networks constructed by the funded energy-related research consortia to assess their support to the objectives of the European Union's energy technologies and research policies. By developing research consortia, partners and projects are linked to form a network that generates relationship networks (innovation systems). Although many authors assessed this innovation system from different perspectives, few studies aim to identify the properties of its networks. From the innovation systems perspective, this study fills this gap in the literature by applying Social Network Analysis to determine the network cohesion properties and the centrality measures of its nodes, thereby enlarging the innovation systems literature in the field of modelling and performance assessment. The results indicate that the effectiveness of the innovation systems depends on the geographical distribution of the consortia and the diversity of the participants, revealing significant performance differences in each of the research fields within the energy programme. Based on these conclusions, this paper provides recommendations for policymakers and participants in these European research programmes.

1. Introduction

The transition from fossil fuels to a cleaner energy system is supported by research policies (Suo et al., 2020; Gong et al., 2020; Schwanitz et al., 2014; Edwards et al., 2008) that aim, among others, to construct innovation systems in which private companies, research centres and institutional actors interact, creating networks of relationships (Alvarez Fernandez et al., 2015; Weber and Rohracher, 2012).[1] In this context, governments and supranational authorities promote the creation of these innovation systems (Chang and Shih, 2004; Liu and White, 2001) by financing collaborative research and innovation projects that support energy policies (Arranz and Fernandez de Arroyabe, 2013). For example, the European Union (EU) finances projects' consortia through the Framework Programmes (FPs), integrating different actors from at least three different countries to deliver innovative results to the market and society (European Commission and Directorate-General for Research and Innovation, 2010). Moreover, Fernandez de Arroyabe et al. (2021) highlighted that funding these consortia promotes the creation of a network (innovation system), in which industries and research entities are connected, facilitating collaboration and access to knowledge and information between themselves (de Juana-Espinosa and Luján-Mora, 2019; Sá and de Pinho, 2019). This effect has been strongly pursued by the latest research policies, in which the knowledge transfer between participants (especially from universities and research centres to companies), the geographical cohesion between countries and regions, and the competitiveness of projects are the main objectives (de Juana-Espinosa and Luján-Mora, 2019; Kashani and Roshani, 2019; Kuhlmann and Edler, 2003).

In this context, prior studies considered the effectiveness of the

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

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[1] In this context, innovation systems emerged as focal points for innovation and technology, facilitating knowledge transfer and collaboration between institutions and companies.

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network of relationships created by these consortia in achieving the objectives of the research policy (Fernandez de Arroyabe et al., 2021; Muñiz and Cuervo, 2018; Kang and Hwang, 2016). While there is extensive work on the performance of these research projects from the perspective of collaboration and consortia composition (Pinheiro et al., 2016; Delanghe and Muldur, 2007; Muldur et al., 2007; Arranz and Fernandez de Arroyabe, 2006), some authors identified a gap regarding the understanding of the created system of relationships and its contribution to the policy objectives (Muñiz and Cuervo, 2018; Kang and Hwang, 2016). Although previous studies made important contributions, they had a partial perspective, leading to inconclusive results in terms of geographic cohesion, knowledge transfer and the competitiveness of the programmes. One group of studies focused on the institutional and political impact of the various research programmes (Gallego-Alvarez et al., 2017; DiMaggio and Powell, 1983), thus neglecting the study of the constructed network and its properties. A second group of studies addressed cohesion, such as regional cohesion (Amoroso et al., 2018; Di Cagno et al., 2016) or the relations between countries (Muñiz and Cuervo, 2018; Scherngell and Barber, 2009), forgetting aspects such as the competitiveness of the programmes and the connectivity between the various programmes. A last set of research emphasized how to integrate Small and Medium Enterprises (SMEs) in the innovation system (de Marco et al., 2020), forgetting about the other type of agents integrated within innovation systems, which play an important role in the diffusion and transfer of knowledge in innovation systems. Fernandez de Arroyabe (2021) and Muñiz and Cuervo (2018) highlighted the need to study the properties of the relationships between consortia in order to evaluate the efficiency of the innovation systems created in terms of collaboration, geographic cohesion and knowledge and technology transfer.

This study fulfils this gap in the literature by studying the properties of the networks constructed by the funded research consortia in the field of energy to assess their contribution to the objectives of the energy technologies and research policies. First, this study takes the perspective of innovation systems (Lundvall, 1992; Freeman, 1987). From this perspective, the research consortia create a network of relationships that constitute an innovation system. In this innovation system, the actors are linked as they work jointly in a given project, and projects are connected as they share partners, thus sharing information and knowledge among them. Second, this study proposes an approach to analyse the topology and properties of the networks (Kang and Hwang, 2016). For this purpose, the networks are assessed by means of Social Network Analysis (SNA) (Morisson et al., 2020; Borgatti et al., 2002; Wasserman and Faust, 1994). In recent years, the use of SNA helped researchers characterise innovation systems and their related research networks, providing insights about their operations and enabling the identification of dysfunctions and strengths (Rijnsoever et al., 2015; Kofler et al., 2018; Decourt, 2019; Li et al., 2019; Porto-Gomez et al., 2019).By relying on SNA, and particularly by evaluating the network cohesion and the node centrality metrics, this study assesses the dissemination of information, collaboration potential and transfer of knowledge and information. Thirdly, this study examines the case of the EU. As prior studies examined the EU previously (e.g. Fernandez de Arroyabe, 2012; Muñiz and Cuervo, 2018; Kang and Hwang, 2016), this enables a comparison and generalization of the results.

Considering the EU case, this study considers the European Strategic Energy Technology Plan (SET-Plan), which is expected to contribute to the decarbonisation of the energy system and enhance the competitiveness of European industry (European Commission 2007a, 2018a).[2] These EU energy technology objectives are supported by the EU research policy, which, since 2000, aimed to construct the European Research Area (ERA) (European Commission, 2012). The ERA was created as a unified research area to enable the free circulation of researchers, scientific knowledge and technology(European Commission, 2005). Two of the ERA's main priorities are (1) *fostering transnational cooperation and competition* and (2) the *circulation, access to and transfer of scientific knowledge*.

This study analyses a set of 311 consortia, corresponding to the FP7 Cooperation Theme 5-Energy projects funded under a Collaborative Project Scheme. Projects financed within Activity 1, which are related to Hydrogen and Fuel Cells, have not been considered, as they were transferred to the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), established based on Article 187 TFEU (ex-Article 171 TEC) and the data were not included in the CORDIS database. The set of consortia analysed included 2 061 entities, including 516 recurring participants. Using SNA,[3] the position of each organisation in the network through different centrality measures (*degree, betweenness, eigenvector,* and *closeness*) is measured to consider the active role of the nodes within the innovation system. In this approach, the centrality of the nodes within the network gives them a positional value in terms of knowledge and information access, as it has been considered in prior studies (Arranz et al., 2020; Arranz and Fernandez de Arroyabe, 2013). Additionally, different node attributes are considered in the network of participants: entity type (public sector, higher education establishment, research organisation, private company and other), role in the project (coordinator or participant) and nationality; while for the network of projects the research field is considered as the primary attribute. This study examines how the network properties and the position of the different nodes, considering their characteristics, affect the achievement of the objectives of the EU's research and energy policies. In this context, the two following research questions are proposed:

- *Is the European innovation system constructed under the FP7 in the field of energy contributing to the ERA's goals of fostering transnational cooperation and competition, while enabling the circulation, access to and transfer of scientific knowledge?*
- *Is the European innovation system constructed under the FP7 in the field of energy answering the technology challenges identified by the SET-Plan to reach the EU energy decarbonisation goals?*

This paper is structured as follows. Section 2 introduces the conceptual framework, linking the current state of the art of the innovation systems, institutional theory and the European energy research policies with the research model presented in this paper. Section 3 describes the data used to develop the empirical model, together with the SNA methodology. Then, in Section 4, the results are summarised and discussed in terms of three main parts: the

[2] In 2019, the EU approved the Clean Energy for All European Package, targeting the following energy goals: 32% renewable energy sources in the EU's energy mix by 2030 and 32.5% energy efficiency by 2030 compared to a business as usual scenario (European Parliament and European Council, 2018a, 2018b, 2018c). Furthermore, the new climate change strategy referred to as "The European Green Deal" (European Commission, 2019b) aims for EU countries to achieve climate neutrality by 2050 by implementing a fair energy transition that accounts for the diversity of the energy sectors in the different member states (Brodny and Tutak, 2020). As an intermediate milestone towards the 2050 Paris Agreement commitment of achieving a climate neutral economy, the EU targets a 40% reduction of the greenhouse gas emissions by 2030 compared to the 1990 levels (European Council, 2014).

[3] More specifically, the software UCINET (Borgatti et al., 2002).

participants and projects characteristics, the analysis of the network of projects and the analysis of the network of entities. Finally, Section 5 presents the conclusions, including the contribution to the theoretical framework, the answers to the research questions and some conclusions and remarks.

