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REDES Y SISTEMAS DE INNOVACIÓN EN EL SECTOR DE LA ENERGÍA

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A mis padres, por su apoyo incondicional y
fomento de mi vocación por aprender y
seguir mejorando cada día.

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Contenido

1. Introducción

Esta tesis evalúa, desde distintos puntos de vista, cómo **el impulso institucional contribuye al desarrollo de los sistemas de innovación para el cumplimiento de los objetivos políticos en materia de innovación y energía**. Para realizar esta evaluación se consideran las redes de innovación promovidas por la Unión Europea mediante la financiación de consorcios de investigación en el ámbito energético. Estos consorcios generan redes de innovación en las que las entidades participantes colaboran en diferentes proyectos, y que se pueden caracterizar mediante técnicas de Análisis de Redes Sociales (ARS). De esta manera, se evalúan tanto propiedades de las redes a nivel global utilizando métricas de cohesión, como el rol de cada uno de sus nodos, mediante métricas de centralidad. La relación entre las propiedades de estas redes y el funcionamiento de los sistemas de innovación se aborda en el marco de tres trabajos ya publicados en revistas de investigación:

- **El primer trabajo, presentado en Calvo-Gallardo et al. (2021),** estudia las propiedades de las redes construidas por los consorcios financiados en ámbito energético por el Séptimo Programa Marco de I+D+i de la Unión Europea, para evaluar su contribución a los objetivos de las políticas energéticas y de innovación comunitarias. Mediante la financiación de estos consorcios, la Unión Europea genera redes de entidades y de proyectos que, a su vez, conforman el sistema de innovación. Aunque este sistema de innovación se ha estudiado por diferentes autores desde distintas perspectivas, pocos estudios han evaluado las propiedades de las redes subyacentes. En este trabajo, se contribuye a cubrir este déficit en la literatura aplicando técnicas de Análisis de Redes Sociales para determinar la cohesión de las redes, así como la centralidad de sus nodos. Se contribuye por tanto a la literatura existente sobre sistemas de innovación en los ámbitos del modelado y evaluación del desempeño. Los resultados indican que la efectividad de los sistemas de innovación depende de la distribución geográfica de los consorcios, así como de la diversidad y características de los participantes; revelando además diferencias relevantes en la eficacia para cada área tecnológica dentro del ámbito de la energía. Finalmente, tomando en cuenta estos resultados, se proponen recomendaciones para el desarrollo de nuevas políticas, así como para participantes en estos programas de investigación.
- **El segundo trabajo, recogido en Calvo-Gallardo et al. (2022a),** estudia cómo el impulso institucional desarrollado por la Unión Europea ha influenciado la evolución del sistema de innovación europeo en el ámbito de la energía. Considerando la contribución que desempeñan los sistemas de innovación en el desarrollo de nuevo conocimiento y tecnología, se puede establecer que el impulso institucional desarrollado por la Unión Europea a través de los Programas Marco crea una red de relaciones entre entidades y proyectos. Esto permite el intercambio de información y experiencia, lo que se considera

un elemento clave para el desarrollo de la innovación. Estudios anteriores han tratado de determinar hasta qué punto el impulso institucional es un elemento esencial para comprender la eficacia de los sistemas de innovación, así como de las políticas de investigación asociadas. Sin embargo, estas investigaciones no han alcanzado resultados concluyentes. Utilizando la base de datos de proyectos de la Comisión Europea, este trabajo contribuye a completar este déficit evaluando el sistema de innovación europeo en dos periodos (2007-2013y 2014-2020) correspondientes a dos programas de financiación (FP7 y H2020) con objetivos diferentes. Para ello, se utilizan técnicas de Análisis de Redes Sociales para examinar cómo cambios en el impulso institucional, reflejados en nuevos objetivos del programa de investigación H2020 frente a FP7, se asocian con cambios en las propiedades estructurales y topológicas de las redes subyacentes a los sistemas de innovación. La primera contribución indica que los sistemas de innovación responden a cambios en los objetivos de los programas de financiación, ya que la taxonomía, topología y propiedades estructurales de las redes subyacentes se vieron modificadas debido a los nuevos objetivos propuestos. La segunda contribución muestra que las propiedades de las redes, tanto en las métricas relacionadas con la cohesión como con la centralidad de los nodos, pueden explicar la eficiencia y la efectividad de los sistemas de innovación, proponiendo conclusiones de utilidad para el desarrollo de políticas y para la mejora de la participación de entidades individuales. Esta última contribución tiene fuertes implicaciones, ya que sienta las bases para comprender cómo los objetivos de las políticas de innovación se pueden conseguir mediante cambios en el impulso institucional capaces de orientar a los sistemas de innovación hacia esos objetivos.

- **El tercer trabajo, presentado en Calvo-Gallardo et al. (2022b),** evalúa cómo los sistemas de innovación regionales contribuyen a las estrategias de especialización inteligente en regiones intensivas en carbón. Aunque varios atores han analizado las vías de transición energética para las regiones intensivas en carbón, ningún estudio ha evaluado cómo las propiedades de las redes que subyacen a los sistemas de innovación corresponden con las prioridades identificadas en las estrategias de especialización inteligente. Este estudio contribuye a esta carencia utilizando técnicas de análisis de redes sociales para evaluar las redes subyacentes a los sistemas de innovación, considerando un rol activo de sus nodos y, por tanto, contribuyendo a la literatura sobre modelado, simulación y evaluación del desempeño de los sistemas de innovación. En este trabajo, los sistemas de innovación regionales se modelan como redes de investigación. Estas redes son promocionadas por los consorcios financiados por el programa de investigación europeo H2020. La evaluación de la topología y propiedades de estas redes permite la evaluación del funcionamiento de los sistemas de innovación, de sus fortalezas tecnológicas, así como la contribución de las entidades participantes. Considerado estos resultados, las características de los sistemas de innovación se comparan con las prioridades establecidas por las estrategias de especialización inteligente. Tres regiones españolas intensivas en carbón se consideran como caso de uso para este estudio: Aragón, Asturias y Castilla y León. Los resultados obtenidos indican que, en algunos casos, las fortalezas tecnológicas de los sistemas de innovación no están consideradas en la identificación de las prioridades de las estrategias de especialización inteligente y viceversa, algunas de las prioridades de las estrategias de especialización inteligente no tienen un respaldo por parte del sistema de innovación. Teniendo en cuenta estos resultados, el trabajo propone recomendaciones para el desarrollo de políticas regionales y europeas, así como para participantes en los programas de investigación.

Adicionalmente, considerando la situación especial de pandemia generada por la COVID-19 que tuvo lugar durante la preparación de la tesis, se desarrolló un trabajo en paralelo mediante el cual, utilizando las mismas herramientas de análisis de redes sociales empleadas en los tres estudios anteriores, se propuso un método capaz de prevenir brotes de SARS-COV-2 en entornos laborales. Este trabajo fue recogido por la Organización Mundial de la Salud dentro de la literatura de referencia para hacer frente al coronavirus. Además, este método se implementó, en colaboración con una empresa dedicada a la Prevención de Riesgos Laborales, en una herramienta informática. Esta herramienta está registrada como propiedad intelectual y sobre ella existe un acuerdo de explotación con la empresa MAS Prevención.

- Este **trabajo complementario (Calvo-Gallardo et al., 2020),** tiene como objetivo desarrollar y demostrar, en un caso real, una metodología para ayudar a los servicios de prevención de riesgos laborales de las empresas en el diseño y evaluación de medidas preventivas capaces de reducir el riesgo de brotes de COVID-19 en el entorno laboral. La metodología propuesta aplica los conceptos de análisis de redes sociales para prevenir riesgos de contagio por virus como SARS-COV-2 en las empresas e instituciones. Con ese propósito, se construye una red de empleados cuya interacción se desencadena por determinados eventos, definidos como circunstancias comunes entre dos empleados que pueden resultar en un contagio, como compartir una oficina, participar en una reunión o compartir un medio de transporte. Una vez construida esta red, se evalúa su cohesión, así como cuales son los nodos que más contribuyen a su integración, para, de esta manera, abordarlos en el diseño de medidas preventivas. El impacto en la cohesión de la red de las medidas preventivas identificadas se evalúa para priorizar aquellas más eficaces. La metodología se ha demostrado en un caso real, un centro tecnológico español, obteniendo resultados prometedores de manera rápida y sencilla. Los resultados objetivos que proporciona la aplicación de esta metodología resultan valiosos para los servicios de prevención de riesgos laborales en el diseño y evaluación del conjunto de medidas preventivas a implementar antes del regreso a las instalaciones de los trabajadores después del periodo de confinamiento. El desarrollo de la pandemia de COVID-19 hace necesario el desarrollo de herramientas y métodos que ayuden a las empresas e instituciones en el uso de técnicas de análisis de redes sociales para prevenir brotes entre sus empleados. Aunque existe cierta literatura en el ámbito de la aplicación de análisis de redes sociales en epidemiología, su adaptación para un uso extensivo por parte de los servicios de prevención de riesgos laborales es todavía un reto.

2. Hipótesis y objetivos de la investigación

La transición hacia un sistema energético bajo en carbono, sostenible, seguro y competitivo se apoya en las políticas de investigación. Estas políticas tienen como uno de sus objetivos la construcción de sistemas de innovación en los que empresas, centros de investigación, universidades y otros actores institucionales interactúen creando redes de relaciones. En este contexto, gobiernos y autoridades promocionan el desarrollo de estos sistemas de innovación financiando proyectos de investigación colaborativa que soporten el despliegue de las políticas energéticas. Los consorcios que desarrollan estos proyectos forman redes de innovación en las que aquellas entidades que colaboran en un mismo proyecto están vinculadas entre sí y, análogamente, los proyectos en los que participa una misma entidad también se encuentran conectados. Esta tesis analiza cómo las propiedades de estas redes, en términos de topología, cohesión y centralidad de sus nodos, se relacionan con la efectividad de las políticas de innovación.

En primer lugar, esta tesis asume la perspectiva de los sistemas de innovación, desde la cual los consorcios de investigación crean una red de relaciones que constituye un sistema de innovación. En este sistema, las entidades están vinculadas al participar en un mismo proyecto y los proyectos están conectados al compartir algún socio, intercambiando por tanto información y conocimiento entre ellos. En segundo lugar, esta tesis tiene en cuenta la teoría del impulso institucional, en la que se explica cómo, teniendo en cuenta que las entidades de un mismo sistema de innovación comparten normas y prácticas organizacionales, los gobiernos y autoridades buscan la creación de condiciones y contextos comunes capaces de promocionar sistemas de innovación eficaces para el cumplimiento de sus objetivos políticos. En tercer lugar, esta tesis sigue la teoría del capital social, entendiendo que las redes de relaciones constituyen en sí mismas un activo valioso, en tanto en cuanto son responsables de la difusión del conocimiento, proveen a sus participantes de acceso a información, experiencia y capacidades de otros participantes. En cuarto lugar, esta tesis se aproxima al análisis de la topología y propiedades de las redes mediante la aplicación de técnicas de Análisis de Redes Sociales. Finalmente, en la tesis se han utilizado datos correspondientes a la participación en los Programas Marco de Investigación de la Unión Europea, en concreto, de los programas FP7 y H2020. De esta manera, se considera el marco energético europeo proporcionado por el Plan Estratégico de Tecnologías Energéticas (SET-Plan) y los distintos planes de descarbonización, el contexto de investigación europeo que plantea el Área de Investigación Europea (ERA) y las Estrategias Regionales de Especialización Inteligente (RIS3).

Para estudiar cómo los sistemas de innovación se desarrollan y evolucionan para apoyar el desarrollo de las citadas políticas energéticas y de innovación, en los trabajos desarrollados se abordan las siguientes preguntas de investigación.

En relación con el sistema de innovación europeo en el ámbito energético y su relación con el SET-Plan y las políticas de innovación planteadas por la ERA (Calvo-Gallardo et al., 2021):

- ¿El sistema de innovación construido bajo el programa FP7 en el ámbito de la energía contribuye a los objetivos de la ERA de favorecer la colaboración transnacional y la competitividad, al tiempo que facilita la circulación, acceso y transferencia de conocimiento científico?
- ¿El sistema de innovación construido bajo el programa FP7 en el ámbito de la energía responde a los retos tecnológicos identificados en el SET-Plan para conseguir los objetivos europeos de descarbonización?

En relación con la respuesta de los sistemas de innovación frente a cambios en el impulso institucional (Calvo-Gallardo et al., 2022a) y, en particular, para valorar la evolución del sistema de innovación europeo en energía frente a los cambios planteados por H2020 (periodo 2014-2020) frente al programa anterior FP7 (2007-2013):

- ¿De qué manera el impulso institucional desarrollado por la Unión Europea a través de los programas de investigación afecta la evolución del sistema de innovación europeo en el ámbito energético?
- ¿Cómo han cambiado las propiedades de las redes subyacentes al sistema de innovación energético europeo entre los periodos 2007-2013 y 2014-2020? ¿Corresponden estos cambios con los nuevos retos perseguidos por H2020 en comparación con su predecesor H2020?

En relación con la correspondencia entre las políticas regionales de especialización inteligente (RIS3) y las propiedades de las redes subyacentes a los sistemas de innovación en regiones intensivas en carbón (Calvo-Gallardo et al., 2022b):

- ¿Cómo contribuyen los sistemas de innovación al despliegue de las prioridades de la RIS3 en las regiones en transición del carbón)
- ¿Cómo están considerados los sistemas de innovación e el diseño de la RIS3en las regiones en transición del carbón?

Finalmente, en el trabajo relativo al uso de técnicas de análisis de redes sociales para la prevención de brotes de COVID-19 en entorno laborales, se plantea el siguiente objetivo:

- Guiar el diseño a medida y evaluación de medidas preventivas dirigidas a contener brotes de COVID-19 en el entorno laboral mediante la aplicación de técnicas de Análisis de Redes Sociales.

3. Marco teórico

La tesis se enmarca en la teoría de los sistemas de innovación, tomando en consideración la aproximación del impulso institucional, así como el enfoque de capital embebido en las redes de innovación. Este enfoque se aplica, dentro de la tesis, en el ámbito de las políticas de innovación y de energía.

Los sistemas de innovación se entienden como el conjunto de relaciones complejas que se forman entre entidades cuyo objetivo funcional es el de facilitar la innovación y el desarrollo tecnológico. Éstos se construyen como un proceso interactivo que comienza por la generación de conocimiento y concluye con el despliegue en mercado de las nuevas tecnologías. En este contexto, las interacciones entre entidades aumentan la competitividad industrial aumentando la capacidad de innovación de las empresas que, a su vez, comparten riesgos y recursos, al tiempo que reducen los tiempos de llegada al mercado y disfrutan de acceso a nuevo conocimiento, tecnología y mercado.

Los sistemas de innovación operan en contextos específicos desde el punto de vista geográfico, político, social, económico y regulatorio. Estos contextos juegan un rol fundamental en la evolución de dichos sistemas de innovación. Se ha demostrado como el apoyo gubernamental y los programas de financiación de la innovación relacionados con las tecnologías bajas en carbono pueden generar un contexto favorecedor del desarrollo tecnológico, capaz de reducir el tiempo de llegada al mercado del nuevo conocimiento. La teoría del impulso institucional toma en cuenta estas consideraciones para generar contextos específicos que lleven a las organizaciones de un sistema de innovación a adoptar nuevas prácticas y procesos. Considerando esta teoría del impulso institucional, la Unión Europea concibe el Área de Europea de Investigación (ERA) como un mecanismo para promocionar un sistema de innovación más competitivo, en el que se favorezca la libre circulación de investigadores, conocimiento y tecnología. Para dirigir y nutrir la ERA, la Unión Europea se apoya en los programas marco de investigación, que financian investigación colaborativa enfocada a sus principales objetivos políticos.

Los programas marco de la Unión Europea han invertido cuantiosos recursos durante los últimos treinta años. Los dos programas marco finalizados más recientes, FP7 y H2020, correspondientes a los periodos 2007-2013 y 2014-2020 respectivamente, han financiado en el área de energía cerca de mil proyectos consorciados en los que se abordan las distintas tecnologías energéticas necesarias para alcanzar los objetivos de descarbonización y neutralidad climática de las Unión Europea. En estos proyectos, empresas, universidades, centros tecnológicos y otros organismos comparten conocimientos, recursos y capacidades para el desarrollo de actividades de innovación colaborativas. De esta manera, además de favorecer la transferencia de conocimiento, la Unión Europea busca mejorar la competitividad de las empresas, proponiendo convocatorias competitivas.

La teoría del capital social proporciona el marco teórico para entender los recursos que una red de relaciones puede proveer. De esta manera, se entiende la red de entidades y proyectos generada por los programas marco como un activo capaz de generar valor a sus participantes al proporcionarles acceso a conocimiento, recursos, mercados y nuevas tecnologías. En esta teoría, la topología y estructura de la red, su cohesión y cómo cada nodo está embebido, impacta en la eficacia de la red y, por tanto, del sistema de innovación representado.