2. Literature review and conceptual framework

2.1. Innovation systems

Open Innovation theory (Chesbrough, 2012) conceives innovation as an evolving process of collective learning in which the different actors (companies, research institutions, clients, governments, financial institutions) cooperate to develop collaborative projects (Arranz and Fernandez de Arroyabe, 2006). For this purpose, the acceleration of this innovation process relies on the management of the inputs and outputs of knowledge (Chesbrough, 2003; Rahman and Ramos, 2010) within a flexible and dynamic organizational structure (Chesbrough, 2012) in which the stakeholders form an innovation system.

The innovation system approach has drawn the academic attention since the pioneering works of Freeman (1987), (Lundvall, 1988, 1992), Nelson (1993) and Edquist (1997), while being widely adopted by policymakers and research management practitioners (Lundvall et al., 2009; Mytelka and Smith, 2002; Edquist and Hommen, 2008).

According to Freeman (1987), an innovation system is ‘a network of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies’. Lundvall (1992) defined it as the ‘elements and relationships which interact in the production, diffusion, and use of new, and economically useful, knowledge, and are either located within or rooted inside the borders of a nation-state’. This study examines the EU networks of relationships created by the consortia funded by the FP7 EnergyTheme as an innovation system.

2.2. Institutional theory

Innovation systems are conceived within geographical and institutional frameworks, in which the institutional impulse is a critical element of the innovative capacity of the innovation system, as it provides incentives to collaborate and develop innovation projects (Ades et al., 2013; Parida et al., 2014).

Institutional theory (Gao et al., 2019; Gallego-Alvarez et al., 2017; Berrone et al., 2013; Scott, 2005) has been widely adopted to explain how the entities within an innovation system follow common organizational practices and rules. Within this approach, the behaviour of organisations is determined by shared norms, structures, constraints, cognitions and social expectations (DiMaggio, P. J., Powell, W.W., 1983; Scott, 2005; Berrone et al., 2013). Thus, the institutional framework pushes organisations to adopt common concepts and procedures. Hence, the EU has taken the leadership to promote a competitive innovation system in the EU, conceived as the ERA, which is defined as a unified research area enabling the free circulation of researchers, scientific knowledge and technology.

The ERA concept was proposed in 2000 by the European Commission and subsequently endorsed by the European Institutions. Since its creation, the ERA focused on a better organisation of research in Europe by addressing the fragmentation, isolation and compartmentalisation of national research systems and the lack of policy coordination between the member states and the EU (European Commission and Directorate-General for Research and Innovation, 2016).

The ERA concept is an example of an innovation system that closely follows the Metcalfe (2005) definition: ‘*that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such, it is a system of interconnected institutions to create, store, and transfer the knowledge, skills, and artefacts which define new technologies*’ (Metcalfe, 1995). This definition can demonstrate how the EU promoted the creation of the ERA by establishing rules and policies that fostered transnational collaboration between European entities, which currently form an innovation system that includes thousands of institutions and projects that cooperate to create and transfer new knowledge and technologies.

2.3. Energy research policies and programmes

Since 1952, with the Coal and Steel Treaty, and 1957, with the Euratom Treaty, the EU founding member states saw the need for a common approach to energy. Although the geopolitical considerations changed considerably, energy is still a key element of the European policy that became highly relevant in the last two decades. In 2007, the European Commission communicated the new European Energy Policy (European Commission. 2007a) that was based on three pillars: sustainability, security of supply and competitiveness. The European Energy Policy evolved to cope with more ambitious challenges driven by climate change (European Commission, 2019a). It was in 2007, when the EU established the need to implement a European Strategic Energy Technology Plan (SET-Plan) (European Commission. 2007b) and to commit to increasing the EU’s annual spending on energy research by 50% over the seven years of the 7th Framework Research Programme (FP7), from 2007 to 2013 (Lise Bosman, 2013).

It is important to note that the FP7, following the previous FP6, was intended to support the deployment of the ERA (European Council, 2006). In the energy field, the European Commission tailored the FP7 to jointly contribute to the ERA deployment, as well as to the energy technology objectives established in the SET-Plan (Llombart Estopiñan et al., 2011). Energy was considered one of the major fields of research, with an associated budget of 2 300 million euros under the Cooperation Programme within FP7. The FP7 Energy Theme funded collaborative R&D projects through top-down open calls. The SET-Plan technology roadmaps actively guided this top-down approach in the Energy Theme, which was structured according to ten research activities (Table 1).

An ex-post evaluation of the FP7 was made by the European Commission based on evidence and considering more than 120 external evaluation studies (European Commission and Directorate-General for Research and Innovation Directorate, 2015); (European Commission, 2015). Although many perspectives were considered, the inherent characteristics of the constructed networks of entities and projects were not addressed, and were thus not considered an influential factor of the effectiveness of FP7 in the energy field in supporting the ERA and SET-Plan objectives. According to the European Commission, improved EU research and innovation performance is required to meet the energy targets for 2030 (European Commission, 2018). Therefore, considering the relevance of the institutional impulse in the development of cohesive innovation systems, it is urgent to assess the EU FPs’ efficiency in terms of evaluating their underlying research networks. An evaluation is especially urgent considering that the following Framework Program for the 2021–2027 period—Horizon Europe—is currently being defined.

Table 1
Research activities funded under the FP7 Energy Theme.

Activities	Main purpose
1. Hydrogen and fuel cells	To build a competitive EU fuel cell and hydrogen supply and equipment industry, addressing transport, stationary and portable applications. *This priority was not managed under FP7, but by the Joint Technology Initiative on hydrogen and fuel cells, constituted based on Article 171 of the Treaty.*
2. Renewable Electricity Generation	To develop and demonstrate integrated technologies for electricity production from renewables, suited to different regional conditions where sufficient economic and technical potential were identified to provide the means to raise the share of renewable electricity production in the EU substantially.
3. Renewable fuel production	To develop and demonstrate improved fuel production systems and conversion technologies for the sustainable production and supply chains of solid, liquid and gaseous fuels from Biomass.
4. Renewables for Heating and Cooling	To increase the potential of active and passive heating and cooling from renewable energy sources to contribute to sustainable energy through a portfolio of technologies and devices, including storage technologies.
5. CO_2 Capture and Storage Technologies for Zero-Emission Power Generation	To drastically reduce the adverse environmental impact of fossil fuel use, targeting highly efficient and cost-effective power and/or steam generation plants with near-zero emissions, based on CO_2 capture and storage technologies, particularly underground storage.
6. Clean Coal Technologies	To substantially improve the efficiency, reliability and cost of coal- (and other solid hydrocarbons) fired power plants, including the production of secondary energy carriers (including hydrogen) and liquid or gaseous fuels.
7. Smart Energy Networks	To facilitate the transition to a more sustainable energy system, a wide-ranging R&D effort is required to increase the efficiency, flexibility, safety, reliability and quality of the European electricity and gas systems and networks, notably within the context of a more integrated European energy market.
8. Energy Efficiency and Savings	To harness the vast potential for final and primary energy consumption savings and improvements in energy efficiency through research into optimising, validating and demonstrating new concepts; optimising proven and new concepts and technologies for buildings, transport, services and industry.
9. Knowledge for Energy Policy Making	To develop tools, methods and models to assess the main economic and social issues related to energy technologies.
10: Horizontal Programme Actions	The topics described in this section had a horizontal character and were not explicitly linked to any particular technology.

2.4. Research model

The European FPs aim to strengthen the scientific and technological base of European industry while promoting research that supports EU policies. The deployment of the ERA and, in the energy field, the implementation of the SET-Plan, are essential to achieve the EU's energy and environmental objectives.

For this purpose, the institutional impulse is focused on enabling the circulation, access to and transfer of scientific knowledge, as established in the ERA objectives. Attending to this, the FPs promote collaborative research by funding consortia ready to disseminate knowledge and ideas while sharing research capabilities and market insights. This study applies SNA techniques to evaluate the research networks developed under the energy area as an innovation system. The cohesion properties of the research networks give an idea of the structure of this innovation system and offer detailed information about the subgraphs constructed at each technological specialisation considered in the Energy Theme. Additionally, the centrality measures of the different categories of nodes provide insights about how each type of entity, depending on their origin and their role in the projects, are embedded in the overall network and contribute to its cohesion.

Furthermore, to increase the competitiveness of the EU industry, the energy-related FPs are funding top-down research and thus funding the best projects for answering the technological challenges identified by the sector's stakeholders. These challenges are organised in the technology roadmaps developed under the SET-Plan umbrella and addressed by the FPs energy calls. Thus, understanding each technological subgraph embedded within the overall energy research network provides insights into the progress of this technology field.

Finally, the FPs aim to overcome the current fragmentation to avoid duplicated efforts, thus making the research system more effective. Overall, the FPs are fostering both competition and collaboration by developing transnational networks for cooperation in research. Considering that competition is ensured by the very low success rate of the competitive calls, the collaboration can be assessed by studying the cohesion and characteristics of the networks developed by the participating entities.

3. Methods

3.1. Data

This study aims to assess how the innovation system constructed under (FP7) contributed to the ERA and SET-Plan objectives. For this reason, the data considered are restricted to the projects and consortia funded under Cooperation Theme 5. Energy, of FP7, and include only the projects conducted under a Collaborative Project Funding Scheme. Thus, this study does not consider Coordination and Support Actions, in which research and development activities are not performed. The data were obtained from the CORDIS database (European Commission, 2020).