En esta tesis, además de considerar las políticas de innovación de la Unión Europea relativas a la ERA y a los programas marco, también se estudian las estrategias regionales de especialización inteligente que, a iniciativa de la Unión Europea, se desarrollan a nivel regional. Adicionalmente, más relacionado con el ámbito energético y dentro del marco de los objetivos de descarbonización y neutralidad climática, se estudian el Plan Estratégico de Tecnologías Energéticas (SET-Plan) y las implicaciones de los procesos de transición hacia la descarbonización que se están dando en las regiones intensivas en la extracción y uso del carbón.

4. Metodología

En los trabajos desarrollados, los sistemas de innovación se representan mediante la red bimodal que generan los proyectos consorciados por los programas marco. Esta red está compuesta por dos tipos de nodos: entidades y proyectos. En ella, las entidades están conectadas a los proyectos en los que participan. Los nodos correspondientes a entidades están caracterizados por atributos relativos a su localización geográfica (país o región), tipo de entidad (empresa, universidad, centro de investigación, administración pública u otros) y si han desarrollado o no labores de coordinación en alguno de los proyectos en los que participan. Los nodos correspondientes a los proyectos se caracterizan mediante atributos relativos al área de conocimiento y tecnología que abordan, siguiendo la clasificación que adoptan los propios programas FP7 y H2020. De la red bimodal se deducen dos redes unimodales, una relativa a proyectos, en la que los que proyectos que comparten socios están conectados, y otra relativa a entidades, en la que las entidades que colaboran en un proyecto están conectadas.

Teniendo en cuenta que la topología, estructura y cohesión de la red, así como la centralidad de sus nodos, afectan a la capacidad de la misma para distribuir el conocimiento, se calculan estos parámetros como una métrica para evaluar la efectividad del sistema de innovación representado. Teniendo además en cuenta la teoría del impulso institucional, se evalúa cómo estas métricas responden a cambios en los objetivos políticos de los programas de financiación.

Las redes cohesionadas permiten la colaboración entre entidades, lo que se ha identificado como un elemento crítico para el desarrollo de la innovación y la transferencia tecnológica. Además, la consideración de la centralidad y la integración de los nodos dentro de la red como un elemento clave para favorecer su actividad, permite identificar aquellos en situaciones de mayor privilegio. Cuando se caracterizan los nodos teniendo en cuenta diferentes atributos, es posible identificar subredes dentro de la red general, de manera que se puede evaluar cada subred de manera independiente y comparar su contribución al desempeño general del sistema.

Teniendo en cuenta lo anterior, y una vez construidas las distintas redes utilizando los datos de participación en FP7 y H2020 que proporciona la Unión Europea, en esta tesis se han aplicado técnicas de Análisis de Redes Sociales para el cálculo de diferentes métricas relativas tanto a la cohesión de las redes y subredes, como a la centralidad de cada uno de sus nodos. Para el desarrollo de los cálculos se ha utilizado el programa UCINET.

Teniendo en cuenta las métricas obtenidas y, en algunos casos, su evolución entre los distintos programas, en la tesis se extraen conclusiones sobre cómo las propiedades de las redes de los sistemas de innovación se relacionan con los objetivos marcados por las políticas de innovación y energía estudiadas. De esta forma se analiza cómo los sistemas de innovación apoyan el desarrollo de las diferentes políticas y viceversa, cómo las políticas tienen en cuenta los sistemas de innovación sobre los que se despliegan.

5. Copia completa de las publicaciones

5.1. Analysis of the European Energy Innovation System: Contribution of the Framework Programmes to the EU Policy Objectives

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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%

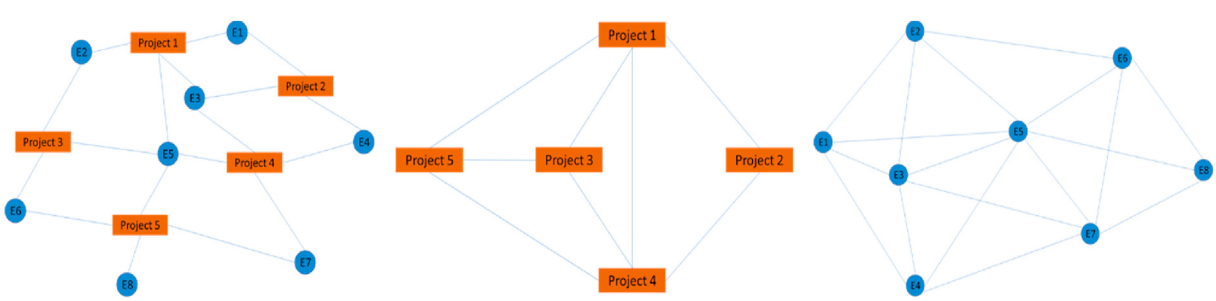

Fig. 1. Illustrative example of a 2-mode network of entities and projects and its associated 1-mode network of projects and 1-mode network of entities.

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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References

Abreu, António, 2020. Model to estimate the project outcome's likelihood based on social networks analysis. KnE engineering. https://doi.org/10.18502/keg.v5i6.7048.

Ades, C., Figlioli, A., Sbragia, R., Porto, G., Ary Plonski, G., Celadon, K., 2013. Implementing open innovation: the case of natura, IBM and Siemens. J. Technol. Manag. Innovat. 8, 12–25. https://doi.org/10.4067/S0718-27242013000300057. SPL.ISS.1.

Altuntas, Fatma, Mehmet, Gök, 2020. Technological evolution of wind energy with social network analysis. Kybernetes. https://doi.org/10.1108/K-11-2019-0761 ahead-of-print.

Alvarez Fernandez, Roberto, Zubelzu, Sergio, Díaz, Guzmán, Lopez, Alberto, 2015. Analysis of low carbon super credit policy efficiency in European Union greenhouse gas emissions. Energy 82. https://doi.org/10.1016/j.energy.2015.01.110.

Amoroso, S., Coad, A., Grassano, N., 2018. European R&D networks: a snapshot from the 7th EU Framework Programme. Econ. Innovat. N. Technol. 27 (5–6), 404–419. https://doi.org/10.1080/10438599.2017.1374037.

Arranz, N., de Arroyabe, J.C.F., 2013. Network embeddedness and performance of joint R&D projects. In: Ehrmann, T., Windsperger, J., Cliquet, G., Hendrikse, G. (Eds.), Network Governance. Contributions to Management Science. Physica, Berlin, Heidelberg. http://doi-org-443.webvpn.fjmu.edu.cn/10.1007/978-3-7908-2867-2_3.

Arranz, N., Fernandez de Arroyabe, J.C., 2006. Joint R&D projects: experiences in the context of European technology policy. Technol. Forecast. Soc. Change 73 (7), 860–885. https://doi.org/10.1016/j.techfore.2005.11.003.

Arranz, N., Arroyabe, M.F., Fernandez de Arroyabe, J.C., 2020. Network embeddedness in exploration and exploitation of joint R&D projects: a structural approach. Br. J. Manag. 31 (2), 421–437. https://doi.org/10.1111/1467-8551.12338.

Barre, R., Henriques, L., Pontikakis, D., Weber, K.M., 2013. Measuring the integration and coordination dynamics of the European Research Area. Sci. Publ. Pol. 40 (2) https://doi.org/10.1093/scipol/scs080, 187-20.

Berrone, P., Fosfuri, A., Gelabert, L., Gomez-Mejia, L.R., 2013. Necessity as the mother of 'green' inventions: institutional pressures and environmental innovations. Strat. Manag. J. 34 (8), 891–909. https://doi.org/10.1002/smj.2041.

Borgatti, S.P., Everett, M.G., Freeman, L.C., 2002. Ucinet 6 for Windows: Software for Social Network Analysis. Analytic Technologies, Harvard, MA.

Bosman, Lise, 2013. Renewable Energy Sources: A Chance to Combat Climate Change, ISBN 9041148116, pp. 61–62.

Brodny, Jarosław, Tutak, Magdalena, 2020. Analyzing similarities between the European union countries in terms of the structure and volume of energy production from renewable energy sources. Energies 13, 913. https://doi.org/10.3390/en13040913.

Cambini, Carlo, Meletiou, Alexis, Bompard, Ettore, Masera, Marcelo, 2016. Market and regulatory factors influencing smart-grid investment in Europe: evidence from pilot projects and implications for reform. Util. Pol. 40 https://doi.org/10.1016/j.jup.2016.03.003.

Chang, P.L., Shih, H.Y., 2004. The innovation systems of Taiwan and China: a comparative analysis. Technovation 24 (7), 529–539. https://doi.org/10.1016/S0166-4972(02)00117-7.

Chesbrough, Henry, 2003. Open Innovation: the New Imperative for Creating and Profiting from Technology, ISBN 1-57851-837-7.

Chesbrough, Henry, 2012. Open Innovation: where We've Been and where We're Going, vol. 55. Research-Technology Management. https://doi.org/10.5437/08956308X5504085.

de Juana-Espinosa, S., Luján-Mora, S., 2019. Open government data portals in the European Union: considerations, development, and expectations. Technol. Forecast. Soc. Change 149, 119769. https://doi.org/10.1016/j.techfore.2019.119769.

de Marco, C.E., Martelli, I., Di Minin, A., 2020. European SMEs' engagement in open innovation. When the important thing is to win and not just to participate, what should innovation policy do? Technol. Forecast. Soc. Change 152, 119843. https://doi.org/10.1016/j.techfore.2019.119843.

Decourt, B., 2019. Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. Int. J. Hydrogen Energy 44, 17411–17430. https://doi.org/10.1016/j.ijhydene.2019.05.149.

Delanghe, H., Muldur, U., 2007. Ex-ante impact assessment of research programmes: the experience of the European Union's 7th Framework Programme. Sci. Publ. Pol. 34 (3), 169–183. https://doi.org/10.3152/030234207X218125.

Deloitte, 2016. Energy Efficiency in Europe. The Levers to Deliver the Potential.

Di Cagno, D., Fabrizi, A., Meliciani, V., Wanzenböck, I., 2016. The impact of relational spillovers from joint research projects on knowledge creation across European regions. Technol. Forecast. Soc. Change 108, 83–94. https://doi.org/10.1016/j.techfore.2016.04.021.

DiMaggio, P.J., Powell, W.W., 1983. The iron cage revisited: institutional isomorphism and collective rationality in organisational fields. Am. Socio. Rev. 48 (2), 147–160. https://doi.org/10.2307/2095101.

Edquist, Charles, Hommen, Leif, 2008. Small country innovation systems: globalization, change and policy in asia and Europe. https://doi.org/10.4337/9781847209993.

Edwards, P.P., Kuznetsov, V.L., David, W.I., Brandon, N.P., 2008. Hydrogen and fuel cells: towards a sustainable energy future. Energy Pol. 36 (12), 4356–4362. https://doi.org/10.1016/j.enpol.2008.09.036.

European Commission, 2005. Communication COM(2005)118 from the Commission. Building the ERA of Knowledge for Growth.

European Commission, 2007a. Communication COM(2007)1 from the Commission to the European Council and the European Parliament. An Energy Policy for Europe.

European Commission, 2007b. Communication COM(2007)723 from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. A European Strategic Energy Technology Plan (Set-Plan):'Towards A Low Carbon Future.

European Commission, 2010. Communication COM(2010)2020 from the Commission Euope2020: A Strategy for Smart and Inclusive Growth.

European Commission, 2012. Communication COM(2012)392 from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. A Reinforced European Research Area Partnership for Excellence and Growth.

European Commission. High-Level Expert Group. Chair: Louise O. Fresco. 2015a. COMMITMENT and COHERENCE Essential Ingredients for Success in Science and Innovation Ex-Post-Evaluation of the 7th EU Framework Programme (2007-2013).

European Commission, 2016. Communication COM(2016)5 from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions on the Response to the Report of the High-Level Expert Group on the Ex Post Evaluation of the Seventh Framework Programme.

European Commission, 2018. SET-Plan delivering results: the implementation plans. Research & Innovation enabling the EU's Energy Transition. https://doi.org/10.2833/25250.

European Commission, Directorate-General for Energy, 2019a. Clean energy for Europeans. https://doi.org/10.2833/9937.

European Commission, 2019b. Communication COM(2019)640 final from the commission to the European parliament, the European Council, the Council, the European economic and social committee and the committee of the region. The European Green Deal.

European Commission, 2020. European union open data portal. CORDIS data set of EU research projects under FP7 (2007-2013). Downloaded in january 2020. https://data.europa.eu/euodp/en/data/dataset/cordisfp7projects.

European Commission, Directorate-General for Research and Innovation, 2010. Communication SEC(2010)1161 from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Europe 2020 Flagship Initiative Innovation Union.

European Commission, Directorate-General for Research and Innovation, 2016. Open innovation, open science, open to the world – a vision for Europe. https://doi.org/10.2777/061652.

European Commission, Directorate-General for Research and Innovation Directorate, 2015. A –policy development and coordination unit A5—evaluation. 2015. Study on network analysis of the 7thFramework programme participation final Report. https://doi.org/10.2777/50633.

European Commission, Directorate-General for Research and Innovation Directorate G – Energy, 2018. The strategic energy technology plan – at the heart of energy research and innovation in Europe. https://doi.org/10.2777/04888.

European Parliament and European Council, 2006. Decision No 1982/2006/EC Concerning the Seventh Framework Programme of the European Community for Research, Technological Development and Demonstration Activities (2007-2013).

European Council, 2014. European Council Conclusions EUCO 169/14.

European Parliament and European Council, 2018a. Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. Official Journal of the European Union. L 328/82-L 328/209.

European Parliament and European Council, 2018b. Directive (EU) 2018/2002 Amending Directive 2012/27/EU on Energy Efficiency. Official Journal of the European Union. L 328/210- L 328/230.

European Parliament and European Council, 2018c. Regulation (EU) 2018/1999 on the governance of the energy union and climate action. Official Journal of the European Union. L 328/1- L 328/77.

Fernandez de Arroyabe, J.C., Schumann, M., Sena, V., Lucas, P., 2021. Understanding the network structure of agri-food FP7 projects: an approach to the effectiveness of innovation systems. Technological Forecasting and Social Change Journal 162. https://doi.org/10.1016/j.techfore.2020.120372.

Franco, Bermúdez, Juan, Ruiz, Castañeda, Walter, 2019. Social Network Analysis for an Innovation System Generated Starting from an Agent-Based Simulation Model, vol. 22, pp. 23–46. https://doi.org/10.22430/22565337.1183.

Freeman, C., 1987. Technology policy and economic performance: Lessons from Japan. Pinter Publishers, London.

Gallego-Alvarez, I., Ortas, E., Vicente-Villardón, J.L., Álvarez Etxeberria, I., 2017. Institutional constraints, stakeholder pressure and corporate environmental reporting policies. Bus. Strat. Environ. 26 (6), 807–825. https://doi.org/10.1002/bse.1952.

Gao, Y., Gu, J., Liu, H., 2019. Interactive effects of various institutional pressures on corporate environmental responsibility: institutional theory and multilevel analysis. Bus. Strat. Environ. 28 (5), 724–736. https://doi.org/10.1002/bse.2276.

Gong, J.W., Li, Y.P., Suo, C., Lv, J., 2020. Planning regional energy system with consideration of energy transition and cleaner production under multiple uncertainties: a case study of Hebei province, China. J. Clean. Prod. 250, 119463. https://doi.org/10.1016/j.jclepro.2019.119463.

Grohnheit, P.E., Mortensen, B.O.G., 2003. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. Energy Pol. 31 (9), 817–826. https://doi.org/10.1016/S0301-4215(02)00066-6.

Gugler, Klaus, Liebensteiner, Mario, Schmitt, Stephan, 2017. Vertical disintegration in the European electricity sector: empirical evidence on lost synergies. Int. J. Ind. Organ. 52 https://doi.org/10.1016/j.ijindorg.2017.04.002.

Hagedoorn, J., Link, A.N., Vonortas, N.S., 2000. Research partnerships. Res. Pol. 29 (4–5), 567–586. https://doi.org/10.1016/S0048-7333(99)00090-6.

Husted, B.W., Allen, D.B., 2007. Strategic corporate social responsibility and value creation among large firms: lessons from the Spanish experience. Long. Range Plan. 40 (6), 594–610. https://doi.org/10.1016/j.lrp.2007.07.001.

International Energy Agency, 2017. The Untapped Potential of Energy Efficiency. IEA, Paris. https://www.iea.org/commentaries/the-untapped-potential-of-energy-efficiency.