The project's sample includes collaborative research and innovation projects funded under the FP7-Energy programme. From the ten activities funded in this Theme, projects addressing the "Hydrogen and Fuel Cells" Activity were excluded from the study as they were transferred to the Fuel Cells and Hydrogen Joint Undertaking and therefore not managed by the FP7.

In total, this category includes 311 projects performed by 2 061 distinct entities, where 516 of them recurring partners (entities that participate in two or more projects). The total number of participations in the project sample, established as the participation of one entity in one project, rises to 3 816.

3.1.1. Entity types and roles in the project

The participating entities are categorised by their nature and main activity into the following types: public sector (PUB), higher education establishments (HES), research organisations (REC), private companies (PRC), and other (OTH). It is important to note that each consortium is led by one entity that acts as a 'coordinator', while the remaining consortium partners are considered as 'participants'.

PUB consists mainly of national, regional and local public authorities, as well as energy agencies. HES comprise mainly Universities. The REC category is composed of two main types of stakeholders: national research centres with a public nature, and research and technology organisations, which are mostly private, non-profit organisations. PRCs include both large and Small and

Medium companies. Finally, the OTH category includes sector-level associations, including some research institutes that are legally constituted as associations.

Table 2 summarises the total number of participations per entity category based on their involvement, either as a coordinator or as a participant.

A quick analysis of Table 2 shows that participation is driven by three main types of participants: HES, PRC and REC. PRC are the biggest participants, accounting for 48% of the total number of participations, followed by HES and REC, accounting 23% of the total participation each. Nevertheless, REC hold the top position in terms of coordination involvement, coordinating 40% of the projects, followed by PRC (32%) and HES (24%). REC act as coordinators in 14% of their participations, while this rate decreases to 9% and 6% for HES and PRC, respectively.

3.1.2. Countries and roles in the project

The 2 061 entities participating in the project sample are based in 67 different countries. Nevertheless, 72% of the participations belong to partners from ten countries, while 81% of the project coordinators reside in these ten countries.

Table 3 presents the number of participants per country for the ten countries with the most significant number of participations according to their role in the projects. While Germany has the largest number of observations (541), Spain has the largest number of coordinators (45). Regarding the share of coordinated projects, Spain coordinated the most projects, at 11.7%, followed by Italy (11,5%) and France (9.6%). Germany, despite being the top country in terms of participations, ranks ninth position in coordination share (7.9%), followed by Switzerland, which only coordinated 4.7% of the projects in which it participates. Notably, no Central and Eastern European country is present in this top-ten list of participants, which may be a consequence of the FPs design or related to their lower experience with participating in these programmes due to their recent entry to the EU. It is important to note that this top-ten list is not presented to evaluate the performance of each country, as for this purpose, new country normalised metrics would be needed to consider the different country sizes, probably using the gross domestic product or the population as a normalisation variable.

3.1.3. Project types, research areas and consortia composition

The sample of projects in the analysis corresponds to those funded within the Collaborative Project Funding Scheme in Theme 5, Energy under the Cooperation Programme of the FP7. This Theme consists of the ten activities summarised in Table 1. The projects were selected for funding over the seven-year duration of the FP7. Thus, considering that the average duration of the projects was 3.73 years and that the FP7 lasted from 2007 to 2013, the first projects started in 2007, and the last ones ended around 2017–2018.

Table 4 presents the number of projects funded every year for each of the nine Activities under the Energy Theme.

The average number of partners in the consortia was 12.3, with a standard deviation of 6.4. Regarding the evolution of the number of partners over the years, the last year of the program (2013) increased up to 16.8, probably due to the early transition to the next FP (Horizon, 2020), which was already under negotiation and aimed at higher-impact projects. The coefficient of variation of the sample in terms of the number of partners in the consortia ranks between 40% and 52%, depending on the year; thus showing a high dispersion, with significantly differentiated consortia concerning the number of partners. Table 5 shows the evolution of the consortia composition from the number of partners perspective, providing the average, minimum, maximum, standard deviation and coefficient of variation along the years.

3.2. Methodology

Several studies discussed the use of SNA to evaluate the performance of innovation systems (Franco and Ruiz, 2019; Morisson et al., 2020; Abreu, 2020), but no studies focused on energy or on the research and innovation projects of the FP7 Energy Theme in particular. The conclusions achieved in other fields demonstrated how the innovation systems' performance is positively linked with its related networks' connectivity, thus illustrating how the networks act as efficient mechanisms of knowledge diffusion and creation (Woods et al., 2019; Altuntas and Mehmet, 2020; Lin et al., 2009).

A well-meshed and integrated network, involving all the different actors of the innovation value chain and connecting all the related projects, is a critical success factor in the high performance of a research programme (Kolleck, 2013). Research networks enable information exchange and experience sharing. Well-functioning research networks can avoid overlapping actions and the fragmentation of activities, which are critical challenges for improving the EU's R&D performance (European Commission, 2010). Therefore, increasing the integration of the energy research networks will accelerate the delivery and deployment of the R&D results so highly requested by the energy sector to achieve their ambitious targets.

This study employs the software UCINET (Borgatti et al., 2002) to evaluate the contribution of the innovation system developed under the EU FPs to the ERA objectives and the SET-Plan technology challenges. The results from this analysis may be used by the European Commission and national research funding agencies in their R&D funding programme definitions and to design the rules for participation. Additionally, the entities participating in FPs may also take advantage of the insights from the SNA to improve their position and embeddedness within the networks. Thus, participants can gain a direction to establish new connections with other entities or projects to enhance their access to and transfer of new knowledge.

The innovation system constructed by the FP7 energy projects is understood as a 2-mode network, in which entities are tied to projects. From this 2-mode network, two 1-mode networks can be deducted: one of the projects linked by shared entities and one of the entities tied by common partners. Fig. 1 illustrates an example of these networks.

Table 2
Total number of participations by entity type and role within the FP7 Energy projects.

Entity type	Total number of participations	Involvement as a coordinator	Involvement as a participant
PUB	105 (3%)	4 (1%)	101 (3%)
HES	874 (23%)	76 (24%)	798 (23%)
REC	874 (23%)	123 (40%)	751 (21%)
PRC	1827 (48%)	101 (32%)	1726 (49%)
OTH	136 (3%)	7 (2%)	129 (4%)
Total	3816	311	3505

Table 3
Ten largest participant countries within the FP7 Energy Theme: participation volume and roles.

	Total number of participations	Involvement as a coordinator	Involvement as a participant
DE – Germany	541	43	498
ES – Spain	386	45	341
UK – United Kingdom	340	29	311
IT – Italy	321	37	284
FR – France	313	30	283
NL – Netherlands	265	22	243
BE – Belgium	191	16	175
DK – Denmark	151	12	139
SE – Sweden	131	11	120
CH - Switzerland	129	6	123
	2768	251	2517

Table 4
Number of projects funded per year at each Activity within the FP7 Energy Theme.

Call year	Total number of funded projects	Renewable Electricity Generation	Renewable Fuel Production	Renewables for Heating and Cooling	CO_2 Capture and Storage Technologies for Zero-Emission Power Generation	Clean Coal Technologies	Smart Energy Networks	Energy Efficiency and Savings	Knowledge for Energy Policy Making	Horizontal Programme Actions
2007	57	22	10	4	5		5	6	5	
2008	39	8	7		2	2	4	8		8
2009	37	12	6	1	9	2	5	2		
2010	37	10	4	2	3	3	3	3		9
2011	45	15	2	8	7	1	4	8		
2012	52	14	5	1	3		9	7		13
2013	44	9	3	1	9	1	13	4		4
	311	**90**	**37**	**17**	**38**	**9**	**43**	**38**	**5**	**34**

Table 5
Consortium composition characteristics within the FP7 Energy Theme.

	Total	2007	2008	2009	2010	2011	2012	2013
Average number of partners	12,3	12,3	11,3	12,9	11,2	10,9	10,7	16,8
Minimum number of partners	4	4	5	5	4	4	4	6
Maximum number of partners	43	30	25	34	27	23	30	43
Standard deviation	6,4	6,4	5,8	6,5	5,2	4,4	5,5	8,2
Coefficient of variation	52%	52%	51%	50%	46%	40%	51%	49%

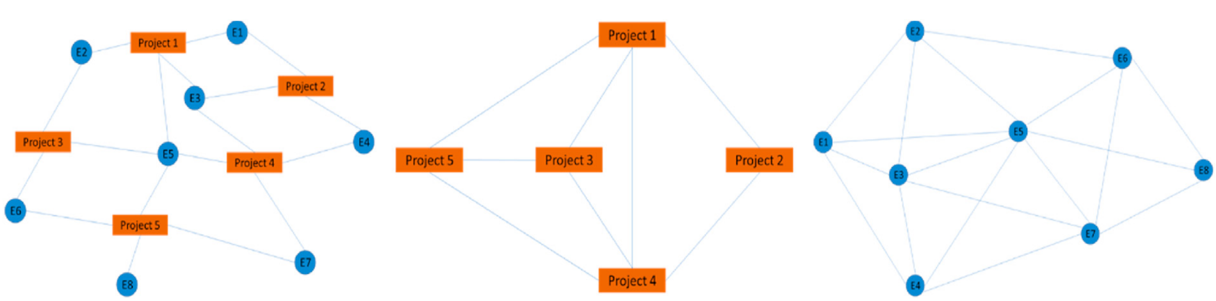

Fig. 1. Illustrative example of a 2-mode network of entities and projects and its associated 1-mode network of projects and 1-mode network of entities.