Kalthaus, Martin, Graf, Holger, 2016. International research networks: determinants of country embeddedness. https://doi.org/10.1016/j.respol.2018.04.001.

Kang, M.J., Hwang, J., 2016. Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector. Energy Pol. 96, 471–490. https://doi.org/10.1016/j.enpol.2016.06.017.

Kashani, E.S., Roshani, S., 2019. Evolution of innovation system literature: intellectual bases and emerging trends. Technol. Forecast. Soc. Change 146, 68–80. https://doi.org/10.1016/j.techfore.2019.05.010.

Kofler, I., Marcher, A., Volgger, M., Pechlaner, H., 2018. The special characteristics of tourism innovation networks: the case of the Regional Innovation System in South Tyrol. J. Hospit. Tourism Manag. 37, 68–75. https://doi.org/10.1016/j.jhtm.2018.09.004.

Kolleck, Nina, 2013. Understanding the chances and limits of social network analysis for innovation research. Eur. J. For. Res. 1 https://doi.org/10.1007/s40309-013-0025-2.

Kuhlmann, S., Edler, J., 2003. Scenarios of technology and innovation policies in Europe: investigating future governance. Technol. Forecast. Soc. Change 70 (7), 619–637. https://doi.org/10.1016/S0040-1625(03)00027-1.

Li, Min, Xiao, Fangbin, Cheng, Yang, Xie, Bi-Jun, Liu, Chen-Yun, Xu, Baoni, 2019. Exploring the relationship between network position and innovation performance: evidence from a social network analysis of high and new tech companies from a less-developed area in China. Chinese Management Studies. ahead-of-print. https://doi.org/10.1108/CMS-10-2018-0717.

Lin, Julia, Fang, Shih-Chieh & S.R., Fang & Tsai, Fu-Sheng, 2009. Network embeddedness and technology transfer performance in R&D consortia in Taiwan. Technovation 29, 763–774. https://doi.org/10.1016/j.technovation.2009.05.001.

Liu, X., White, S., 2001. Comparing innovation systems: a framework and application to China's transitional context. Res. Pol. 30 (7), 1091–1114. https://doi.org/10.1016/S0048-7333(00)00132-3.

Llombart Estopiñan, A., Martin Jimenez, I., Calvo Gallardo, E., 2011. The strategic energy technology plan: financial instruments. Renewable Energy and Power Quality Journal 15–22. https://doi.org/10.24084/repqj09.006.

Lundvall, B.-Å., 1988. Innovation as an interactive process: From user-producer interaction to the National Innovation Systems. In: Technology and economic theory. Pinter Publishers, London.

Lundvall, B-Å. (Ed.), 1992. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter Publishers, London.

Lundvall, Bengt-Åke, Vang, Jan, Joseph, K.J., Chaminade, Cristina, 2009. Innovation system research and developing countries. Handbook of innovation systems in developing countries. Building Domestic Capabilities in A Global Setting 1–32, 978 1 84720 609 1.

Metcalfe, S., 1995. The Economic Foundations of Technology Policy: Equilibrium and Evolutionary Perspective. Handbook of the Economics of Innovations and Technological Change. Stoneman, Paul. Blackwell, Oxford, UK, ISBN 0-631-17773-6. OCLC 31170120.

Morisson, Arnault, Bevilacqua, Carmelina, Doussineau, Mathieu, 2020. Smart specialisation strategy (S3) and social network analysis (SNA): mapping capabilities in calabria. https://doi.org/10.1007/978-3-030-52869-0_1.

Muldur, U., Corvers, F., Delanghe, H., Dratwa, J., Heimberger, D., Sloan, B., Vanslembrouck, S., 2007. A new deal for an effective European research policy: the design and impacts of the 7th Framework Programme. Springer Science & Business Media. Https://doi.org/10.1007/978-1-4020-5551-5.

Muñiz, A.S., Cuervo, M.R., 2018. Exploring research networks in Information and Communication Technologies for energy efficiency: an empirical analysis of the 7th Framework Programme. J. Clean. Prod. 198, 1133–1143. https://doi.org/10.1016/j.jclepro.2018.07.049.

Mytelka, Lynn, Smith, Keith, 2002. Policy learning and innovation theory: an interactive and co-evolving process. Res. Pol. 31, 1467–1479. https://doi.org/10.1016/S0048-7333(02)00076-8.

Nelson, R.R. (Ed.), 1993. National Innovation Systems: A Comparative Analysis. Oxford University Press, Oxford.

Pandza, K., Wilkins, T.A., Alfoldi, E.A., 2011. Collaborative diversity in a nanotechnology innovation system: evidence from the EU Framework Programme. Technovation 31 (9), 476–489. https://doi.org/10.1016/j.technovation.2011.05.003.

Parida, Vinit, Oghazi, Pejvak, Ericson, Åsa, 2014. Realization of open innovation: a case study in the manufacturing industry. J. Promot. Manag. 20, 372–389. https://doi.org/10.1080/10496491.2014.908801.

Pinheiro, M.L., Serôdio, P., Pinho, J.C., Lucas, C., 2016. The role of social capital towards resource sharing in collaborative R&D projects: evidences from the 7th Framework Programme. Int. J. Proj. Manag. 34 (8), 1519–1536. https://doi.org/10.1016/j.ijproman.2016.07.006.

Porto-Gomez, I., Zabala-Iturriagagoitia, J.M., Leydesdorff, L., 2019. Innovation systems in México: a matter of missing synergies. Technol. Forecast. Soc. Change 148, 119721. https://doi.org/10.1016/j.techfore.2019.119721.

Rahman, Hakikur, Ramos, Isabel, 2010. Open innovation in SMEs: from closed boundaries to networked paradigm. Issues Inf. Sci. Inf. Technol. 7, 471–487. https://doi.org/10.28945/1221.

Rijnsoever, F.J., Berg, J.V., Koch, J., Hekkert, M.P., 2015. Smart innovation policy: how network position and project composition affect the diversity of an emerging technology. Res. Pol. 44, 1094–1107. https://doi.org/10.1016/j.respol.2014.12.004.

Sá, E.S., de Pinho, J.C., 2019. Effect of entrepreneurial framework conditions on R&D transfer to new and growing firms: the case of European Union innovation-driven countries. Technol. Forecast. Soc. Change 141, 47–58. https://doi.org/10.1016/j.techfore.2019.01.017.

Scharpf, F.W., 2010. The asymmetry of European integration, or why the EU cannot be a 'social market economy'. Soc. Econ. Rev. 8 (2), 211–250. https://doi.org/10.1093/ser/mwp031.

Scherngell, T., Barber, M.J., 2009. Spatial interaction modelling of cross-region R&D collaborations: empirical evidence from the 5th EU framework programme. Pap. Reg. Sci. 88 (3), 531–546. https://doi.org/10.1111/j.1435-5957.2008.00215.x.

Schwanitz, V.J., Piontek, F., Bertram, C., Luderer, G., 2014. Long-term climate policy implications of phasing out fossil fuel subsidies. Energy Pol. 67, 882–894. https://doi.org/10.1016/j.enpol.2013.12.015.

Scott, W.R., 2005. Institutional theory: contributing to a theoretical research program. In: Smith, Ken G., Hitt, Michael A. (Eds.), Great Minds in Management: the Process of Theory Development. Oxford University Press, Oxford, UK.

Suo, C., Li, Y.P., Nie, S., Lv, J., Mei, H., Ma, Y., 2020. Analyzing the effects of economic development on the transition to cleaner production of China's energy system under uncertainty. J. Clean. Prod. 279, 123725. https://doi.org/10.1016/j.jclepro.2020.123725.

Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications, vol. 8. Cambridge university press. https://doi.org/10.1017/CBO9780511815478.

Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change: combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. Res. Pol. 41 (6), 1037–1047. https://doi.org/10.1016/j.respol.2011.10.015.

Woods, Judith, Galbraith, Brendan, Hewitt-Dundas, Nola, 2019. Network centrality and open innovation: a social network analysis of an SME manufacturing cluster. IEEE Trans. Eng. Manag. 1–14. https://doi.org/10.1109/TEM.2019.2934765.

5.2.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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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

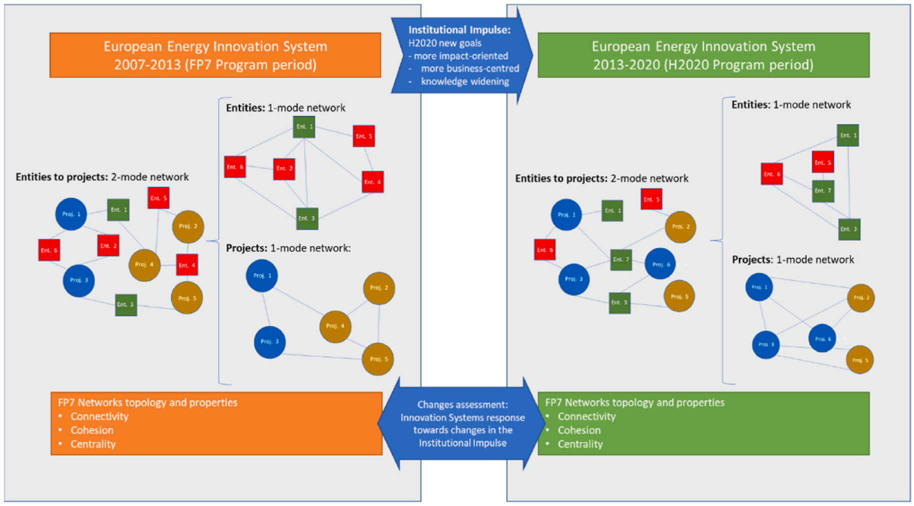

Fig. 1. Overview of the conceptual framework.

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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References

Ades, C., Figlioli, A., Sbragia, R., Porto, G., Plonski, G., Celadon, K., 2013. Implementing open innovation: the case of natura, IBM and Siemens. J. Technol. Manag. Innovat. 8, 57-57.
Alkemade, F., Kleinschmidt, C., Hekkert, M., 2007. Analysing emerging innovation systems: a functions approach to foresight. Int. J. Foresight Innovation Policy 3 (2), 139–168.
Amoroso, S., Coad, A., Grassano, N., 2018. European R&D networks: a snapshot from the 7th EU Framework Programme. Econ. Innovat. N. Technol. 27 (5–6), 404–419.
Arranz, N., Arroyabe, M.F., Schumann, M., 2020. The role of NPOs and international actors in the national innovation system: a network-based approach. Technol. Forecast. Soc. Change 159, 120183.
Arroyabe, M.F., Arranz, N., Fdez de Arroyabe, J.C., 2015. R&D partnerships: an exploratory approach to the role of structural variables in joint project performance. Technol. Forecast. Soc. Change 90, 623–634.
Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transit. 16, 51–64.
Berrone, P., Fosfuri, A., Gelabert, L., Gomez-Mejia, L.R., 2013. Necessity as the mother of 'green'inventions: institutional pressures and environmental innovations. Strat. Manag. J. 34 (8), 891–909.
Bonnet, C., Hache, E., Seck, G.S., Simoën, M., Carcanague, S., 2019. Who's winning the low-carbon innovation race? An assessment of countries' leadership in renewable energy technologies. Int. Econ. 160, 31–42.
Borgatti, S.P., Everett, M.G., Freeman, L.C., 2002. Ucinet *6 for Windows*. Software for Social Network Analysis. Analytic Technologies, Harvard, MA.
Borgatti, S.P., Halgin, D.S., 2011. On network theory. Organ. Sci. 22 (5), 1168–1181.
Brem, A., Nylund, P.A., 2021. Home bias in international innovation systems: the emergence of dominant designs in the electric vehicle industry. J. Clean. Prod. 321, 128964.
Caloghirou, Y., Protogerou, A., Spanos, Y., Papagiannakis, L., 2004. Industry-versus firm-specific effects on performance: contrasting SMEs and large-sized firms. Eur. Manag. J. 22, 231–243.
Calvo-Gallardo, E., Arranz, N., Fernández de Arroyabe, J.C., 2021. Analysis of the European energy innovation system: contribution of the Framework Programmes to the EU policy objectives. J. Clean. Prod. 298, 126690.
Chaminade, C., Edquist, C., 2006. From theory to practice. The use of the systems of innovation approach in innovation policy. In: Hage, J., De Meeus (Eds.), Innovation, Learning and Institutions. Oxford University Press, London.
Chaminade, C., Edquist, C., 2010. Rationales for public policy intervention in the innovation process: a systems of innovation approach. In: Kulhman, S., Shapira, P., Smits, R. (Eds.), The Theory and Practice of Innovation Policy: an International Research Handbook. Edward Elgar.
Chen, Y., Lin, B., 2020. Slow diffusion of renewable energy technologies in China: an empirical analysis from the perspective of innovation system. J. Clean. Prod. 261, 121186.
Cheng, C.C.J., Chen, J., 2013. Breakthrough innovation: the roles of dynamic innovation capabilities and open innovation activities. J. Bus. Ind. Market. 28 (5), 444–454.
Chesbrough, H., Crowther, A.K., 2006. Beyond high tech: early adopters of open innovation in other industries. R D Manag. 36 (3), 229–236.
Chou, J.C.P., Hu, M.C., Tsung-Ying Shih, T.T.Y., 2019. Green transformation: lessons from the fuel cell innovation system in Taiwan. J. Clean. Prod. 240, 118182.
Dahesh, M.B., Tabarsa, G., Zandieh, M., Hamidizadeh, M., 2020. Reviewing the intellectual structure and evolution of the innovation systems approach: a social network analysis. Technol. Soc. 63, 101399.
De Arroyabe, J.C.F., Schumann, M., Sena, V., Lucas, P., 2021. Understanding the network structure of agri-food FP7 projects: an approach to the effectiveness of innovation systems. Technol. Forecast. Soc. Change 162, 120372.
De Juana-Espinosa, S., Luján-Mora, S., 2019. Open government data portals in the European Union: considerations, development, and expectations. Technol. Forecast. Soc. Change 149, 119769.
De Marco, C.E., Martelli, I., Di Minin, A., 2020. European SMEs' engagement in open innovation. When the important thing is to win and not just to participate, what should innovation policy do? Technol. Forecast. Soc. Change 152, 119843.
Decourt, B., 2019. Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. Int. J. Hydrogen Energy 44 (33), 17411–17430.
Dolphin, T., Nash, D., 2012. Complex New World: Translating New Economic Thinking into Public Policy. IPPR, London.
Echols, A., Tsai, W., 2005. Niche and performance: the moderating role of network embeddedness. Strat. Manag. J. 26 (3), 219–238.
Edquist, C., 1997. *Systems of Innovation. Technologies, Institutions and Organisations*. Pinter, London.
Enkel, E., Gassmann, O., Chesbrough, H., 2009. Open R&D and open innovation: exploring the phenomenon. R D Manag. 39 (4), 311–316.
Esmailzadeh, M., Noori, S., Nouralizadeh, H., Bogers, M.L.A.M., 2020. Investigating macro factors affecting the technological innovation system (TIS): a case study of Iran's photovoltaic TIS. Energy Strat. Rev. 32, 100577.
European Commission, 2021. Cordis Data Set of EU Research Projects under. European Union. https://data.europa.eu/data/datasets/cordish2020projects H2020 (2014-2020.
Ferraris, A., Santoro, G., Scuotto, V., 2018. Dual relational embeddedness and knowledge transfer in European multinational corporations and subsidiaries. J. Knowl. Manag. 24 (3), 519–533.
Gallego-Alvarez, I., Ortas, E., Vicente-Villardón, J.L., Álvarez Etxeberria, I., 2017. Institutional constraints, stakeholder pressure and corporate environmental reporting policies. Bus. Strat. Environ. 26 (6), 807–825.
Gao, Y., Gu, J., Liu, H., 2019. Interactive effects of various institutional pressures on corporate environmental responsibility: institutional theory and multilevel analysis. Bus. Strat. Environ. 28 (5), 724–736.
Gatignon, H., Tushman, M.L., Smith, W., Anderson, P., 2002. A structural approach to assessing innovation. Construct development of innovation locus, type, and characteristics. Manag. Sci. 48 (9), 1103–1122.
Granovetter, M.S., 1992. Problems of explanation in economic sociology. In: Nohria, N., Eccles, R.G. (Eds.), Networks and Organization. Harvard Business School Press, Boston, pp. 29–56.
Granstrand, O., Holgersson, M., 2020. Innovation ecosystems: a conceptual review and a new definition. Technovation 90–91, 102098.
Grewal, Rajdeep, Lilien, Gary, Mallapragada, Girish, 2006. Location, location, location: how network embeddedness affects project success in open source systems. Manag. Sci. 52, 1043–1056. https://doi.org/10.1287/mnsc.1060.0550.
Gulati, R., 1995. Does familiarity breed trust? The implications of repeated ties for contractual choice in alliances. Acad. Manag. J. 38, 85–112.
Hannan, M.T., Freeman, J., 1989. Organizational Ecology. Harvard University Press, Cambridge, MA.
Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74 (4), 413–432.
Huang, H.C., Lai, M.C., Lin, L.H., Chen, C.T., 2013. Overcoming organizational inertia to strengthen business model innovation: an open innovation perspective. J. Organ. Change Manag. 26 (6), 977–1002.
Jackson, D.J., 2011. What Is an Innovation Ecosystem? National Science Foundation, Arlington, VA. http://erc-assoc.org/sites/default/files/topics/policy_studies/DJackson_Innovation%20Ecosystem_03-15-11.pdf.
Jacobsson, S., 2008. The emergence and troubled growth of a "biopower" innovation system in Sweden. Energy Pol. 36 (4), 1491–1508.
Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: contributions and suggestions for research. Environ. Innov. Soc. Transit. 1 (1), 41–57.
Janssen, M.J., 2019. What bangs for your buck? Assessing the design and impact of Dutch transformative policy. Technol. Forecast. Soc. Change 138, 78–94.
Johnson, A., Jacobsson, S., 2001. Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. In: Technology and the Market. Edward Elgar Publishing.
Kang, Moon, Hwang, Jongwoon, 2016. Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector. Energy Pol. 96, 471–490. https://doi.org/10.1016/j.enpol.2016.06.017.
Kapetaniou, C., Samdanis, M., Lee, S.H., 2018. Innovation policies of Cyprus during the global economic crisis: aligning financial institutions with National Innovation System. Technol. Forecast. Soc. Change 133, 29–40.
Karaulova, M., Shackleton, O., Liu, W., Gök, A., Shapira, P., 2017. Institutional change and innovation system transformation: a tale of two academies. Technol. Forecast. Soc. Change 116, 196–207.
Kashani, E.S., Roshani, S., 2019. Evolution of innovation system literature: intellectual bases and emerging trends. Technol. Forecast. Soc. Change 146, 68–80.

Kofler, I., Marcher, A., Volgger, M., Pechlaner, H., 2018. The special characteristics of tourism innovation networks: the case of the Regional Innovation System in South Tyrol. J. Hospit. Tourism Manag. 37, 68–75.
Koka, B.R., Prescott, J.E., 2008. Designing alliance networks: the influence of network position, environmental change, and strategy on firm performance. Strat. Manag. J. 29 (6), 639–661.
Kuhlmann, S., Edler, J., 2003. Scenarios of technology and innovation policies in Europe: investigating future governance. Technol. Forecast. Soc. Change 70 (7), 619–637.
Kumar, K., Boesso, G., Favotto, F., Menini, A., 2012. Strategic orientation, innovation patterns and performances of SMEs and large companies. J. Small Bus. Enterprise Dev. 19 (1), 132–145.
Li, M., Xiao, F., Cheng, Y., Xie, B.J., Liu, C.Y., Xu, B., 2019. Exploring the relationship between network position and innovation performance: evidence from a social network analysis of high and new tech companies from a less-developed area in China. Chin. Manag. Stud. 14 (1), 93–111.
Li, X., 2009. China's regional innovation capacity in transition: an empirical approach. Res. Pol. 38 (2), 338–357.
Lyu, L., Wu, W., Hu, H., Huang, R., 2019. An evolving regional innovation network: collaboration among industry, university, and research institution in China's first technology hub. J. Technol. Tran. 44 (3), 659–680.
Lyu, Y., He, B., Zhu, Y., Li, L., 2019. Network embeddedness and inbound open innovation practice: the moderating role of technology cluster. Technol. Forecast. Soc. Change 144, 12–24.
Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: response to six criticisms. Environ. Innov. Soc. Transit. 16, 76–86.
Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework. Res. Pol. 37 (4), 596–615.
Metcalfe, S., 1995. The economic foundations of technology policy: equilibrium and evolutionary perspective. In: Handbook of the Economics of Innovations and Technological Change. Stoneman. Paul. Blackwell, Oxford, UK.
Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. J. Clean. Prod. 128, 105–115.
Mitsuhashi, H., Min, J., 2016. Embedded networks and suboptimal resource matching in alliance formations. Br. J. Manag. 27 (2), 287–303.
Montenegro, R.L.G., Ribeiro, L.C., Britto, G., 2021. The effects of environmental technologies: evidences of different national innovation systems. J. Clean. Prod. 284, 124742.
Moore, J.F., 1993. Predators and prey: a new ecology of competition. Harv. Bus. Rev. 71 (3), 75–86.
Moran, P., 2005. Structural vs. relational embeddedness: social capital and managerial performance. Strat. Manag. J. 26 (12), 1129–1151.
Musiolik, J., Markard, J., Hekkert, M., Furrer, B., 2020. Creating innovation systems: how resource constellations affect the strategies of system builders. Technol. Forecast. Soc. Change 153, 119209.
Muñiz, A.S., Cuervo, M.R., 2018. Exploring research networks in Information and Communication Technologies for energy efficiency: an empirical analysis of the 7th Framework Programme. J. Clean. Prod. 198, 1133–1143. https://doi.org/10.1016/j.jclepro.2018.07.049.
Mytelka, L.K., Smith, K., 2002. Policy learning and innovation theory: an interactive and co-evolving process. Res. Pol. 31 (8–9), 1467–1479.
Nahapiet, J., Ghoshal, S., 1998. Social capital, intellectual capital and the organizational advantage. Acad. Manag. Rev. 23 (2), 242–266.
Negro, S.O., Suurs, R.A.A., Hekkert, M.P., 2008. The bumpy road of biomass gasification in The Netherlands: explaining the rise and fall of an emerging innovation system. Technol. Forecast. Soc. Change 75 (1), 57–77.
Newman, M.E.J., 2003. The structure and function of complex networks. SIAM Rev. 45 (2), 167–256.
Oh, D.S., Phillips, F., Park, S., Lee, E., 2016. Innovation ecosystems: a critical examination. Technovation 54, 1–6.
Papaioannou, Th, Wield, D., Chataway, J., 2009. Knowledge ecologies and ecosystems? An empirically grounded reflection on recent developments in innovation systems theory. Environ. Plann. C Govern. Pol. 27 (2), 319–339.
Parida, V., Oghazi, P., Ericson, Å., 2014. Realization of open innovation: a case study in the manufacturing industry. J. Promot. Manag. 20 (3), 372–389.
Pinheiro, M.L., Serôdio, P., Pinho, J.C., Lucas, C., 2016. The role of social capital towards resource sharing in collaborative R&D projects: evidences from the 7th Framework Programme. Int. J. Proj. Manag. 34 (8), 1519–1536.
Porto-Gomez, I., Zabala-Iturriagagoitia, J.M., Leydesdorff, L., 2019. Innovation systems in México: a matter of missing synergies. Technol. Forecast. Soc. Change 148, 119721.
Ruef, M., Aldrich, H., Carter, N., 2003. The structure of founding teams: Homophily, strong ties, and isolation among U.S. Entrepreneurs. Am. Socio. Rev. 68, 10.1177.
Sá, E.S., de Pinho, J. C. M. Rd, 2019. Effect of entrepreneurial framework conditions on R&D transfer to new and growing firms: the case of European Union innovation-driven countries. Technol. Forecast. Soc. Change 141, 47–58.
Schot, J., 1998. The usefulness of evolutionary models for explaining innovation. The case of The Netherlands in the nineteenth century. Hist. Technol. 14 (3), 173–200.
Scott, W.R., 2005. Institutional theory: contributing to a theoretical research program. In: Smith, K.G., Hitt, M.A. (Eds.), Great Minds in Management: the Process of Theory Development. Oxford University Press, Oxford, UK.
Subramaniam, M., Youndt, M.A., 2005. The influence of intellectual capital on the types of innovative capabilities. Acad. Manag. J. 48 (3), 450–463.
Van Alphen, K., Hekkert, M.P., van Sark, W.G.J.H.M., 2008. Renewable energy technologies in the Maldives – realizing the potential. Renew. Sustain. Energy Rev. 12 (1), 162–180.
Van Alphen, K., Noothout, P.M., Hekkert, M.P., Turkenburg, W.C., 2010. Evaluating the development of carbon capture and storage technologies in the United States. Renew. Sustain. Energy Rev. 14 (3), 971–986.
Van der Loos, A., Normann, H.E., Hanson, J., Hekkert, M.P., 2021. The co-evolution of innovation systems and context: offshore wind in Norway and The Netherlands. Renew. Sustain. Energy Rev. 138, 110513.
Van Rijnsoever, F.J., Van Den Berg, J., Koch, J., Hekkert, M.P., 2015. Smart innovation policy: how network position and project composition affect the diversity of an emerging technology. Res. Pol. 44 (5), 1094–1107.
Wang, S., Wang, H., Wang, J., 2019. Exploring the effects of institutional pressures on the implementation of environmental management accounting: do top management support and perceived benefit work? Bus. Strat. Environ. 28 (1), 233–243.
Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications. Cambridge Press, UK.
Weber, K.M., Truffer, B., 2017. Moving innovation systems research to the next level: towards an integrative agenda. Oxf. Rev. Econ. Pol. 33 (1), 101–121.
Yin, H., Zhao, J., Xi, X., Zhang, Y., 2019. Evolution of regional low-carbon innovation systems with sustainable development: an empirical study with big-data. J. Clean. Prod. 209, 1545–1563.
Zhang, J.J., Guan, Jc, 2019. The impact of competition strength and density on performance: the technological competition networks in the wind energy industry. Ind. Market. Manag. 82, 213–225.
Zhao, Y., Peng, B., Elahi, E., Wan, A., 2021. Does the extended producer responsibility system promote the green technological innovation enterprises? An empirical study 2021 based on the difference-indifferences model. J. Clean. Prod. 319, 128631.

5.3. Contribution of the Horizon2020 Programme to the Research and Innovation Strategies for Smart Specialisation in the coal regions in transition: the Spanish case

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Article

Contribution of the Horizon2020 Program to the Research and Innovation Strategies for Smart Specialization in Coal Regions in Transition: The Spanish Case

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Abstract: This work aims to assess how regional innovation systems support research and innovation smart specialization strategies (RIS3) in coal intensive regions. Although many authors have analyzed energy transition paths for the European coal regions, no study has assessed how the network properties of their innovation systems are aligned with the priorities identified in their RIS3. This work fills this gap, relying on social network analysis (SNA) to assess innovation systems' underlying networks, considering the active role of their nodes, thus, contributing to the innovation systems literature in the areas of modelling, simulation and performance evaluation. Within this work, regional innovation systems are modelled as research networks. These networks are promoted by the consortia funded by the European H2020 program. The assessment of the topology and properties of these networks enables the evaluation of the functioning of the innovation system, its technological strengths, as well as the key players involved. Based on these results, the characteristics of the innovation systems are compared to the priorities established by the RIS3. Three Spanish coal intensive regions (Aragón, Asturias and Castilla y León) are considered as use cases in this study. The obtained results indicate that, in some cases, the technological strengths of the regional innovation systems are not considered in the identification of the RIS3 priorities, while some RIS3 priorities are not supported by the innovation system. Considering these results, this paper proposes recommendations for regional and European policymakers, as well as for participants in the European research programs.

Keywords: regional innovation systems; European Union; H2020; research and innovation smart specialization strategies; coal intensive regions; just transition; research networks

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Highlights

- The EU finance collaborative research to support the fulfillment of social, competitiveness and climate goals.
- The EU regions have put in place smart specialization strategies (RIS3), identifying their priorities.
- The EU funded innovation projects and related consortia construct innovation systems at a regional level, developing networks of projects and partners.
- The properties of the innovation systems' underlying networks are related to the consecution of the RIS3 priorities.
- The networks' properties can be assessed by means of social network analysis, obtaining network cohesion and node centrality metrics.
- There is a misalignment between the innovation systems' properties and the RIS3 priorities.
- The innovation system networks assessment can be a fundamental tool for policymakers and participants to reach greater results.

1. Introduction

1.1. Overall Approach

The concept of regional smart specialization has become central for European policies related to innovation, growth and sustainable development since 2013 [1], when the European Commission started the process for developing regional research and innovation smart specialization strategies (RIS3). For the regions that are not major innovation players, RIS3 aligned policies are crucial to promote innovation in those sectors or technological domains that may provide them with a competitive advantage [2]. This is the case of the European coal regions in transition, which are facing the challenge of shifting towards a low carbon economy, and which may significantly benefit from a well designed and implemented RIS3 [3]. While most of the related literature focuses on the deployment of other energy technologies [4–6] or in the evaluation of the social impacts—especially in the employment—of the energy transition in these regions [7,8], there is a gap in addressing how the innovation systems promoted in the coal in transition regions contribute to their RIS3 implementation, as well as in evaluating how the RIS3 designs consider the existing innovation systems.

The research and innovation collaborative projects funded by the European Union under the Horizon 2020 program (H2020) contribute to the creation of innovation systems [9,10]. Although H2020 looks for transnational collaboration, it has been established by previous authors that this program is particularly interesting for evaluating the role of regional innovation networks [11]. Previous studies have assessed how actors and institutions interact in the energy transition process from a regional innovation system perspective, drawing conclusions mainly from semistructured, qualitative interviews [12]. Nevertheless, although different authors have pointed out the relevance of studying innovation systems' network properties [13–16], the properties of the regional innovation systems' underlying networks promoted by H2020 in the European coal regions in transition have not been characterized, neither has their contribution to the RIS3 implementation been assessed.

This study addresses the correspondence between the H2020 regional innovation networks' properties and the RIS3 priorities. For this purpose, and considering that H2020 projects promote innovation systems that can be studied relying on the properties of their underlying networks of partners and projects, the authors propose the following research questions:

- How do innovation systems contribute to the deployment of the RIS3 priorities in the coal in transition regions?
- How are the Innovation Systems for the RIS3 design in the coal in transition regions considered?

The novelty of this work remains the assessment of the support of regional innovation systems to the RIS3, considering the regional research networks' topology and properties. The assessment of these networks provides information about the innovation system's functioning, its technological strengths, as well as the key players involved. These results are then compared to the RIS3 priorities, to identify synergies and misalignments.

For addressing the research questions, the use case of the three Spanish coal regions in transition (Aragón, Asturias and Castilla y León) has been considered. Thus, the networks of projects and partners within each region are constructed relying on the H2020 participation data from the period 2013–2020. The consideration of the entities' characteristics (type and role in the project), as well as the thematic area of the projects, allows the consideration of the nodes as active players within the network. Therefore, conclusions may be drawn regarding the degree of contribution of the H2020 promoted innovation systems to each RIS3 priority, as well as about innovation systems' strengths not yet considered in the RIS3 priorities.

Regarding the instrumental and operational framework, this study relies on social network analysis (SNA). SNA has been proven as a powerful tool, previously used by different authors to assess sustainability aspects [17–19], as well as collaboration and projects' relationships [20,21]. Taking into account that the H2020 program funds projects that are developed by consortia composed by at least three entities, this study analyzes the two underlying networks behind the innovation system: (1) the network of projects, in which projects that share partners are linked and (2) the network of entities, in which entities that cooperate in the same project are connected. These networks can be geographically restricted to the entities and projects nestled in a region and, thus, can enable the study of the relationships between the different types of entities within the region (industry, university, research centers, etc.), as well as the main research fields and technologies tackled by the projects developed in the region. The assessment of these networks enables the evaluation of the competitiveness increase of the regional industries, as well as the framework in which knowledge transfer and exchange is facilitated, or enabled [22,23].

The main characteristics of the regional innovation systems are assessed following a twofold approach: (1) the study of the regional networks as a whole and single system, and (2) the analysis of the contribution and role of the networks' nodes, considering them as active members of the system. A better understanding of the regional innovation system is enabled by this twofold approach, at system—and actor—level [24], thus enabling the assessment of how the regional innovation systems' characteristics are considered in the RIS3 design.

This paper is organized as follows: Section 2 presents the research model, providing the conceptual framework and the literature review related to regional innovation systems and smart specialization strategies, emphasizing the coal in transition regions' particularities. The materials and methods used in the study are detailed in Section 3, providing the data used for developing the empirical study; thus, a summary of the coal regions' characteristics, their RIS3 and the data used for constructing the regional networks underlying the innovation systems is provided. The results of the study are presented in Section 4, explaining the correlation between the network and nodes' properties and the RIS3. Finally, Section 5 provides a discussion of the obtained results and the final conclusions of the study.

1.2. Smart Specialisation Strategies: The European RIS3

The definition of smart specialization strategies (S3) has been recently set as "the strategic approach to plan for regional economic development directed at economic diversification, supported by technological, practice, and evidence-based innovations, using a bottom-up approach" [1,25,26]. In this context, the European Commission requested that regional authorities across Europe design their research and innovation smart specialization strategies (RIS3) to achieve more efficient use of the European Structural Investment Funds and the H2020 Funds [27,28]. Each RIS3 represents the transformation agenda in which the regional innovation priorities, challenges and needs are identified and tackled, to build a competitive advantage by developing and matching research and innovation's own strengths to business needs, to address emerging opportunities and market developments in a coherent manner.