In the network of entities, the nodes are represented by the participants. An edge connects two entities (nodes) if they participate in the same project. The network is weighted considering that the connection between two entities is as strong as the number of projects in which they both participate.

In the network of projects, the nodes are represented by projects. Two projects (nodes) are connected by an edge if there is one entity participating in both projects. The network is weighted considering that the connection between two projects is as strong as the number of entities that participate in both projects.

In addition, the nodes are characterised using attributes. For the network of entities, the attributes are the entity type (HES; REC, PRC and OTH), the entity country and the entity role within a project (coordinator or participant). For the network of projects, the energy technology specialisation (Activity) of the projects is the primary attribute.

Two different analyses are conducted for both 1-mode networks: (1) a network-level analysis to determine the global cohesion metrics of the network and (2) a node-level analysis to calculate different centrality metrics for each of the nodes.

Regarding the network analysis, the following cohesion metrics were analysed:

- Average degree: calculated as the average degree of all nodes, where the degree is the number of connections of a given node. It is a measure of network activity.
- Average distance: determined as the average distance between all reachable pairs of nodes, where the distance between two connected nodes is the length of the shortest path, calculated as the number of edges it contains. It gives a measure of how compact or dispersed the network is.
- Diameter: calculated as the longest geodesic distance (minimum distance between two nodes) between connected nodes within the network, so the longest length of the shortest paths of all the reachable nodes. It is a measure of the network extent.
- Density: calculated as the total number of ties divided by the total number of possible ties. For a weighted network, like the ones considered in this study, it is the total of all values divided by the number of possible ties.
- Components: defined as sets of connected nodes that are not linked to the rest of the network. It determines the number of non-connected subnetworks.
- Average tie strength between groups: represents the average of the weighted connections of the links between nodes with different attributes. It suggests the strength of the connection between other types of nodes within the network.
- H-Index: corresponds to the maximum number of nodes that have at least the same number of connections to other nodes. It is a measure of network cohesion that avoids the effects of outliers.

Regarding the node-level analysis, also known as dyadic analysis, the following centrality metrics were considered:

- Degree: calculated as the number of nodes connected to a given node. For weighted networks, as in this case, it consists of the sums of the values of the ties. It provides a measure of the immediate probability of a node to receive whatever is flowing through the network, which is knowledge and expertise in this case.
- Closeness: calculated for a given node as the average of the lengths of the shortest paths to every other node of the network. It is a measure of how close a node is to all the other nodes.
- Eigenvector: measures the influence of a node in a network, being a kind of prestige score. For this purpose, relative scores are assigned to all nodes in the network, where connections to high-scoring nodes contribute more to the score of the considered node than do equal connections to low-scoring ones.
- Betweenness: quantifies the number of times that a given node acts as a bridge within the shortest paths between two other nodes. It quantifies the control of a given node on the communications between all the other nodes of a network.

3.3. Networks analysis

3.3.1. Network of projects analysis

3.3.1.1. Network-level analysis: Cohesion. The network is constructed by 311 nodes (projects) and 16 378 ties (connections between two projects by a shared partner of the consortia). The average degree of the network is 52.66, thus, on average, all the consortium members of a given project are participating in 52.66 other different projects in the network. The network has an H-Degree of 75, so there are 75 projects with at least 75 connections to other projects. Only one project, NANOBAK, which has a very specific and narrow scope (low-energy proofing and cooling in SME bakeries), is not connected to the whole network of projects.

The density of the network is 0.17. Therefore, 17% of all the possible connections between projects do exist. The diameter of the network is 5, meaning that the longest connection between two projects goes through four other projects. The average distance between projects is 1.942; thus, on average, pairs of projects are connected by an intermediate project.

From the values above, it may be established that the network is well meshed. Furthermore, if the projects are clustered by Activity (Table 4), the density at each subgraph (projects related to the same Activity) increases far beyond the general density (0.17). The density of each Activity is presented, together with the number of projects for each Activity, in Table 6.

The lowest levels of density appear in Activities (2), (3) and (8). Considering that the Activities of Theme 5 were divided into technology areas, a more detailed analysis of these three activities is performed. Activity (2) involves all generation technologies. Regarding the three technology areas with the highest number of projects, which are 2.1 Photovoltaics, 2.3 Wind and 2.5 Concentrated Solar Power, with 32, 19 and 13 projects each, respectively, the density rises to 0.442, 0.971 and 0.321, respectively. Thus, when the different technologies are analysed separately, Activity (2) Renewable Electricity Generation seems to be much more integrated than analysed as a whole.

This higher integration at the technology area level does not exist in Activities (3) and (8). A total of 22 projects of the 39 involved in Activity three are related to the production of Second-Generation Biofuel from Biomass, with a density of the subgraph being 0.16. It may be caused by a large number of different biofuel feedstocks, production technologies and uses that can be considered, which widens the scope of this area, which has unclear technologies or undetermined leading partners than in other areas. Finally, for Activity (8), the two areas with the largest sets of projects are 8.1 Efficient Energy Use in the Manufacturing Industry and Building Sector and 8.2 Smart Cities and Communities, with 20 and 9 projects, respectively. For the 8.1-related subgraph, the density is 0.147, probably due also to the wide application in many sectors of many energy efficiency technologies, which widens the scope of this area. Nevertheless, the density for Smart Cities is 0.611, so it seems to indicate a high relation between these projects, which may foster the replicability of their results.

3.3.1.2. Node- (project) level analysis: Centrality measures. By developing an analysis of the different nodes and their position within the network, it is possible to identify the projects that contribute to the highest level of network integration. For this purpose, four main measures of centrality were considered:

- Degree: quantifies how many other projects to which a given project is linked; that is, the shared partners with other projects.
- Closeness: associated with the average of the minimum paths that connects a project with the other projects of the network; that is, how close a project is to the others.
- Eigenvector: represents how influential a project is within the network, by considering, in addition to the number of projects to which it is connected, how well these connected projects are in themselves linked to other projects.
- Betweenness: represents the number of times that a project serves as a link within the minimum path between two other projects.

The 20 projects scoring the highest values for the four parameters are presented in Table 7. They have been ordered following by decreasing centrality.

To assess the centrality of the projects of each research Activity or Area, the average of the four normalised measures for all the projects of a given activity and area are calculated and presented in

Table 6
Number of projects and density of the subgraph per activity type within the FP7 Energy Theme.

Activity	Nº of projects	Density
(2) Renewable Electricity Generation	90	0.287
(3) Renewable Fuel Production	37	0.197
(4) Renewables for Heating and Cooling	17	0.309
(5) CO_2 Capture and Storage Technologies for Zero-Emission Power Generation	38	0.856
(6) Clean Coal Technologies	9	0.833
(7) Smart Energy Networks	43	0.864
(8) Energy Efficiency and Savings	38	0.186
(9) Knowledge for Energy Policy Making	5	0.600
(10) Horizontal Programme Actions	34	0.371

Table 7
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	
Top20 projects	Value	Top20 projects	Value	Top20 projects	Value	Top20 projects	Value
CHEETAH	405	CHEETAH	417	CHEETAH	1,0000	CHEETAH	2224,25
ELECTRA	332	ELECTRA	444	IRPWIND	0,8713	STAGE-STE	1314,63
IRPWIND	310	IRPWIND	463	ELECTRA	0,8332	S2BIOM	1261,93
STAGE-STE	274	STAGE-STE	463	INNWIND.EU	0,7402	ELECTRA	1221,02
INNWIND.EU	266	INNWIND.EU	473	TWENTIES	0,6898	INNWIND.EU	1074,63
TWENTIES	238	MACPLUS	477	STAGE-STE	0,6603	IRPWIND	930,52
MACPLUS	219	AVATAR	485	EERA-DTOC	0,6397	EUROBIOREF	816,17
EERA-DTOC	215	COTEVOS	499	BEST PATHS	0,6222	MACPLUS	788,47
AVATAR	210	EERA-DTOC	500	AVATAR	0,4918	EQUIMAR	729,68
BEST PATHS	201	TWENTIES	505	MACPLUS	0,4858	SUPRA-BIO	716,86
COTEVOS	178	HERCULES	508	ECOGRID EU	0,4449	SECTOR	715,08
MARINA PLATFORM	174	MARINA PLATFORM	510	MARINA PLATFORM	0,4317	AVATAR	631,67
ECOGRID EU	173	S2BIOM	513	COTEVOS	0,4267	CORES	583,43
S2BIOM	162	ECOGRID EU	514	GARPUR	0,3972	REACCESS	505,47
HERCULES	158	ROBUST DSC	515	E-HIGHWAY2050	0,3829	H2-IGCC	504,90
OCTAVIUS	158	OPTS	516	S2BIOM	0,3731	PROETHANOL2G	499,35
APOLLON	156	APOLLON	517	NORSEWIND	0,3700	CONSTRUCT-PV	482,48
OPTS	156	PROETHANOL2G	517	HIPRWIND	0,3612	CESAR	459,01
ADDRESS	154	ECCOFLOW	520	APOLLON	0,3600	TWENTIES	436,13
DECARBIT	152	HETMOC	520	SUSPLAN	0,3593	MEDIRAS	430,33

Table 8.