1.3. Regional Innovation Systems

The S3 approach is linked with the regional innovation systems field [2], which is receiving increasing attention from the energy transitions research area [29,30]. In this context, the promotion of regional innovation systems enables the support of RIS3 implementation, and is considered a key factor for successfully shifting towards a low carbon economy in the coal regions in transition.

Regional innovation systems may be assessed by means of the properties of the research networks resulting from H2020 program within these regions [31]. Within this approach, the funded H2020 consortia develop, on the one hand, networks of partners—in which those entities collaborating in the same project are linked—and, on the other hand, networks of projects—in which those projects sharing partners are connected. Social network analysis has recently emerged as a powerful technique to evaluate innovation systems, which has the unexploited potential to study the consistency between smart specialization policies and innovation systems [32].

1.4. Coal Regions in Transition

Previous authors [33–37] have established that the transition towards a low carbon economy may have pernicious effects at regional and local levels, particularly, in coal-reliant regions. To mitigate the social consequences of the low carbon transition and to ensure a just transition, the European Commission launched the European Coal Regions in Transition Initiative.

Theoretical frameworks related to energy transitions, including coal intensive regions, integrate the concept of innovation systems [38–40] as a key influence for a successful process. In this respect, innovation systems related research has evaluated how institutional impulses have contributed to the development of innovation systems by means of characterizing the research networks promoted by the research funding programs. Nevertheless, the particular case of the coal in transition regions and, especially, how the innovation systems in these regions have been developed compared to the RIS3 agendas, has not been addressed.

The European Commission identifies the coal in transition regions in Europe as the most carbon intensive, or with the most people working in fossil fuels. Although coal mining and using regions are easily identified attending to the location of mines and coal power plants, the European Commission accepts [41] that the concept of carbon intensive regions has not yet been defined and would require further work. Nevertheless, the European Commission has already identified the 31 regions in the European Union that compose the Coal Regions in Transition Platform, in which the three considered in this work participate.

2. Materials and Methods

2.1. Research Design

To answer the research questions, the regional innovation systems' network properties (topology, cohesion, centrality) are firstly assessed and, then, the obtained results are compared to the RIS3 priorities established at each coal in transition region. Within this section, the research design is presented considering the following approach. Firstly, to provide the minimum context of the situation and challenges of each region, this section presents the main social, economic and innovation activity data of the three regions considered in the study.

Then, the two main sources of data considered in this study are presented. From one perspective, the three regional research and innovation smart specialization strategies (RIS3) are used to collect the priorities from each region. From the other perspective, the data from the projects and consortia funded under the Horizon 2020 program are the basis for the analysis of the innovation systems' underlying networks.

In addition to the data considered, this section presents the methods used for their analysis. While the RIS3 strategies are examined by means of a comparative analysis, the H2020 participation data are analyzed relying on social network analysis (SNA). For this purpose, once the underlying networks of the innovation systems are constructed, two different approaches are considered: firstly, the networks are studied from the point of view of the connections between the partners (networks of partners) and from the point of view of the links between the projects (technological trajectories). Secondly, the innovation systems are assessed considering the network as a whole (the cohesion proprieties of the network) and, in addition, evaluating the role played by each node (the centrality metrics of the nodes). For this last purpose, the SNA is performed taking into account the intrinsic characteristics of the nodes: for an entity, its geographical location, the type of activity performed and if it has acted as a coordinator, while, for a project, the research area tackled, broken down by the pillar, programme and subprogramme within H2020, within which it has been funded.

Finally, the results obtained from the comparative analysis of the three RIS3, together with the ones coming from the innovation systems' underlying networks SNA, are contrasted to answer the proposed research questions.

2.2. Socioeconomic and Innovation Data of the Three Spanish Coal Regions

In order to give the minimum context of each Spanish coal region, Tables 1 and 2 present the basic information related to region size, economic activity and innovation development [42].

Table 1. Gross domestic product, population and surface of the three regions and Spain.

	GDP (Million Euros)		Population		GDP Per Capita (EUR)	Surface (km^2)	
Region	**Total**	**Percentage**	**Total**	**Percentage**	**Total**	**Percentage**	**Total**
Spain	1,253,988 €	100.00%	47,431,256	100.00%	EUR 26,438	100.00%	505,909
Aragón	38,525 €	3.10%	1,328,753	2.80%	EUR 28,993	9.43%	47,720
Asturias	23,894 €	1.90%	1,018,706	2.10%	EUR 23,455	2.10%	10,604
Castilla y Leon	59,253 €	4.70%	2,393,285	5.00%	EUR 24,758	18.63%	94,226

Table 2. Research activity in economic terms and in human resources dedication of the three regions and Spain.

	Internal Expenditure on R&D Activities (Thousand Euros)		R&D Internal Expenditure per GDP	Researchers (Full-Time Equivalent)		Researcher per Population	R&D Expenditure per Researcher
Region	Total	Percentage	Total	Total	Percentage	Total	Total
Spain	14,945,692	100.00%	1.19%	140,120	100.00%	0.30%	EUR 106,664
Aragón	339,741	2.30%	0.88%	4049	2.90%	0.30%	EUR 83,907
Asturias	188,453	1.30%	0.79%	2299	1.60%	0.23%	EUR 81,972
Castilla y León	762,659	5.10%	1.29%	6435	4.60%	0.27%	EUR 118,517

The Aragón region includes 2.8% of the Spanish population; nevertheless, it represents 3.1% of the national gross domestic product (GDP), with the greatest GDP per capita of the three regions (EUR 28,993), even higher than the national average (EUR 26,438). In addition, Aragón holds a large territory, with 9.43% of the total Spanish surface. In terms of innovation, the number of researchers is in line with the national rate, while the internal expenditure is significantly lower, representing only 2.3% of the total national internal expenditure. The internal expenditure per GDP in the region accounts for 0.88%, significantly lower than the national rate of 1.19%. The number of researchers per population is the highest of the three regions and coincides with the national average (0.3%).

Asturias is the smallest region of the three Spanish coal regions in terms of population and surface, with both being 2.1% of the total national. Nevertheless, its GDP share of the national total accounts only for 1.9%, and the GDP per capita is below the national value (EUR 23,455 compared to EUR 26,438). This weak position also appears in terms of research expenditure, which represents only 1.3% of the total national and constitutes 0.79% of internal expenditure per GDP, also significantly lower than the national rate of 1.19%. The number of researchers is also the smallest of the three, 0.23% of the total population; with the R&D expenditure per researcher also being the smallest one, EUR 81,972 compared to the EUR 106,664 of the national average.

Castilla y León is the largest region in terms of GDP and population, accounting for 4.7% and 5% of the total national, respectively, and with a large surface that represents 18.63% of the Spanish total. Nevertheless, the GDP per capita is below the national average, at EUR 24,758 compared to the national, EUR 26,438. Castilla y León stands out for its high internal expenditure in research, which represents 1.29% of its total GDP, above the national average (1.19%). The number of researchers is slightly below the average national rate (0.27% compared to 0.3%), which increases the total research expenditure per researcher up to EUR 118 517, which is clearly above the ones of Aragón (EUR 83,907) and Asturias (EUR 81,972), as well as the national average (EUR 106,664).

Although coal production was stopped in Spain by 31 December 2018, this milestone happened after a decreasing period. The total extraction of coal in Spain diminished from 8434 kt in 2010 to 2407 kt in 2018. From the total coal produced in Spain in 2018, 55.4% came from Aragón, 30.3% from Castilla y León and 14.3% from Asturias. Meanwhile, the employment associated with coal extraction decreased in Spain from 45,212 jobs in 2012 to 1253 in 2018, all based on the three Spanish regions considered in this study [43].

2.3. Smart Specialization Strategies: Data Analysis of the Three Spanish Coal Regions

The priorities identified in the RIS3 by each of the three Spanish coal regions are presented in Tables 3–5, including the priority name and its description. As a first conclusion, there are great differences between the scope of the proposed priorities, especially considering the level of detail and specificity. Thus, in some cases, within one priority, many technologies, sectors, applications or aspects are considered in its description. While Aragón and Asturias identify and describe more clearly their 9 and 5 priorities, respectively, Castilla y León provides a long description of its 6 priorities, integrating different and, in some cases, disconnected aspects. This disparity of criteria complicates the process of finding synergies or common priorities.

Table 3. Aragón priorities identified in the RIS3.

Priority Name	Description
Management of water resources	Information systems and monitoring of hydrological management
ICT	Digital Agenda
Resources efficiency	Closing cycles of water, materials and energy.
Transport and logistics	Integration and improvement of supply chains (resources efficiency and intermodal transport).
Tourism and leisure	Touristic activities based on natural resources and cultural heritage and quality of life; new technologies for innovative solutions in tourism.
Healthy ageing	Improvement of the quality of life, with special attention to the dispersed and ageing population.
Development of more efficient vehicles	Innovation in vehicle engineering and design, and in equipment for vehicle refueling, particularly for hydrogen fuels.
Energy storage and efficiency	Storage and integration of energy systems, including hydrogen and fuel cells, smart grids and water cycles.
Agri-food value chain	Development of new products, processes and technologies in the agricultural, food and forestry sectors.

Table 4. Asturias priorities identified in the RIS3.

Priority Name	Description
Steel and maritime industry	Open innovation processes in steel production and shipbuilding manufacturing.
Advanced manufacturing and materials	Digital manufacturing and additive manufacturing; nanomaterials and graphene.
Health research and medical care	Health research and management; biomedicine and ageing population medical care; demographic change effects and wellbeing.
Technologies for energy production and supply	Energy supply and demand, including smart grids and energy storage; natural water cycle management; big data; and sensors.
New technologies applied to agri-food	Development of systems and processes for agri-food resources management, particularly the application of biotechnology for dairy industries

Table 5. Castilla y León priorities identified in the RIS3.

Priority Name	Description
Agri-food and sustainable use of natural resources	Food security; development of bioindustries. Agriculture, livestock and continental aquaculture, food quality and food technology, bioenergy and forestry.
Transport (in particular automotive and aeronautics)	Productive efficiency in the transport sectors. Applications of KETs such as advanced materials (including nanocomposites and graphene), ICT, biotechnology (bio-polymers, use of biofuels and biocatalysts) and advanced manufacturing and processing. Sustainability, security and mobility of persons and goods (logistics).
Health, social care, demographic change and wellbeing	Biomedical research and applications, innovative medicines, research and innovation in social care, ageing and ambient assisted living. Cancer research and new therapeutic and diagnostic solutions, biomedical research, attention to long term patients, technologies for social inclusion. KETs: biotechnology (cellular therapy, molecular diagnostic, pharmacology, tissue engineering), ICT (e-Health), and advanced materials (biopolymers, nanomaterials)
Cultural and natural heritage and Spanish language	Heritage and language as endogenous resources for economic development and social welfare. Language technologies and applications to cultural heritage. Environmental sustainability, climatic change and water. Application of ICT and new production processes in languages. Application of KETs to diagnostics, conservation and management. Advanced materials (new treatments for wood, stone, and other materials, advanced materials for the conservation of cultural heritage). Biotechnology (biodamagers, biocleaning and bioconsolidation) and fossil DNA.
ICT	Cybersecurity, applications and technologies of mobility, M2M communications, big data and cloud computing technologies and the Internet of the future.
Energy and sustainability	Technologies for energy management, energy efficiency, renewable energies, environmental sustainability of the industry and human habitat (buildings, constructions, etc.). Smart cities, energy efficient buildings, factories of the future, sustainable processing industry through resource and energy efficiency. ICT applied to energy and sustainability (home automation, district heating and cooling, monitoring), advanced materials (biomaterials, recyclable and recycled materials, new treatments for wood and construction materials), advanced manufacturing and processing.

Despite the different scopes considered in each region, there are some common priorities that are related to four main areas: energy, resource efficiency, health and agri-food.

In the energy field, Aragón is interested in the integration of energy systems (smart grids, energy storage and hydrogen and fuel cells); Asturias includes a more holistic approach, also including energy generation, and Castilla y León emphasizes the demand side, targeting energy efficiency, smart cities and energy management technologies.

Considering the resource sfficiency area, Aragón identifies water and materials efficiency as priorities, proposing a circular economy approach. Asturias, in addition to water cycle management, is interested in resource efficiency in the process industry (mainly steel). Castilla y León also proposes sustainability in the process industry and water management as key priorities.

Health is a priority for the three regions. Aragón emphasizes attention to the dispersed and ageing population, thus tackling demographic change. Asturias also considers its ageing population, also including biomedicine, as a relevant field. Castilla y León, in addition to the previous areas, identifies cancer research and innovative medicines as important fields.

Agri-food is widely considered in Aragón, including agricultural, food and forestry sectors. In Asturias, the special mention of biotechnologies for dairy industries is considered, while, in Castilla y León, food security, together with agriculture, aquaculture and forestry, are identified as priorities.

Finally, there are some enabling technologies, such as new materials or ICT, that are widely considered in the three regions.

Regarding the current low transition paths in the three regions, the Spanish government proposed an Urgent Action Plan in 2020 [44], addressing the coal regions to promote new activities and employment. This plan aims to compensate for the vulnerabilities created after the coal sector's closing and promotes low carbon transition paths. This plan provides funding, regulatory and administrative support for the deployment of new renewable energy capacity, as well as for industrial and research projects, together with social initiatives targeting the affected citizens. At the moment of the publication of this paper, the process is still open, having completed the diagnosis phase and being about to start identifying investments and projects to promote low carbon transition paths. Once the diagnosis has been completed and made public [45], the regions will benefit from their participation in the Just Transition Platform, for identifying the most promising low carbon transition paths.

2.4. Participation in Horizon2020 Program: Spanish Coal Regions' Participation Data Analysis

For developing this study, data corresponding to the Horizon 2020 Research program coming from the European Commission database (https://data.europa.eu/data/datasets/cordish2020projects?locale=es, accessed on 19 October 2020) are used. The entities based on the three regions are identified relying on their postal code, as included in their addresses.

Table 6 present the entities participating in H2020 based on the three Spanish coal regions, categorized by their activity type and by their role within the consortium. Five different activity types are considered: private companies, in which large, small and medium enterprises are considered; research centers, including technology centers and public research institutes; higher education establishments, in which universities are considered; public bodies, in which local and regional authorities are included; and, finally, other entities, in which associations, among others, are included. Regarding the role played in the projects, those entities that have coordinated at least one project have been categorized as coordinators, while those that have never acted as coordinators are considered as participants.

Table 6. Entities participating in each region distributed by activity type and role.

	Total	Aragón	Asturias	Castilla y León
Private companies	**229 (70%)**	**98 (75%)**	**53 (78%)**	**78 (62%)**
Coordinator	88	42	20	26
Participant	141	56	33	52
Research centers	**37 (11%)**	**13 (10%)**	**6 (9%)**	**18 (14%)**
Coordinator	14	7	1	6
Participant	23	6	5	12
Higher education	**9 (3%)**	**3 (2%)**	**1 (1%)**	**5 (4%)**
Coordinator	7	2	1	4
Participant	2	1	0	1
Public bodies	**22 (7%)**	**9 (7%)**	**2 (3%)**	**11 (9%)**
Coordinator	2	1	0	1
Participant	20	8	2	10
Other entities	**28 (9%)**	**8 (6%)**	**6 (9%)**	**14 (11%)**
Coordinator	4	0	2	2
Participant	24	8	4	12
Total general	**325**	**131**	**68**	**126**
Coordinator	115 **(35%)**	52 **(40%)**	24 **(35%)**	39 **(31%)**
Participant	210 **(65%)**	79 **(60%)**	44 **(65%)**	87 **(69%)**

A total of 325 entities from the three regions are participating in H2020, 131 from Aragón, 68 from Asturias and 126 from Castilla y León. Private companies represent 70% of the participants, with this proportion being higher in Aragón (75%) and in Asturias (78%)

compared to Castilla y León (62%). Research centers represent 11% of the participants, with a higher share in Castilla y León (14%) than in Aragón (10%) and Asturias (9%). Public bodies constitute, on average, 7% of the participants, with only 3% in Asturias compared to Aragón (7%) and Castilla y León (9%).

In coordination terms, 35% of all the entities have played the coordination role at least once. This proportion is higher in Aragón (40%) and lower in Castilla y León (31%). Private companies are more prone to take the coordinator role, constituting 77% of all the coordination, on average.