These calculations show how Activity (2), which has a low density, now appears slightly over the average in terms of centrality. Nevertheless, in Activities (3), Renewable Fuel Production, and (8), Energy Efficiency and Savings, which also had low density, also again have low centrality measures.

3.3.2. Network of partners analysis

The network consists of 2 061 nodes (partners) and 50 536 ties (connections between two partners that collaborate in each project). The average degree of the network is 24.52, meaning that on average, a partner is linked with another 24.52 entities through the different projects in which it participated. The network has an H-Degree of 85, so there are at least 85 partners with at least 85 connections to other entities. The network is composed of two components, as the partners participating in the NANOBAK project consortium have no connections with the rest of the network entities.

The density of the network is 0.012; thus, only 1.2% of the possible links between partners exist. The diameter of the network is 6, so the longest connection between two entities goes through five other entities. The average distance between two entities is 2.801, meaning that on average, pairs of partners are connected by 2.8 entities.

To have a detailed analysis of the density, considering the different types of partners presented in the first section, the average tie strength between the different types of partners is calculated and shown in Table 9. This table illustrates how REC have the highest level of collaboration between them, which is the opposite for PRC, whose intrinsic tie is the weakest of the five groups. Regarding the collaboration between different groups, REC appear again as the most interlinked type of entity, having the most substantial ties with all the other types of entities. Remarkably, PRC and PUB have the weakest ties of all the groups. Additionally, the analysis indicates a weak link between HES and PUB.

In terms of project role density, the Project Coordinators density reaches 12%, which is ten times larger than the density of the overall project network. Thus, it seems that the connections between the Project Coordinators actively contribute to the global network cohesion.

Table 10 presents the average tie strength between the different partner countries. Regarding the relations between entities from the same country, Danish partners have the highest collaboration among them within European projects, with a density of 0.0894. This internal collaboration rate is more than twice the one of next country, Sweden, with a 0.0437. There may be national programmes that foster this national collaboration, or perhaps the national network is stronger than in other countries. The lowest collaboration rates between entities from the same country are in Germany (0.0148), France (0.0232), Italy (0.0254) and the United Kingdom (0.0262).

Regarding the collaboration between entities from the top ten participant countries, which may be related to the actual European scope of the network, three groups of pairs of countries may appear in terms of their average tie strength: one with the strongest ties, one with the weakest links and one in the middle. The pairs of

Table 8
Average centrality measures of the FP7 Energy Theme network of projects of each activity and area.

Activities and Areas	Number of projects	Average Degree	Average Closeness	Average Eigenvector	Average Between
(2) Renewable Electricity Generation	90	2,28E-01	5,21E-01	4,30E-02	3,08E-03
Photovoltaics	32	2,32E-01	5,28E-01	4,21E-02	2,92E-03
Biomass	6	2,02E-01	5,15E-01	3,79E-02	2,00E-03
Wind	19	2,67E-01	5,24E-01	5,54E-02	3,73E-03
Geothermal	2	2,45E-01	5,32E-01	3,55E-02	2,91E-03
Concentrated Solar Power	13	1,83E-01	5,12E-01	3,28E-02	2,08E-03
Ocean	9	2,19E-01	5,01E-01	4,24E-02	3,69E-03
Hydro	3	9,14E-02	4,89E-01	1,14E-02	1,06E-03
Cross-Cutting Issues	6	2,83E-01	5,45E-01	5,56E-02	5,21E-03
(3) Renewable Fuel Production	**37**	**1,36E-01**	**4,88E-01**	**2,23E-02**	**3,11E-03**
First-Generation Biofuel from Biomass	1	4,74E-01	5,96E-01	7,88E-02	7,81E-03
Second-Generation Fuel from Biomass	22	9,78E-02	4,77E-01	1,51E-02	1,76E-03
Biorefinery	5	1,06E-01	4,75E-01	1,94E-02	3,11E-03
Biofuels from Energy Crops	3	8,92E-02	4,72E-01	1,42E-02	6,62E-04
Alternative Routes to Renewable Fuel Production	2	1,94E-01	5,27E-01	2,46E-02	2,37E-03
Biofuel Use in Transport	1	1,94E-02	3,93E-01	8,96E-04	0,00E+00
Cross-Cutting Issues	3	4,02E-01	5,76E-01	7,43E-02	1,54E-02
(4) Renewables for Heating and Cooling	**17**	**1,73E-01**	**5,04E-01**	**3,05E-02**	**2,91E-03**
Low/Medium Temperature Solar Thermal Energy	13	1,80E-01	5,08E-01	3,12E-02	3,26E-03
Biomass	2	1,90E-01	5,26E-01	3,67E-02	2,59E-03
Geothermal Energy	1	1,81E-01	5,21E-01	3,82E-02	1,16E-03
Cross-Cutting Issues	1	3,23E-02	3,93E-01	1,64E-03	6,53E-04
(5) CO_2 Capture and Storage Technologies for Zero-Emission Power Generation	**38**	**2,65E-01**	**5,36E-01**	**4,34E-02**	**2,84E-03**
CO2 Capture	18	2,99E-01	5,49E-01	5,11E-02	3,51E-03
CO2 Storage	15	2,49E-01	5,27E-01	3,78E-02	2,35E-03
Cross-Cutting and Regulatory Issues	5	1,88E-01	5,14E-01	3,22E-02	1,86E-03
(6) Clean Coal Technologies	**9**	**2,70E-01**	**5,38E-01**	**4,79E-02**	**3,86E-03**
Conversion Technologies for Zero-Emission Power Generation	9	2,70E-01	5,38E-01	4,79E-02	3,86E-03
(7) Smart Energy Networks	**43**	**2,70E-01**	**5,33E-01**	**5,05E-02**	**2,52E-03**
Development of Inter-Active Distribution Energy Networks	15	2,70E-01	5,30E-01	5,07E-02	2,42E-03
Pan-European Energy Networks	10	3,19E-01	5,39E-01	6,69E-02	2,95E-03
Cross-Cutting Issues and Technologies	18	2,42E-01	5,33E-01	4,11E-02	2,36E-03
(8) Energy Efficiency and Savings	**38**	**1,39E-01**	**4,83E-01**	**2,46E-02**	**1,45E-03**
Efficient Energy Use in the Manufacturing Industry and Building Sector	20	1,83E-01	4,99E-01	3,36E-02	1,90E-03
High Efficiency Poly-Generation	4	5,24E-02	4,50E-01	7,59E-03	6,71E-04
Innovative Integration of Renewable Energy Supply and Energy Efficiency in Large Communities: CONCERTO	4	7,90E-02	4,55E-01	1,38E-02	5,88E-04
Innovative Strategies for Clean Urban Transport: CIVITAS-PLUS	1	6,45E-03	3,34E-01	9,02E-05	2,72E-05
Smart Cities and Communities	9	1,20E-01	4,91E-01	1,97E-02	1,35E-03
(9) Knowledge for Energy Policy Making	**5**	**4,92E-01**	**5,92E-01**	**9,55E-02**	**1,31E-02**
Knowledge Tools for Energy-Related Policy Making	5	4,92E-01	5,92E-01	9,55E-02	1,31E-02
(10) Horizontal Programme Actions	**34**	**2,38E-01**	**5,29E-01**	**4,34E-02**	**3,79E-03**
Integration of the European Energy Research Area	12	3,71E-01	5,60E-01	7,44E-02	7,59E-03
Other Horizontal Actions	22	1,65E-01	5,13E-01	2,65E-02	1,72E-03
Total average	**311**	**2,20E-01**	**5,18E-01**	**3,97E-02**	**3,03E-03**

Table 9
Average tie strength between the different types of partners in the FP7 Energy Theme.

Type	Public Sector	Higher Education	Research Organisations	Private Companies	Others
Public Sector	3,10E-02	8,43E-03	1,64E-02	7,12E-03	1,44E-02
Higher Education	8,43E-03	2,99E-02	3,88E-02	1,26E-02	1,80E-02
Research Organisations	1,64E-02	3,88E-02	6,80E-02	1,63E-02	2,85E-02
Private Companies	7,12E-03	1,26E-02	1,63E-02	7,68E-03	8,90E-03
Others	1,44E-02	1,80E-02	2,85E-02	8,90E-03	1,72E-02

countries for each group is presented in Table 11, together with the value of the tie strength.

3.3.2.1. Node- (entity) level analysis: Centrality measures. By developing an analysis of the different nodes and their position within the network, it is possible to identify the entities that contribute to a high network integration level. The same four main measures of centrality were considered as for the network of projects, which, in this context, may be interpreted as follows:

- Degree: quantifies the number of other partners to which a given entity is linked; that is, the shared projects between partners.
- Closeness: associated with the average of the minimum paths that connects an entity to the other entities of the network; that is, how close a partner is to the others.
- Eigenvector: represents how influential an entity is within the network, where in addition to the number of entities to which it is connected, it indicates how well these connected entities are themselves linked to other partners.

Table 10
Average tie strength between the partner's countries in the FP7 Energy Theme.

Country	DE	ES	UK	IT	FR	NL	BE	DK	SE	CH
DE	1,48E-02	1,38E-02	1,24E-02	1,23E-02	1,42E-02	1,30E-02	1,37E-02	1,44E-02	1,19E-02	1,68E-02
ES	1,38E-02	3,20E-02	1,28E-02	1,70E-02	1,70E-02	1,07E-02	1,86E-02	1,42E-02	1,57E-02	1,33E-02
UK	1,24E-02	1,28E-02	2,62E-02	1,35E-02	1,44E-02	1,59E-02	1,59E-02	1,63E-02	1,27E-02	9,07E-03
IT	1,23E-02	1,70E-02	1,35E-02	2,54E-02	1,39E-02	1,15E-02	1,61E-02	1,01E-02	1,25E-02	1,44E-02
FR	1,42E-02	1,70E-02	1,44E-02	1,39E-02	2,32E-02	1,82E-02	1,81E-02	1,53E-02	1,37E-02	2,02E-02
NL	1,30E-02	1,07E-02	1,59E-02	1,15E-02	1,82E-02	3,43E-02	1,49E-02	1,41E-02	1,20E-02	1,42E-02
BE	1,37E-02	1,86E-02	1,59E-02	1,61E-02	1,81E-02	1,49E-02	3,23E-02	2,67E-02	1,14E-02	1,10E-02
DK	1,44E-02	1,42E-02	1,63E-02	1,01E-02	1,53E-02	1,41E-02	2,67E-02	8,94E-02	3,16E-02	7,94E-03
SE	1,19E-02	1,57E-02	1,27E-02	1,25E-02	1,37E-02	1,20E-02	1,14E-02	3,16E-02	4,37E-02	1,07E-02
CH	1,68E-02	1,33E-02	9,07E-03	1,44E-02	2,02E-02	1,42E-02	1,10E-02	7,94E-03	1,07E-02	3,33E-02

Table 11
Average tie strength between the different pairs of partner countries in the FP7 Energy Theme.

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
DK	SE	3,16E-02	NL	BE	1,49E-02	ES	UK	1,28E-02
BE	DK	2,67E-02	UK	FR	1,44E-02	UK	SE	1,27E-02
FR	CH	2,02E-02	IT	CH	1,44E-02	IT	SE	1,25E-02
ES	BE	1,86E-02	DE	DK	1,44E-02	DE	UK	1,24E-02
FR	NL	1,82E-02	ES	DK	1,42E-02	DE	IT	1,23E-02
FR	BE	1,81E-02	NL	CH	1,42E-02	NL	SE	1,20E-02
ES	IT	1,70E-02	DE	FR	1,42E-02	DE	SE	1,19E-02
ES	FR	1,70E-02	NL	DK	1,41E-02	IT	NL	1,15E-02
DE	CH	1,68E-02	IT	FR	1,39E-02	BE	SE	1,14E-02
UK	DK	1,63E-02	DE	ES	1,38E-02	BE	CH	1,10E-02
IT	BE	1,61E-02	DE	BE	1,37E-02	SE	CH	1,07E-02
UK	NL	1,59E-02	FR	SE	1,37E-02	ES	NL	1,07E-02
UK	BE	1,59E-02	UK	IT	1,35E-02	IT	DK	1,01E-02
ES	SE	1,57E-02	ES	CH	1,33E-02	UK	CH	9,07E-03
FR	DK	1,53E-02	DE	NL	1,30E-02	DK	CH	7,94E-03

- Betweenness: represents the number of times that an entity serves as a link within the shortest path between two other partners.

The 20 partners scoring the highest values for these four parameters are presented in Table 12. They are presented in descending order.

To assess the centrality of the partners from different countries, the average of the four normalised measures for all the entities from the countries with the highest number of projects (Table 3) has been calculated and presented in Table 13.

Danish entities have the highest number of connections with other countries, including links to influential entities from other member states, as they also have the highest eigenvector value. Nevertheless, the Danish do not have the top position closeness value, thus having the longest paths to get connected.

Spanish entities have high degree, closeness and eigenvector values, and the top closeness value. Therefore, although they rank in the middle in terms of betweenness, they enjoy a good centrality position within the network.

Remarkably German entities, which have the largest number of projects, are in the last position of the top 10 in terms of the degree metric. This may be caused by repeated participation with the same partners.

To assess the centrality of the different types of partners, the average of the four closeness measures were calculated and presented in Table 14. Clearly, REC have the highest values in the four centrality measures, thus confirming their prominent role in the programme.

Table 15 presents the centrality measures for the roles within the consortium. Entities that acted as coordinators have a betweenness more than 20 times higher than those that have not. Additionally, in the degree (number of connected entities) and eigenvector measures, coordinators rank between 3 and 5 times higher. Nevertheless, they have comparable closeness values.

4. Results

4.1. Summary of the participants and projects' characteristics

This study assesses the main characteristics of the participants under the FP7 Energy Theme with a threefold approach. First, the different types of entities were evaluated in terms of participation rates and roles within the projects. From the three main types of participants, REC show the highest coordination rate, coordinating 40% of all the projects while accounting for only 23% of all participation. PRC are the largest participants, accounting for 48% of the participations, while they hold a lower coordination rate, being coordinators of 32% of the projects.

Second, the results indicated that 81% of the project coordinators come from ten countries, the top five being Spain, Germany, Italy, the United Kingdom and France. Regarding the coordination rate (number of coordinated projects per participations in each country), Spain is the highest, followed by Italy and France. Despite being the largest participant, Germany is in the ninth position in terms of coordination rate.

Third, a discussion of the coordination role was presented. The coordination role is usually understood as higher quality participation, as it involves both a greater amount of funding and greater control of the project and visibility. Nevertheless, coordination has the drawback of its associated bureaucracy. Factors like technology specialisation, position within the innovation value chain and

Table 12
Centrality measures of the network of entities within the FP7 Energy Theme, 20 highest values for degree, closeness, eigenvector and betweenness.

Degree		Closeness		Eigenvector		Between	
Top20 entities	Value	Top20 entities	Value	Top20 entities	Value	Top20 entities	Value
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	719	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	3778	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	1,0000	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	299490,5
DANMARKS TEKNISKE UNIVERSITET	535	FUNDACION TECNALIA RESEARCH & INNOVATION	3981	DANMARKS TEKNISKE UNIVERSITET	0,7952	FUNDACION TECNALIA RESEARCH & INNOVATION	140734,4
FUNDACION TECNALIA RESEARCH & INNOVATION	489	STICHTING ENERGIEONDERZOEK CENTRUM NEDERLAND	3995	STICHTING ENERGIEONDERZOEK CENTRUM NEDERLAND	0,5905	TEKNOLOGIAN TUTKIMUSKESKUS VTT	110853,9
STICHTING ENERGIEONDERZOEK CENTRUM NEDERLAND	457	DANMARKS TEKNISKE UNIVERSITET	4017	FUNDACION TECNALIA RESEARCH & INNOVATION	0,5615	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	108641,2
RICERCA SUL SISTEMA ENERGETICO - RSE SPA	406	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	4020	SINTEF ENERGI AS	0,4679	STICHTING ENERGIEONDERZOEK CENTRUM NEDERLAND	96804,1
IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	389	TEKNOLOGIAN TUTKIMUSKESKUS VTT	4063	RICERCA SUL SISTEMA ENERGETICO - RSE SPA	0,4213	DANMARKS TEKNISKE UNIVERSITET	91849,9
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	380	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	4100	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	0,3775	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	91630,6
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	363	RICERCA SUL SISTEMA ENERGETICO - RSE SPA	4131	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	0,3640	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	85197,5
SINTEF ENERGI AS	359	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	4183	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	0,3626	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	84825,5
TEKNOLOGIAN TUTKIMUSKESKUS VTT	354	FUNDACION CENER	4183	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE	0,3585	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	69514,4
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	309	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	4194	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	0,3463	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	67771,1
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE	293	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE	4197	STIFTELSEN SINTEF	0,3455	CONSIGLIO NAZIONALE DELLE RICERCHE	67205,9
STIFTELSEN SINTEF	292	UNIVERSITAET STUTTGART	4203	CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION	0,3439	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE	55142,5
ELECTRICITE DE FRANCE	273	CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION	4211	TEKNOLOGIAN TUTKIMUSKESKUS VTT	0,3428	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	54708,8
FUNDACION CENER	269	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	4219	UNIVERSITY OF STRATHCLYDE	0,3352	TECHNISCHE UNIVERSITEIT DELFT	54454,5
CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION	252	STIFTELSEN SINTEF	4225	FUNDACION CENER	0,3048	RICERCA SUL SISTEMA ENERGETICO - RSE SPA	52399,6
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	250	SINTEF ENERGI AS	4238	CENTRO DE INVESTIGACIONES ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS-CIEMAT	0,2761	UNIVERSITAET STUTTGART	48914,5
TECHNISCHE UNIVERSITEIT DELFT	248	ELECTRICITE DE FRANCE	4245	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	0,2580	FUNDACION CENER	47363,3
EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	233	TECHNISCHE UNIVERSITEIT DELFT	4246	ELECTRICITE DE FRANCE	0,2434	CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION	45718,7
UNIVERSITY OF STRATHCLYDE	231	JRC -JOINT RESEARCH CENTRE-EUROPEAN COMMISSION	4249	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	0,2384	SOFIA UNIVERSITY ST KLIMENT OHRIDSKI	44105,4

access to other research funds may also affect the assumption of the coordination role.