Table 7 presents the number of participations of each entity type to quantify their activity, split into participations as a coordinator or as a participant. The 325 entities from the three regions account for 1016 participations, so, on average, each participating entity is involved in 3.13 projects. Nevertheless, this parameter of recurrence varies between regions, reaching 3.40 in Aragón, 3.13 in Castilla y León and 2.59 in Asturias. Therefore, it can be seen how the recurrence ratio in Asturias is 21% below the average of Aragón and Castilla y León. Considering the entity types, 89% of the participations come from three main actors: private companies (40%), research centers (28%) and higher education establishments (21%). In the three regions, the higher recurrence ratio appears in higher education establishments as, on average, each entity participates 24.22 times. They are followed by research centers, which reach 7.65, with high variability between Aragón (11.31) and Asturias (3.67). Finally, companies present a recurrence rate of 1.79 on average, varying from 1.68 in Castilla to 1.72 in Aragón and 2.06 in Asturias.

Table 7. Number of participations in each region distributed by activity type and role.

	Total	Aragón	Asturias	Castilla y León
Private companies	409 (40%)	169 (38%)	109 (62%)	131 (33%)
Coordinator	116	58	27	31
Participant	293	111	82	100
Research centers	283 (28%)	147 (33%)	22 (13%)	114 (29%)
Coordinator	70	46	2	22
Participant	213	101	20	92
Higher education	218 (21%)	97 (22%)	21 (12%)	100 (25%)
Coordinator	60	19	7	34
Participant	158	78	14	66
Public bodies	59 (6%)	21 (5%)	10 (6%)	28 (7%)
Coordinator	4	2	0	2
Participant	55	19	10	26
Other entities	47 (5%)	11 (2%)	14 (8%)	22 (6%)
Coordinator	8	1	5	2
Participant	39	10	9	20
Total general	1016	445	176	395
Coordinator	258 (25%)	126 (28%)	41 (23%)	91 (23%)
Participant	758 (75%)	319 (72%)	135 (77%)	304 (77%)

The 1016 participations of the 325 entities from the three Spanish coal regions take place in 799 H2020 projects. There are 6 projects on which entities from the three regions collaborate, 4 in which entities from Aragón and Asturias participate together, 19 including entities from Aragón and Castilla y León and 15 with entities from Asturias and Castilla y León. It is relevant that Aragón and Castilla y León are collaborating on 10 projects within the Energy Programme under the Societal Challenges Pillar.

Table 8 presents how these 799 projects cover the different Pillars and Programmes of H2020 and identifies the regions from which there are participating entities. Those projects involving participants from more than one region are included in all those regions. Within the Excellent Science Pillar, the participation is concentrated in the Marie Curie Actions, with 123 projects. In the Industrial Leadership Pillar, 201 out of the 223 projects take place in the Leadership in Enabling and Industrial Technologies. The Science for Society Pillar is covered mainly by Aragón, with 4 out of the 5 projects. The Societal Challenges Pillar includes the highest number of projects, 402, which represent 50.3% of the total. The programs related to the energy and agri-food sectors account for the highest number of projects within this pillar: 129 and 95 projects, respectively, with Aragón being particularly active in both of them, especially in energy, with 79 projects.

Table 8. Number of projects in which entities from Aragón, Castilla y León and Asturias are present, disaggregated by Pillar and Programme.

Pillar and Programme	Number of Projects	Aragón	Asturias	Castilla y León
Excellent Science	**165**	**67**	**25**	**82**
European Research Council	13	6	3	4
Future and Emerging Technologies	17	9	5	9
Marie Curie Actions	123	50	16	60
Research Infrastructures	12	2	1	9
Industrial Leadership	**223**	**92**	**59**	**91**
Innovation in SME	22	10	10	8
Leadership in Enabling and Industrial Technologies	201	82	49	83
Science for Society	**5**	**4**	**0**	**1**
Societal Challenges	**402**	**204**	**62**	**158**
Climate action, environment, resource efficiency and raw materials	44	20	3	23
Secure, clean and efficient energy	129	79	17	47
Food security, sustainable agriculture and forestry, water and bioeconomy	95	48	12	39
Health, demographic change and wellbeing	44	15	10	19
Inclusive, innovative and reflective societies	18	8	3	7
Secure societies—protecting freedom and security	16	2	8	7
Smart, green and integrated transport	56	32	9	16
Spreading Excellence	**4**	**0**	**0**	**4**
Total general	799	367	146	336

2.5. Innovation Systems Network Construction

The participation of the entities from the three Spanish coal regions in Horizon 2020 is studied from the innovation system perspective. For this purpose, the networks of entities and projects fostered by the consortia funded by the European Commission within the Horizon 2020 program are constructed, considering the links between entities cooperating in the same project, as well as the connections between projects sharing common entities. An affiliation matrix, in which entities are assigned to projects, enables the construction of a 2-mode network. From this 2-mode network, two 1-mode networks are constructed, one in which entities participating in the same project are connected and one in which projects sharing common partners are linked. Figure 1 presents a graphic example of these 2-mode and 1-mode networks. This constitutes the first analysis perspective, in which how the entities are collaborating is assessed through the network of entities, and how the projects are connected is assessed in the network of projects.

The second perspective considered in this analysis evaluates the innovation system with a double approach: The first one assesses the network as an innovation system, neglecting the role played by its nodes, thus evaluating how the innovation system as a whole is capable of transmitting information. This first assessment, at the network level, is based on the cohesion metrics, which evaluate the network in its entirely. The second assessment is developed from a node-based perspective, evaluating how each individual node contributes to the network functioning, thus assuming the active role of the nodes.

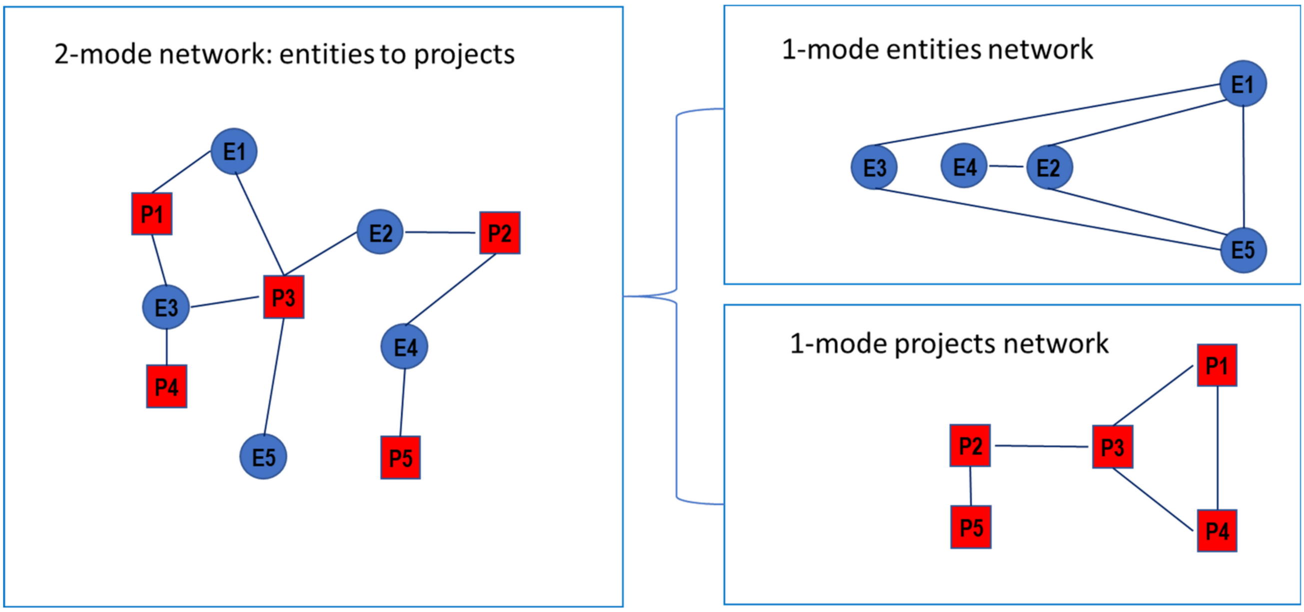

Figure 1. Example of the 1-mode networks (entities network and projects network) that are deducted from the 2-mode network (entities to projects network).

2.6. Network Cohesion and Node Centrality Metrics

The topological, cohesion and centrality characteristics of the regional innovation systems are assessed through a nominalist approach, which enables the construction of the graphs of projects and entities. To build the graphs, an affiliation matrix is constructed, linking entities to projects. Then, attributes are assigned to the nodes, following a methodology usually applied in similar research works [46]. The software UCINET has been employed to perform the SNA (Borgatti, S.P., Everett, M.G. and Freeman, L.C. 2002. Ucinet 6 for Windows: Software for Social Network Analysis. Harvard, MA: Analytic Technologies).

A twofold perspective is used in the analysis: (1) a system approach, in which the cohesion of the network and functioning characteristics of the regional innovation systems are assessed as a whole and (2) a node level approach, in which the role and contribution of each node is measured in terms of its embeddedness in the system, relying on centrality metrics.

The cohesion metrics used in this work to assess the underlying networks of the regional innovation systems are the following:

- Average degree: average degree of all nodes. This represents the network activity.
- Average distance: average distance between all reachable pairs of nodes, with the distance between two connected nodes being the length of the shortest path, calculated as the number of edges that it contains. This represents the level of compactness or dispersion of the network.
- Diameter: longest length of the shortest paths of all the reachable nodes. This represents the network extent.
- Density: total number of existing ties divided by the total number of possible ties. For weighted networks, such as the ones analyzed in this work, this is the total of all values divided by the number of possible ties.
- Components: number of sets of connected nodes that are not linked to the rest of the network. This represents the number of nonconnected subnetworks.
- Average tie strength between groups: average of the weighted connections of the links between nodes with different attributes. This represents the strength of the connection between different types of nodes within the network.

- H-Index: maximum number of nodes that have at least the same number of connections to other nodes. This represents the network cohesion, avoiding the effects of outliers.

The node level analysis, also known as dyadic analysis, assesses the network embeddedness of the nodes, providing the informational value of the nodes attending to its structural position in the network [47]. Furthermore, the node position and embeddedness provide differential access to information within innovation systems [48,49]. The following metrics are considered in this study:

- Degree: number of nodes to which a given one is connected. In the case of weighted networks, as in this work, this calculates the sum of the ties' values. This represents the opportunities of a node to access the knowledge that is flowing through the network.
- Closeness: for a particular node, the average of the lengths of the shortest paths to every other node of the network. This represents how close a node is to all the other nodes.
- Eigenvector: influence of a node in the network. This represents a prestige rating, in which relative ratings are given to all nodes in the network, the connections to high-rating nodes contribute more to the score of the considered node than equal connections to low rating ones.
- Betweenness: number of times that a given node belongs to the shortest paths between two other nodes. This represents the control of a particular node over the knowledge flows between all the other nodes of the network.

3. Results

Within this section, the networks of entities and projects behind the European innovation systems fostered by H2020 are constructed and assessed, considering them as a whole system (network cohesion) and evaluating the individual role of the nodes (node centrality). Then, the relation of the H2020 thematic coverage with the RIS3 scientific domains, prioritized for each region, is presented.

3.1. Regional Networks of Entities: Cohesion and Centrality Metrics

The three networks, one for each Spanish coal region, including the entities exclusively based in this region, have been developed. Table 9 presents different cohesion metrics for the three networks.

Table 9. Regional networks of entities: cohesion metrics.

Cohesion Metrics	Aragón	Asturias	Castilla y León
Number of nodes	131	68	126
Number of ties	146	58	120
Average aegree	1.115	0.853	0.952
Index H-Index	4	4	5
Density	0.009	0.013	0.008
Connectedness	0.134	0.062	0.127
Closure	0.138	0.507	0.099
Diameter	8	6	7

The average degree of the entities from the Aragon network is significantly higher (1.115) than in Castilla y León (0.952) and Asturias (0.853). Thus, although the density (i.e., the number of edges divided by the maximum number possible) is higher in Asturias (0.013) than in Aragón (0.009) or in Castilla y León (0.008), this may be an effect of the lower number of participating entities. In this respect, looking to the connectedness ratio, while 13.4% of the entities from Aragón are connected, this metric is reduced in Asturias (6.2%), achieving 12.7% in Castilla y León. Nevertheless, attending to the closure ratio, which is 0.507 in Asturias, 0.138 in Aragón and 0.099 in Castilla y León, it can be seen that, in Asturias, transitivity in relational triads is higher—partners of a partner are also partners—, with the strongest cohesion among the connected entities. This is in line with the diameter (i.e., the length of the longest geodesic path) that is smaller (6) in Asturias, reaching 7 in Castilla y León and 8 in Aragón.

The role of the different types of entities, considering whether they are coordinators or partners, is assessed relying on the centrality metrics presented in Table 10. Although, in general, it can be seen how the coordinators have a prominent role within the networks, Asturias presents lower centrality rates for the coordinators in terms of degree and betweenness. While coordinators in Aragón rank 10.5 times more than participants in eigenvector and those in Castilla y León 7.75 times more, in Asturias, coordinators only rank 3.8 times more. It can be deducted that coordinators in Asturias are poorly integrated into the network compared with the other two regions.

Table 10. Regional networks of entities: centrality measures disaggregated by the role played in the projects.

Role and Network	Number of Entities	Average Degree	Average Eigenvector	Average Betweenness
Coordinator	**115**	**1.438**	**0.028**	**34.368**
Aragón	52	1.717	0.021	38.422
Asturias	24	0.750	0.038	1.893
Castilla y León	39	1.500	0.031	50.226
Participant	**210**	**1.133**	**0.004**	**4.585**
Aragón	79	1.169	0.002	6.038
Asturias	44	1.675	0.010	5.250
Castilla y León	87	0.845	0.004	3.042
Total general	325	1.255	0.014	16.498

The centrality measures of the different entity types for the three regions are presented in Table 11. Higher education establishments have a prominent position within the networks from the four metrics' perspective, being tractors of the innovation system. This prominent position may be a consequence of the large size of this type of institution, which acts as a knowledge hub. They are followed by research centers, public bodies, other types of entities and, finally, by private companies. It is important to note that, on average, private companies achieve the lowest centrality measures, with the smallest influence in the network. These low centrality measures of the private companies occur, to a larger extent, in Castilla y León, while in Asturias, the situation differs, as private companies hold a more equilibrated situation.

3.1.1. Centrality Measures within the Regional Aragón Network of Entities

Regarding the individual entities, Table 12 presents those entities within the regional network of Aragón with the top ten values at three different indicators: degree, eigenvector and betweenness. A total of 19 entities are participating in these three top ten indexes. Two of them, the University of Zaragoza—the only public University in the region with a long tradition and a generalist scope—and Fundación CIRCE—a private nonprofit technology center focused on energy and sustainability—appear at the two first positions in the three indicators. The public research institute of the region (Instituto Tecnológico de Aragón, with a generalist scope) and the other private nonprofit technology center of the region (Fundación AITIIP, focused on plastics) appear at the third and fourth positions in degree and betweenness, respectively, not being present at the eigenvector top ten; thus having strong participation and serving as a link between other entities, but not having such a relevant position within the network. Then, there are five entities ranking in two of the three lists: one is a public research center focused on hydrogen technologies (Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón), and the other four are private companies, two of them being spin-offs—one from Fundación AITIIP (TecnoPackaging) and the other from the University of Zaragoza (BEOnChip S.L.)—and the other two large companies. Finally, there are nine entities ranking in one of the indicators, two of them are public research institutes linked to the University of Zaragoza—one focused on health (Fundación Instituto de Investigación Sanitaria de Aragón) and one focused on logistics (Fundación Zaragoza Logistics Center)—,one is a public company from the regional government devoted to agriculture and environment (Sociedad Aragonesa de Gestion Agroambiental S.L.), one is the regional federation of businesses (Confederación de Empresarios de Aragón), three are spin-offs from the University of Zaragoza (Ebers Medical technology S.L. and Nanoscale Biomagnetics S.L. and Esciencia Eventos Científicos S.L.) and two are large companies—one devoted to household appliances (BSH Electrodomésticos España S.L.) and a winery (Bodegas Aragonesas S.A.).

Table 11. Regional networks of entities: average centrality measures disaggregated by the entity activity type.

Entity Type and Network	Number of Entities	Average Degree	Average Eigenvector	Average Betweenness	Average Closeness
PRC	**229**	**0.686**	**0.003**	**2.579**	**893.594**
Aragón	98	0.847	0.002	4.374	1085.143
Asturias	53	0.736	0.006	3.057	454.887
Castilla y León	78	0.449	0.002	0.000	951.026
REC	**37**	**3.135**	**0.033**	**73.401**	**875.432**
Aragón	13	4.923	0.010	121.026	1024.000
Asturias	6	1.500	0.012	8.000	436.833
Castilla y León	18	2.389	0.056	60.806	914.333
HES	**9**	**6.000**	**0.249**	**200.000**	**838.667**
Aragón	3	8.667	0.334	244.000	960.333
Asturias	1	7.000	1.000	53.000	389.000
Castilla y León	5	4.200	0.047	203.000	855.600
PUB	**22**	**1.864**	**0.009**	**9.659**	**881.545**
Aragón	9	0.889	0.002	0.000	1047.667
Asturias	2	5.500	0.000	0.000	440.500
Castilla y León	11	2.000	0.017	19.318	825.818
OTH	**28**	**1.429**	**0.006**	**1.536**	**857.286**
Aragón	8	0.625	0.002	0.000	1066.500
Asturias	6	3.667	0.010	0.000	452.333
Castilla y León	14	0.929	0.006	3.071	911.286
Total general	**325**	**1.255**	**0.014**	**16.498**	**886.062**
UNIVERSIDAD DE ZARAGOZA	HES	20	1.000	518.000	

Table 12. Aragón regional network of entities: centrality metrics for the top 10 entities (degree, eigenvector and betweenness).

Short Name	Type	Degree	Eigenvector	Between
FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	REC	24	0.102	747.667
BEONCHIP SL	PRC	5	0.053	-
NANOSCALE BIOMAGNETICS SOCIEDAD LIMITADA	PRC	2	0.026	-
AGROINDUSTRIA ARAGONESA S.A.	PRC	3	0.014	-
BODEGAS ARAGONESAS SA	PRC	3	0.014	-
BSH ELECTRODOMESTICOS ESPANA SA	PRC	1	0.014	-
ESCIENCIA EVENTOS CIENTIFICOS SL	PRC	2	0.014	-
EBERS MEDICAL TECHNOLOGY SL	PRC	1	0.013	-
FUNDACION INSTITUTO DE INVESTIGACION SANITARIA ARAGON	REC	2	0.013	-
FUNDACION AITIIP	REC	10	0.003	295.667
FUNDACION ZARAGOZA LOGISTICS CENTER	HES	4	0.002	214.000

Table 12. *Cont.*

Short Name	Type	Degree	Eigenvector	Between
NUEVAS TECNOLOGIAS PARA EL DESARROLLO DE PACKAGING Y PRODUCTOS AGROALIMENTARIOS CON COMPONENTE PLASTICA SL	PRC	5	0.002	46.000
NUREL SA	PRC	5	0.001	0.667
INSTITUTO TECNOLOGICO DE ARAGON	REC	13	0.000	439.000
CONFEDERACION DE EMPRESARIOS DE ARAGON	REC	5	0.000	-
SOCIEDAD ARAGONESA DE GESTION AGROAMBIENTAL SL	PRC	2	0.000	210.000
INSTRUMENTACION Y COMPONENTES SA	PRC	5	0.000	172.000
FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON	REC	6	0.000	91.000

As a summary, considering the scope of the main players, those related to renewable energy, agri-food and circular economy may have a relevant contribution to the low carbon transition paths in Aragón.

In order to have a picture of the regional network of Aragón, Figure 2 presents the graphical representation of the network, including only those entities with a degree higher than one.

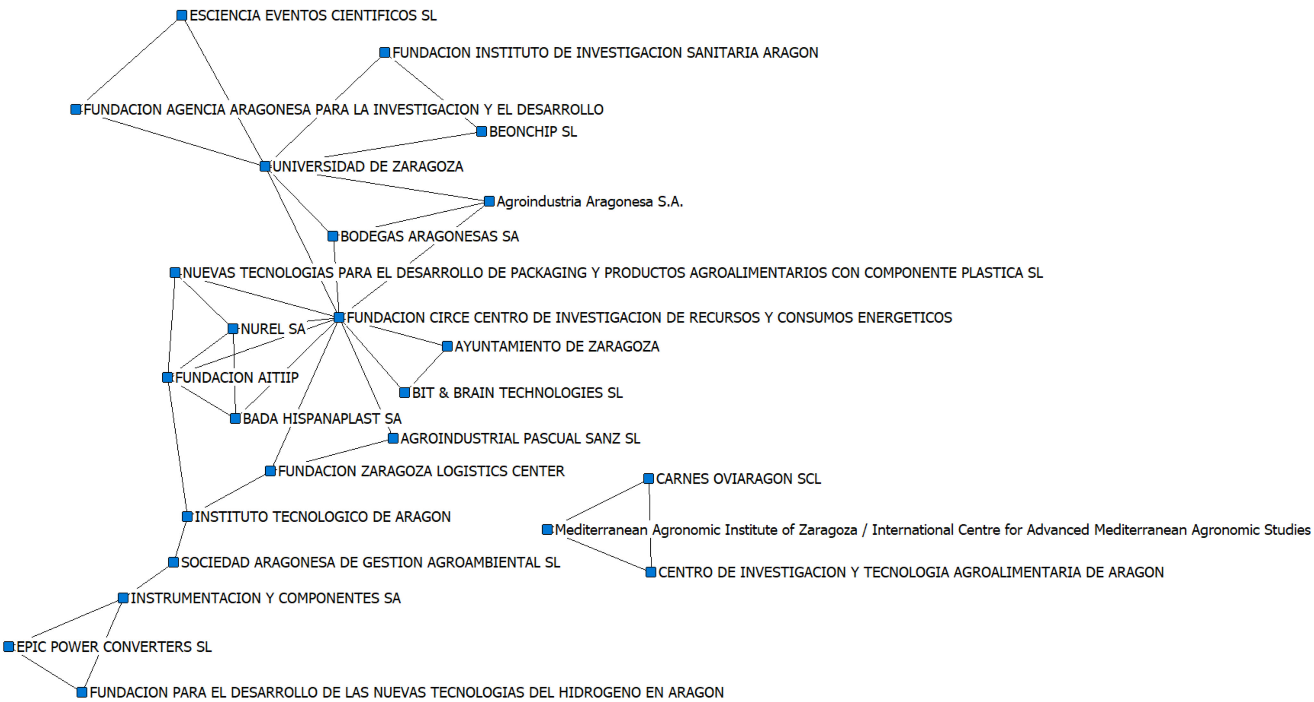

Figure 2. Aragón regional network of entities: graphical representation showing only entities with a degree higher than 1.

Regarding the collaboration between companies in the Aragón region, Figure 3 presents those private companies with a degree higher than one. It can be observed how weak this network is, as well as the role played by the University and the research centers in the network integration.

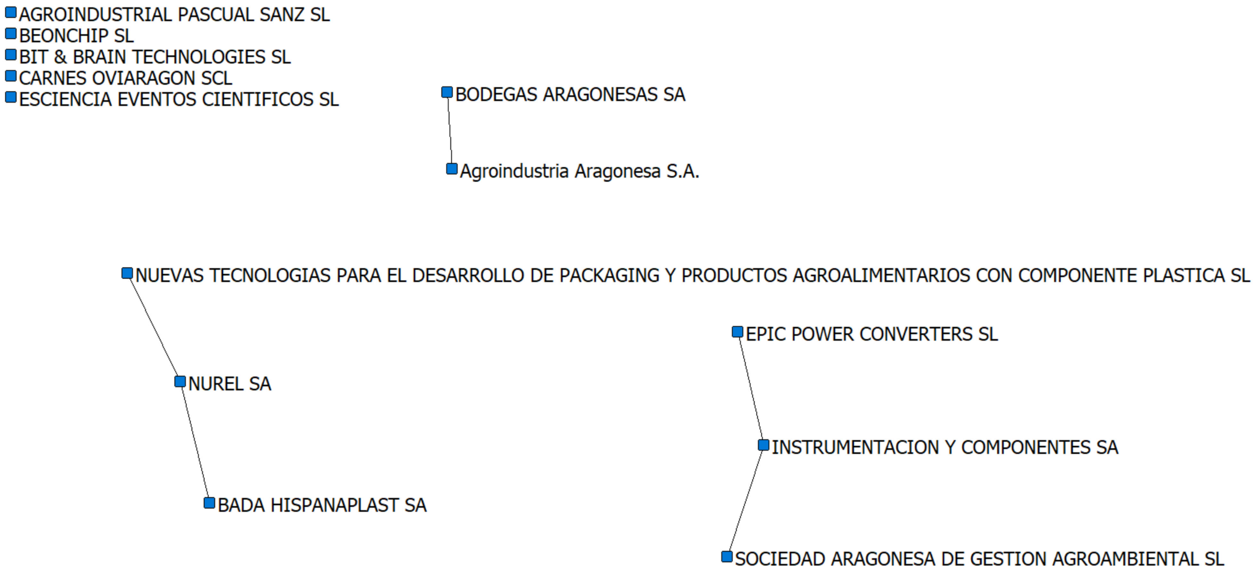

Figure 3. Aragón regional network of entities: graphical representation showing only private companies with a degree higher than 1.

3.1.2. Centrality Measures within the Asturias Regional Network of Entities

Regarding the Asturias network of entities, Table 13 presents those participants with the top ten values at degree, eigenvector and betweenness centrality measures. In the betweenness metric, only seven entities have a score higher than zero. A total of 14 entities are participating in these three top ten indexes. Six of them are ranked in the three metrics: the public university of the region (Universidad de Oviedo), one spin-off from this University devoted to spectroelectrochemical instruments (Metrohm Dropsens S.L., Oviedo, Spain), one company dedicated to big data and artificial intelligence (Tree Technolgy S.A., Madrid, Spain), a dairy company (Industrias Lácteas Asturianas S.A., Anleo, Spain) and the European Business and Innovation Centre from the region (Asociación Centro Europeo de Empresas e Innovación del Principado de Asturias). There are two companies participating in the two top ten lists of eigenvector and betweenness, so with prominent positions, even with a lower number of links: a company related to surgery equipment (MBA Incorporado S.L., Gijón, Spain) and the company Treelogic, from the same group as Tree Technology S.A. Finally, there are two large companies: one dedicated to steel production (Arcelor Mittal España S.A., Avilés, Spain) and one to digital transformation (Izertis S.A., Gijón, Spain), which is a spin-off of the Oviedo University devoted to new drugs for the oncology field (Entrechem S.L., Oviedo, Spain), a high-tetch SME devoted to microalgae (Neoalgae), the public development agency for the region (Instituto de Desarrollo Económico de Asturias), a public foundation devoted to foster research activities in the region, including the participation in Horizon 2020 (Fundación para el Fomento en Asturias de la Investigación Científica Aplicada y Tecnología) and, finally, the regional federation of businesses (Federación Asturiana de Empresarios).

As a summary, considering the scope of the main players, those related to ocean, steel, agri-food and power electronics may have a relevant contribution to the low carbon transition paths in Asturias.

Figure 4 provides a graphical representation of the regional network in Asturias, including only those entities with a degree higher than one.

Table 13. Asturias regional network of entities: centrality metrics for the top 10 entities (degree, eigenvector and betweenness).

Short Name	Type	Degree	Eigenvector	Between
UNIVERSIDAD DE OVIEDO	HES	7	1.000	53
METROHM DROPSENS SL	PRC	7	0.074	51
ASOCIACION DE INVESTIGACION DE INDUSTRIAS CARNICAS DEL PRINCIPADO DE ASTURIAS	REC	5	0.065	48
ASOCIACION CENTRO EUROPEO DE EMPRESAS E INNOVACION DEL PRINCIPADO DE ASTURIAS	OTH	4	0.062	0
INDUSTRIAS LÁCTEAS ASTURIANAS, S.A.	PRC	4	0.059	0
MBA INCORPORADO SL	PRC	2	0.052	15
ENTRECHEM SL	PRC	1	0.052	0
NEOALGAE MICRO SEAWEEDS PRODUCTS SL	PRC	1	0.052	0
TREE TECHNOLOGY SA	PRC	5	0.010	39
ARCELORMITTAL ESPANA SA	PRC	2	0.008	0
TREELOGIC TELEMATICA Y LOGICA RACIONAL PARA LA EMPRESA EUROPEA SL	PRC	6	0.005	29
IZERTIS SOCIEDAD ANONIMA	PRC	3	0.004	28
FEDERACION ASTURIANA DE EMPRESARIOS	OTH	8	0.000	0
INSTITUTO DE DESARROLLO ECONOMICO DEL PRINCIPADO DE ASTURIAS	PUB	10	0.000	0
FUNDACION PARA EL FOMENTO EN ASTURIAS DE LA INVESTIGACION CIENTIFICA APLICADA Y TECNOLOGIA	OTH	10	0.000	0

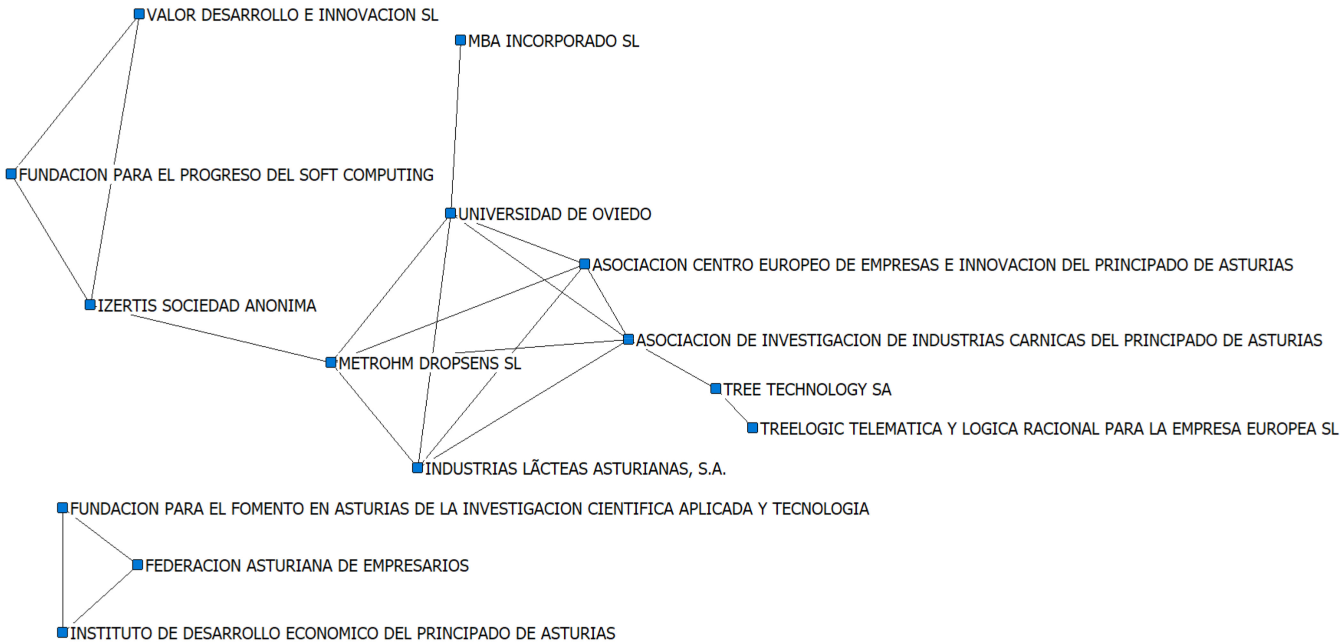

Figure 4. Asturias regional network of entities, showing only entities with a degree higher than one.

In order to depict the collaboration between companies in Asturias, Figure 5 presents the network composed by those private companies with a degree higher than one. It shows a weak network similar to the Aragón one.

Figure 5. Asturias regional network of entities, showing only private companies with a degree higher than one.

3.1.3. Centrality Measures within the Castilla y León Regional Network of Entities

The ten entities with the highest centrality metrics are presented in Table 14. There are four entities present at the three top ten ranks of centrality metrics (degree, eigenvector and betweenness): a horizontal private nonprofit technology center (Fundación CARTIF), two public generalist universities (Universidad de Burgos and Universidad de Valladolid) and the Municipality of Valladolid (Ayuntamiento de Valladolid). Then, there are five entities ranking in the degree and betweenness metrics: a public generalist university (Universidad de Salamanca), a private nonprofit research center focused on new materials (Fundación ICAMCYL), a private nonprofit multisector technology center (Instituto Tecnológico de Castilla y León), a cluster of construction entities (Agrupación Empresarial Innovadora para la Construcción Eficiente) and the Department of Environment of the Regional Government (Consejería de Fomento y Medioambiente). Finally, there are eight additional entities present within the highest centrality scores: a public national research center focused on human evolution (Centro Nacional de Investigación sobre la Evolución Humana), the public water authority of the Duero river (Confederación Hidrográfica del Duero), the public regional energy agency (Ente Público Regional de la Energía de Castilla y León), the public entity for businesses support (Instituto para la Cometitividad Empresarial de Castilla y León), a nonprofit energy consumers cooperative (Energética S. Coop.), a company devoted to disabled employability (Grupo Lince S.L.U., Valladolid, Spain), a company manufacturer of transparent photovoltaics glass for buildings (Onyx Solar Energy S.L., Ávila, Spain), and an IT company (Xeridia S.L., León, Spain).