Once the taxonomy of the participating entities was analysed, a characterisation of the set of projects was developed. With a comparable number of projects every year throughout the programme, there is a clear focus on renewable electricity generation technologies, accounting for 29% of the total number of projects. In this respect, 79% of the funded projects covered five technology areas: renewable electricity generation (29%), smart energy networks (14%), energy efficiency (12%), CO_2 carbon capture and storage (12%) and renewable fuel production (12%). The average number of partners per consortium is 12.3, with a standard deviation of 6.4. Notably, in the last year of the programme (2013), there is a significant increase in the average number of participants, reaching 16.8, probably showing a transition towards the next H2020 research program.

The set of projects considered in this study is comparable to the samples used in prior studies related to the other FP7 research

Table 13
Countries with the highest normalised centrality measures: degree, closeness, eigenvector and betweenness in the FP7 Energy Theme.

Degree		Closeness		Eigenvector		Between	
Top10 entities	Value	Top10 entities	Value	Top10 entities	Value	Top10 entities	Value
DK	1,75E-02	ES	3,68E-01	DK	1,29E-02	CH	1,52E-03
BE	1,55E-02	BE	3,67E-01	ES	1,07E-02	NL	1,24E-03
ES	1,53E-02	FR	3,66E-01	BE	1,05E-02	DK	1,21E-03
FR	1,46E-02	NL	3,62E-01	FR	9,32E-03	DE	1,07E-03
UK	1,40E-02	UK	3,62E-01	UK	8,80E-03	ES	1,06E-03
IT	1,38E-02	IT	3,60E-01	NL	8,66E-03	FR	9,33E-04
NL	1,35E-02	DE	3,60E-01	DE	8,55E-03	IT	9,11E-04
CH	1,30E-02	DK	3,56E-01	IT	8,22E-03	UK	8,76E-04
SE	1,29E-02	CH	3,56E-01	CH	7,47E-03	BE	8,02E-04
DE	1,23E-02	SE	3,53E-01	SE	5,66E-03	SE	6,27E-04

Table 14
Average centrality measures for the five types of entities in the network within the FP7 Energy Theme (PUB, HES, REC, PRC and Others).

Entity Type	Average Degree	Average Closeness	Average Eigenvector	Average Between
PUB	9,71E-03	3,44E-01	3,70E-03	6,93E-05
HES	1,85E-02	3,75E-01	1,23E-02	1,81E-03
REC	2,64E-02	3,79E-01	2,08E-02	3,53E-03
PRC	9,51E-03	3,52E-01	5,18E-03	2,25E-04
OTH	1,32E-02	3,61E-01	7,71E-03	4,95E-04

Table 15
Average centrality measures for entities acting as coordinators or as participants within the EFP7 Energy Theme.

Role	Average Degree	Average Closeness	Average Eigenvector	Average Between
Coordinators	3,90E-02	3,92E-01	3,00E-02	6,25E-03
Participants	1,03E-02	3,56E-01	5,86E-03	2,96E-04

areas. Muñiz and Cuervo (2018) examined the FP7 projects within the ICT Theme under the Area 'ICT for energy efficiency'. They considered 119 research projects, with 1 141 total partners across 43 countries, with Spain, Germany and Italy as the largest participants, as it was found in the present study. Fernandez de Arroyabe and Schuman (2021) studied the networks associated with Agri-Food FP7 projects funded under the FP7 KBBE Theme, which included 224 research projects and 1 529 organisations, with Spain, the United Kingdom and Germany, the largest participants. Kang and Hwang (2016) used a sample that included Energy projects from FP7 and FP6 together with projects funded under the Intelligent Energy for Europe (IEE) programme that targets non-technical barriers. This larger sample of 505 projects and 3 136 participants revealed the links between both Programmes (FPs and IEE), which were merged within the latest Horizon 2020 Programme. In this case, the Coordination and Support Actions (CSA) funding scheme was used to give continuity to the IEE Programme. Considering these particularities of the project samples used in the related literature, the results obtained herein may also be comparable, as will be presented in this section and the following one.

After having analysed the set of projects and entities, their associated networks were constructed and assessed, considering a twofold approach to evaluate (1) the network cohesion and (2) their constituent node (for entities or projects) centrality.

4.2. Summary of the analysis of the network of projects

The network of projects shows high cohesion, being well-meshed and with only one disconnected project from the 311 projects analysed. On average, all the members of a given consortium participated in 52.66 other projects, and the average network density was 17%. When the projects addressing each technology area are considered separately, the cohesion metrics increase considerably, with a maximum density of 86% in the case of smart energy networks and an average density of the five technology areas with the highest number of projects of 47.8%. Nevertheless, the density of the network related to Energy Efficiency and Savings Technologies seems rather low, with a value of 18%. This finding reveals one of the key challenges of the EU to deliver its energy efficiency targets, which currently show an untapped potential (International Energy Agency, 2017) due to, among other factors, fragmentation at the research, policy and market levels.

When the individual projects are assessed within the network, six projects are in the top 10 of the four centrality metrics considered (CHEETAH, ELECTRA, IRPWIND, STAGE-STE, INNWIND.EU and MACPLUS). Four out of these six projects were funded under a scheme that combined collaborative research with coordination and support activities. The European Commission promoted this scheme within the FP7 Energy Theme with the aim of increasing cooperation along the innovation value chain, decreasing fragmentation and fostering market uptake (European Commission, 2016), which is reflected in the network centrality values achieved by these projects. Additionally, when the different specialisation areas are considered, the average centrality metrics of the projects related to the Energy Efficiency and Savings area are the lowest, thus in line with the lowest network density already detected for these technologies. Although this may be due to the large number of technologies, applications and sectors involved in the Energy Efficiency Area, the research performance could be fostered by specific actions to achieve higher integration of the technology trajectories, and thus the project network.

Although existing studies did not address the network of project properties separately, it can be deducted from their 2-mode network analysis that the results presented in this paper are in line with the previous works. Fernandez de Arroyabe and Schuman (2021) concluded that the European innovation system topology for the Agri-Food program, in terms of network centrality and node connectivity, meets the objectives of increasing competitiveness, since it shows a clear technological trajectory derived from its centrality. This is a unique, concentric network, which allows each node to access all kinds of information. This study found that for the Energy Theme of FP7, the whole network is almost entirely connected, having a network core composed of a small number of projects that serve as a knowledge hub for facilitating technological trajectories. Furthermore, when focusing on the different research areas under the Energy Theme, this study reached the same conclusions for the Energy Efficiency Area as Muñoz and Cuervo (2018). They reported a poorly connected network due to the diversity of technological trajectories in the fields of energy efficiency in their study related to the 'ICT for energy efficiency' area under the ICT Theme.

4.3. Summary of the analysis of the network of entities

The network of entities shows a lower cohesion than the network of projects. On average, each entity is linked with another 24.5 projects. The project's coordinators had a ten times larger density than the overall network, being key actors in the network cohesion and forming the network core. The network density is 1,2%, so only 1,2% of the possible connections between the partners exist. The diameter of the network is 6, and the average distance between entities is 8.

When the collaboration between different types of entities is considered, REC are the most frequent collaborators, having strong ties with PRC and HES. REC and HES show a clear preference to collaborate with entities of their same type. Nevertheless, PRC have the opposite behaviour, with the lowest rate of collaboration with other PRC.

Regarding the collaboration between entities from a country-based perspective, the collaboration rates between entities from the same country are the highest. Additionally, some countries clearly show the strongest links with another four or five countries (e.g. France, Denmark and Spain) and some have a more geographically dispersed collaboration network (e.g. Sweden, Switzerland, Italy or the Netherlands).

When the individual entities' centrality within the network is assessed, there are six entities with a prominent position (scoring in the top 10 of the four centrality metrics considered). Four of them are REC (Fraunhofer, Tecnalia, ECN and CNRS) and two are HES (DTU and Imperial College). There is only one PRC in the top 20 values of the four centrality metrics: Electricité de France.

In the centrality measures of the entities analysed from the country perspective, Danish and Spanish entities appear in the most relevant positions, followed by Belgium, Switzerland, the Netherlands and the United Kingdom. Germany, despite being one the most significant participant, is not in this list, an effect that may be linked to its low coordination rate.

Regarding the centrality metrics for the different type of entities, REC are the highest, followed by HES and PRC. This result may be related to the coordination role often assumed by REC, as the average influence in the network (eigenvector) for this role is more than five times higher than for the participants, while reaching a 21 times higher betweenness centrality.

The cohesion metrics obtained are similar to the previous studies of FP7, as the network presents a low density with a high level of clustering (Muñiz and Cuervo, 2018; Kang and Hwang, 2016). Arranz et al. (2020) determined that this effect may occur because research consortia are repeatedly established with the same partners, who form a core within the network, consisting mainly of by project coordinators and REC in the Energy Theme. Nevertheless, in the case of energy, instead of hampering the transmission of information and cohesion, cohesion may be reinforced by the existence of these core participants, which may serve as a hub for the whole network in terms of knowledge gathering and distribution.

Thus, although there is not a strong connection of many participants, the entities are interconnected through a network core composed of the more active participants. As established by Fernandez de Arroyabe et al. (2021), this changes the transfer model between research performers and companies from a distributed model, in which the number of links between university and company prevails, to a model of trajectories, where companies are indirectly linked to the most successful REC through a hub of knowledge consisting of the core network partners.

Finally, in terms of regional cohesion, the results are in line with those of Fernandez de Arroyabe for the Agri-Food Theme under FP7 (Fernandez de Arroyabe et al., 2021), showing lower levels of cohesion between countries than within countries. This result produces an effect of clustering within each country, with a network core that is geographically distributed along the EU, which may contribute to the ERA realisation.

5. Discussion and conclusions

5.1. Discussion

This study has important *theoretical implications* for the efficiency of innovation systems. First, this study provided empirical evidence of how the EU research consortia funded by the FP7 Energy Theme created a network of relationships that forms an innovation system ready to enable knowledge exchange and collaboration, thus supporting the execution of the EU energy research policy goals. Based on these findings and in line with previous works (Fernandez de Arroyabe et al., 2021; Muñiz and Cuervo, 2018), this study focused on how the properties of the network of projects and the network of entities created by the consortia affect the efficiency of the innovation system. Second, unlike previous works that focused on analysing the institutional and political effect of the various actions on achieving the objectives of the innovation policy (Gallego-Alvarez et al., 2017; DiMaggio and Powell, 1983), this work assessed how these networks can deliver the EU energy research policy targets, defined mainly by the SET-Plan and the ERA. In line with Fernandez de Arroyabe et al. (2021), who studied the efficiency of the EU FPs for the Agri-Food sector, the use of SNA has been proven as a powerful tool for the construction and analysis of the networks built under the FP7 Energy Theme. More specifically, the results emphasise that using the nominalist approach (Wasserman and Faust, 1994) and considering two networks—projects and partners—with a twofold scope of analysis—network cohesion and node centrality—provides insights about how the EU energy research ecosystem is functioning. Third, the conception of the node as an active part of the network led to results linking the node centrality measures to their attributes (research area for the project nodes and activity type, country and role in the project for the organisation nodes), and thus the ability of the different actors to disseminate, collaborate and transfer information. Therefore, this work empirically confirms the results of Fernandez de Arroyabe et al. (2021), Kang and Hwang (2016), Kalthaus and Graf (2016) and Muñiz and Cuervo (2018) showing how the position and attributes of the nodes in the network determine the network topology and therefore the effectiveness of the innovation system. From an operational point of view, the study of the centrality of the nodes (*degree, closeness, eigenvector* and *betweenness*) allows researchers to determine the effectiveness of the objectives of the innovation policy (*competitiveness, cohesion* and *information* *transfer*). Finally, this study extends previous works that analysed the influence of cohesion as a topological property of the network (Muñiz et al., 2018; Scherngell and Barber, 2009) or the work of de Marco et al. (2020), who studied the problem of integrating SMEs in innovation systems, showing that not only is cohesion an essential property in innovation efficiency, but that it is also necessary to consider both the centrality and the connectivity of the network.

Moreover, the results have important *policy-making implications* and for *EU energy policy*, helping to explain how the objectives of the energy EU innovation system are achieved. Regarding transnational cooperation, the work shows that FP7 contributed to developing well-meshed and integrated networks of partners and projects across the EU. These results corroborate previous studies that highlighted FPs as a key element in fostering transnational cooperation within the EU framework (see, e.g. Barre et al., 2013). However, regarding the efficiency of transnational cooperation, several concerns echoed widely in the literature were found. First, in line with previous works, such as Scharpf (2010), who pointed out how FPs are characterised by a structural asymmetry in the involvement of member states, the results corroborate the existence of this asymmetry, showing that participation is concentrated in only ten countries, which may cause different levels of access to new energy technologies. Second, the results showed a clear preference of the participants to collaborate with entities from the same country, which may hamper the full potential for transnational collaboration. The joint project literature (Hagedoorn et al., 2000) already highlighted how affinities between partners are the key to consortia formation. Third, regarding cooperation between different types of entities, the results indicated that PRC, which are the largest players, are less prone to collaborate with other PRC, preferring instead to cooperate with REC or HES. This finding has been highlighted in previous works (Grohnheit et al., 2003; Husted et al., 2007), showing that it may be a symptom of competition, which makes it difficult to share knowledge with their competitors. Moreover, the results revealed the high level of centrality of REC. In line with Fernandez de Arroyabe et al. (2021), this result implies their important role in transferring scientific knowledge. The analysis shows that they have a substantial role in consortia coordination, maintaining strong ties with private companies. Therefore, this study has an important implication in terms of cohesion (Fernandez de Arroyabe et al., 2021; Pandza et al., 2011), highlighting how the singularities of the energy sector make the objectives of the energy policy of cohesion and knowledge transfer between companies difficult. Finally, the results emphasise that the projects funded by FP7 contributed to the different technology targets established by the SET-Plan. Remarkably, many well-connected projects address the fields of renewable electricity generation and smart grids, especially in each technology area. Nevertheless, in the field of energy savings and in renewable fuel production, the network cohesion metrics are low. These results are in line with a better execution of the 2020 EU renewables goals, but a poorer achievement of the energy-saving targets.[4] Therefore, in line with Fernandez de Arroyabe et al. (2021), this study demonstrated that the application of SNA is a powerful instrument for EU policies, identifying the efficiency of the various programmes and lines of research.

5.2. Conclusions

This paper analysed an EU innovation system and its impact on the achievement of the objectives of the EU's energy policy. It is assumed that research consortia is the mechanism that the EU uses for the development of its energy policy, which is creating a network of relationships between projects and partners, forming the EU innovation system.

From the *theoretical perspective*, the first group of contributions extends the literature on innovation systems in terms of its modelling and effectiveness. The findings indicated the convenience of conceiving the innovation system as a network of relationships between entities and projects to understand how the effectiveness of this innovation system is related to the node attributes as well as their position within the network. Moreover, the study revealed how the structural properties of the network vary in each research area, affecting the centrality and cohesion, both in terms of knowledge transfer and the geographical cohesion between countries. The second group of *theoretical contributions* is rooted in energy research and development policies. A correct evaluation of the energy policy must analyse the topology and structural properties of the network. First, the cohesion of the innovation systems allows an assessment of the viability of potential collaborations, transfer of information and knowledge, and geographic cohesion. Second, the centrality metrics of the innovation system allow the evaluation of energy policies in terms of competitiveness. Lastly, the connectivity of the network allows an analysis of the transversality between the different research programmes as a way to promote synergistic effects between them.

This study has strong *implications for management and policy making*. First, the FPs should focus on increasing the cohesion of the activities related to Energy Efficiency and Savings to avoid fragmentation, improving the collaboration between projects and transversal actions. Moreover, the involvement in these actions of the project coordinators, particularly REC, may be beneficial, as they are the most influential nodes of the network. Additionally, particular attention should be paid to enhancing the collaboration between countries with different levels of performance to seek reciprocal benefits. All the proposed measures that aim for higher cohesion of the networks may be carefully assessed to avoid promoting a closed R&D ecosystem, which may be a pernicious effect. In addition, the network cohesion criteria should be balanced with open R&D competitiveness. Second, policymakers and FP participants may apply the proposed method and findings. European policymakers may consider these results in order to reshape the next FPs to foster the achievement of the ERA and SET-Plan goals. In addition, national policymakers may rely on this study to design national support programmes to facilitate the participation of their national entities. Finally, individual participants can apply the results of this study to select their consortium partners to enhance their network position, and thus improving their access to knowledge and research capabilities.

Finally, like any other, this study has limitations. The empirical study focused on the FP7 Cooperation Theme 5 Energy projects funded under a Collaborative Project Scheme; thus, further research should analyse Horizon 2020, the successor of FP7, which should be performed to assess the progress of the energy R&D ecosystem. Moreover, subsequent works should focus on the need to establish reference values to determine the most convenient levels of cohesion and centrality for each research area, considering the different type of actors and transnational cooperation.

[4] To judge the cohesion metrics obtained, it is necessary to rely on the review of the networks constructed for the 10 Themes of the FP7 Cooperation Programme (European Commission, 2015b). The Energy Theme has a density almost seven times higher than the overall average of the FP7 Cooperation Programme. The fact that the electricity generation, transmission and distribution sectors are regulated (Cambini et al., 2016), together with a still incomplete unbundling process for increasing market competition (Gugler et al., 2017), may have contributed to this integration of the R&D activities. Nevertheless, when each technology is assessed, the networks related to the energy efficiency and savings technology area show lower cohesion levels than, for example, the renewable energy-related technologies (Kang and Hwang 2016), which could also be related to the high number of market, policy and structural barriers present in this sector (Deloitte, 2016).

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 Fernández 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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Appendix A. Supplementary data

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