As a summary, considering the scope of the main players, those related to sustainable construction and renewable energy may have a relevant contribution to the low carbon transition paths in Castilla y León.

In order to provide a graphical representation of the regional network in Castilla y León, Figure 6 represents the links between the entities with a degree higher than one.

Furthermore, in order to present the collaboration between companies, Figure 7 present the only relation between companies with a degree higher than one. This network is also weak, like in the other regions.

Table 14. Castilla y León regional network of entities: centrality metrics for the top 10 entities (degree, eigenvector and betweenness).

Short Name	Type	Degree	Eigenvector	Between
FUNDACION CARTIF	REC	24	1.000	760.5
UNIVERSIDAD DE BURGOS	HES	8	0.181	270
AYUNTAMIENTO DE VALLADOLID	PUB	7	0.066	44.5
UNIVERSIDAD DE VALLADOLID	HES	9	0.052	546
ENERGETICA S COOP	OTH	2	0.042	0
INSTITUTO PARA LA COMPETITIVIDAD EMPRESARIAL DE CASTILLA Y LEON	PUB	2	0.031	0
ONYX SOLAR ENERGY SL	PRC	1	0.025	0
CONFEDERACION HIDROGRAFICA DEL DUERO	PUB	2	0.022	0
GRUPO LINCE ASPRONA S.L.U.	PRC	2	0.022	0
XERIDIA S.L.	PRC	2	0.022	0
ENTE PUBLICO REGIONAL DE LA ENERGIA DE CASTILLA Y LEON	PUB	2	0.021	43
AGRUPACION EMPRESARIAL INNOVADORA PARA LA CONSTRUCCION EFICIENTE	OTH	3	0.021	43
FUNDACION ICAMCYL	REC	5	0.004	165
UNIVERSIDAD DE SALAMANCA	HES	3	0.003	199
CONSEJERIA DE FOMENTO Y MEDIO AMBIENTE—JUNTA DE CASTILLA Y LEON	PUB	4	0.001	125
INSTITUTO TECNOLOGICO DE CASTILLA Y LEON	REC	4	0.000	126
CENTRO NACIONAL DE INVESTIGACION SOBRE LA EVOLUCION HUMANA	REC	2	0.000	0

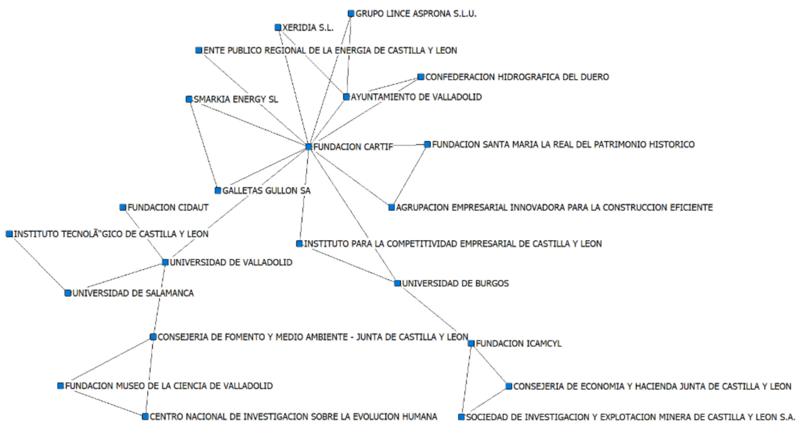

Figure 6. Castilla y León regional network of entities, showing only entities with a degree higher than one.

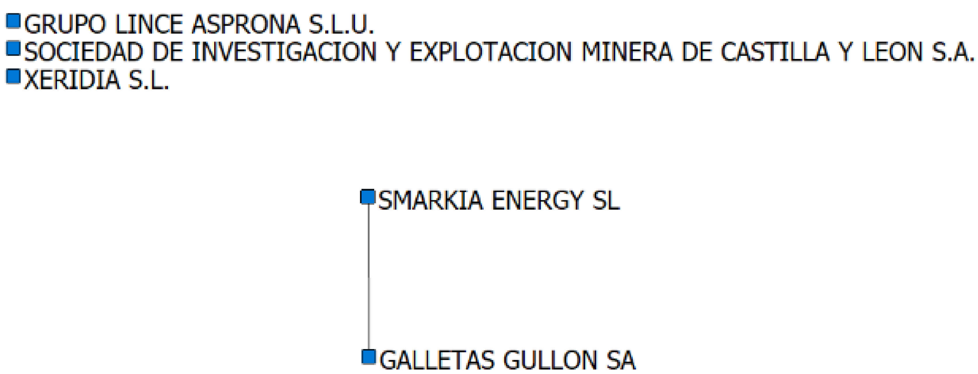

Figure 7. Castilla y León regional network of entities, showing only private companies with a degree higher than one.

3.2. Network of Projects: Cohesion and Centrality Metrics

The network of projects developed in each region is evaluated, as the network of partners, from two perspectives. Firstly, it is assessed as a complete innovation system relying on cohesion metrics. In order to analyze the contribution of each research area to the overall innovation system, the density within each pillar, program and subprogram is calculated. Secondly, in order to assess the role of each project within the network, their centrality metrics are calculated and analyzed, also considering each pillar, program and subprogram.

In Table 15, the cohesion metrics of the network of projects from the three regions is presented. The Aragón region presents the more cohesive network, with significantly higher values in the average degree, H-index, density and closure metrics. These characteristics show that the different projects are well connected, enabling the knowledge exchange and the development of technological trajectories. In contrast, the Asturias region shows the weakest network, with reduced values at all the parameters, especially in average degree, H-index, density and connectedness. Castilla y León, although presenting a high connectedness value—80.8% of its projects are connected—shows reduced levels in the closure ratio, with a density similar to the Asturias one.

Table 15. Aragón, Asturias and Castilla y León networks of projects: cohesion metrics.

Metric	Aragón	Asturias	Castilla y León
Number of nodes	367	146	334
Number of ties	20 368	2 516	14 210
Average degree	55.499	17.233	42.545
H-Index	87	29	67
Density	0.152	0.119	0.128
Connectedness	0.789	0.664	0.828
Closure	0.620	0.529	0.494
Diameter	4	5	5

Regarding the Aragón network, the density at each pillar, program and subprogram, as well as the centrality parameters of their projects, are calculated and presented in Table 16 (only those subprograms with at least 10 projects are included). The highest density appears at the Excellent Science Programme, as there are some consecutive crosscutting projects under the Future and Emerging Technology Programme that are developed by similar consortia, which highly increases the density. The stable participation of the same academic partners in this pillar clearly contributes to its high density and centrality metrics, which is a recurrent fact in the three regions.

The Industrial Leadership and the Societal Challenge Pillars provide clearer information about the thematic research areas in which the regional innovation system is focused. In this respect, resource efficiency and energy arise as the most developed and cohesive research fields. In the area of resource efficiency, there is relevant participation in programs such as Resource Efficiency in the Process Industries (SPIRE), Sustainable supply of Raw materials (under the Climate Programme) and Bio-Based Industries (under the Food Programme). In the area of Energy, the Electricity Grid, Hydrogen and Fuel Cells, and Market Uptake of Energy Innovation are the most remarkable fields. Finally, the subprogram with the highest influence, measured in terms of eigenvector, is the Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing (NMBP).

In summary, Aragon presents its best technological trajectories within six research fields that are mainly related to energy and resource efficiency. In energy, the following three subprograms are included: Electricity grid, Hydrogen and Fuel Cells and market uptake of Energy. While in resource efficiency, the following three are identified: Resource Efficiency in Process Industries (SPIRE), Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing (NMBP) and Bio-Based Industries.

Table 16. Aragón projects network: cohesion (density) and centrality metrics (average degree, betweenness and eigenvector) by pillar, program and subprogram (for the subprograms, only those with more than 10 projects are included).

Pillar/Program/Subprogram	Number of Projects	Density	Average Degree	Average Between	Average Eigenvector
Excellent Science	**67**	**0.993**	**120.104**	**253.039**	**0.060**
European Research Council	6	0.667	63.500	0.000	0.008
Future and Emerging Technologies	9	14.806	357.333	922.364	0.335
Marie Curie Actions	50	0.552	81.480	150.800	0.017
Research Infrastructures	2	6.000	188.000	556.157	0.068
Industrial Leadership	**92**	**0.288**	**72.739**	**133.911**	**0.015**
Innovation in SME (INNOSUP)	10	2.067	36.200	11.296	0.004
Leadership in Enabling and Industrial Technologies	82	0.315	77.195	148.864	0.016
Societal Challenges	**204**	**0.178**	**59.461**	**104.171**	**0.007**
Climate	20	0.079	36.900	130.562	0.005
Energy	79	0.491	75.785	104.627	0.006
Food	48	0.308	52.313	98.308	0.008
Health	15	0.305	62.467	149.769	0.018
Inclusive Societies	8	0.179	42.250	44.617	0.006
Security	2	0.000	47.500	29.194	0.008
Transport	32	0.442	47.625	93.547	0.006
Science for Society	**4**	**0.333**	**38.750**	**61.927**	**0.010**

The metrics of the Asturias projects network are shown in Table 17. Similar to Aragón, the Excellence Science Pillar is the most cohesive one thanks to the large Future and Emerging Technologies projects in which the consortia are almost maintained. Regarding the Industrial Leadership and Societal Challenges Pillars, the most cohesive subprograms are Factories of the Future, followed by NMBP (Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing), SPIRE (Resource Efficiency in Process Industries), Low Carbon Electricity (under the Energy Programme) and Sustainable and healthy Agri-Food (under the Food Programme). In terms of influence, Factories of the Future shows the highest eigenvector. In addition, NMBP (Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing) has a high eigenvector value, followed by Low carbon electricity and Sustainable and Healthy Agri-Food.

In summary, Asturias presents its best technological trajectories under the following five subprograms (1) Factories of the Future (FoF), (2) Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing (NMBP), (3) Resource Efficiency in Process Industries (SPIRE), (4) Low carbon electricity and (5) Sustainable and healthy agri-food.

Regarding the Castilla y León network, the high density of the Excellence Pillar is supported by, in addition to the Future and Emerging technology projects like in the other two regions, nine Research Infrastructures projects related to laser technologies, atmosphere, archaeological heritage and carbon capture and storage.

In terms of cohesion and influence, the most remarkable programs in which the best technological trajectories in Castilla y León appear are Leadership in Enabling and Industrial Technologies, Energy, Health and Transport. When the Subprogrammes are analysed, Energy Efficient Buildings (EeB), Factories of the Future (FoF), Information and Communication Technologies (ICT), Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing (NMBP) and Low carbon electricity are the most remarkable ones. Table 18 presents a summary of these metrics.

Table 17. Asturias projects network: cohesion (density) and centrality metrics (average degree, betweenness and eigenvector) by pillar, program and subprogram (for the subprograms, only those with more than 5 projects are included).

Pillar/Program/Subprogram	Number of Projects	Density	Average Degree	Average Between	Average Eigenvector
Excellent Science	**25**	**2.277**	**83.040**	**137.855**	**0.075**
European Research Council	3	1.000	20.000	0.000	0.000
Future and Emerging Technologies	5	45.400	296.000	453.438	0.346
Marie Curie Actions	16	0.475	28.438	61.060	0.007
Research Infrastructures	1	-	81.000	202.223	0.028
Industrial Leadership	**59**	**0.237**	**26.559**	**42.933**	**0.005**
Innovation in SME (INNOSUP)	10	1.133	15.000	0.395	0.000
Leadership in Enabling and Industrial Technologies	49	0.272	28.918	51.615	0.006
Societal Challenges	**62**	**0.097**	**16.823**	**35.686**	**0.003**
Climate	3	0.667	24.000	94.153	0.004
Energy	17	0.176	14.412	35.579	0.003
Food	12	0.212	16.417	27.810	0.004
Health	10	0.067	15.400	32.671	0.002
Inclusive Societies	3	-	17.000	17.073	0.005
Security	8	0.857	32.875	68.661	0.006
Transport	9	0.056	6.778	7.147	0.001

Table 18. Castilla y León projects network: cohesion (density) and centrality metrics (average degree, betweenness and eigenvector) by pillar, program and subprogram (for the subprograms, only those with more than 10 projects are included).

Pillar/Programme/Subprogramme	Number of Projects	Density	Average Degree	Average Between	Average Eigenvector
Excellent Science	**82**	**0.510**	**77.280**	**199.683**	**0.045**
European Research Council	4	0.167	28.750	10.258	0.002
Future and Emerging Technologies	9	13.139	270.333	820.546	0.321
Marie Curie Actions	60	0.220	40.100	84.630	0.007
Research Infrastructures	9	4.833	153.667	430.022	0.044
Industrial Leadership	**91**	**0.258**	**61.110**	**126.025**	**0.012**
Innovation in SME (INNOSUP)	8	1.857	18.375	1.276	0.000
Leadership in Enabling and Industrial Technologies	83	0.290	65.229	138.049	0.013
Societal Challenges	**156**	**0.177**	**52.391**	**115.376**	**0.009**
Climate	23	0.356	68.000	216.258	0.011
Energy	47	0.558	71.170	102.371	0.009
Food	39	0.200	29.405	68.861	0.004
Health	19	0.819	51.632	124.761	0.014
Inclusive Societies	7	0.238	37.571	59.041	0.005
Security	7	0.190	32.143	51.739	0.009
Transport	16	0.533	44.188	157.473	0.010
Spreading Excellence	**4**	**0.333**	**65.250**	**214.619**	**0.010**
Science for Society	**1**	**-**	**40.000**	**71.563**	**0.001**

4. Discussion

This paper analyses the regional innovation systems and their alignment with the priorities of the smart specialization strategies (RIS3) in the three Spanish coal regions. More precisely, this work analyzes how the regional innovation systems promoted by the H2020 program at a regional level support the consecution of the RIS3 priorities in the three Spanish coal in transition regions (Aragón, Asturias and Castilla y León). For this purpose, and in line with previous works [9,10], this study considers that these regional innovation systems are generated by the H2020 funded research projects and consortia and present underlying networks in which entities are linked by joint projects and projects linked by common partners. It is assumed that funding research consortia is the mechanism that the EU uses for the development of its research policy, which is creating a network of relationships between projects and partners, forming the regional innovation system.

First, our results show that institutional impulse plays a relevant role in the evolution of regional innovation systems. It is considered that the Institutional Impulse of the EU through the framework programs creates a network of relationships between actors that propitiates the exchange of knowledge and information, which, in line with previous research [50,51], is a crucial element for the innovation and technology development. Moreover, following similar works [52,53], the topological and structural characteristics of the regional innovation systems have been assessed. From our results, it can be concluded that, contrary to previous works [54,55], the centrality metrics provide information to consider the efficiency and efficacy of the regional innovation systems.

Second, regarding the first research question, how do regional innovation systems contribute to the deployment of the RIS3 priorities in the coal in transition regions, the application of SNA allowed the identification of the effectiveness of the innovation policies in the EU. Thus, as a first conclusion, in line with previous research [9,10], it is shown that the network centrality metrics enable the identification of the technological trajectories of the regional innovation systems. The results indicate that, in some cases, the technological strengths of the regional innovation systems are not considered in the RIS3 priorities, while some RIS3 priorities do not have support from the innovation system. In more detail, it is seen that the strategies from the three regions present big differences regarding its scope in terms of broadening and definition; however, energy and resource efficiency have been identified as the two priorities established by the three coal regions that are supported by their regional innovation systems. Moreover, the analysis of the centrality in the regional innovation systems enables the determination of the effectiveness of the institutional impulse [10,56], facilitating the prioritization of the technological trajectories depending on the European energy and sustainability policies. As an example, our results show that several priorities of the regional innovation systems, such as health, which is targeted in the three considered regions, are not supported by their innovation system. Therefore, our results demonstrate the existence of incongruences during the RIS3 definition of priorities, considering the existing innovation systems, which enlarges the evidence presented by previous authors who have already highlighted that existing regional capacities are frequently neglected in the implementation of smart specialization policies [57].

Third, regarding the second research question, how are the innovation systems for the RIS3 design in the coal in transition regions considered, our results corroborate those from previous works [10] that show the relevance of the innovation systems' cohesion and connectivity properties for its effectiveness. Thus, regarding innovation system performance, regions with lower levels of innovation expenditure and a critical mass of researchers present the weakest innovation systems, with lower cohesion rates, which is in line with previous works [58–60] that established that public–private regional innovation networks do have a positive correlation to R&D investment and personnel. This also supports previous studies [11], in which the H2020 program was identified as particularly interesting for evaluating the role of regional innovation networks. Based on these findings, and aligned with the literature [9,10,53], it can be highlighted how the properties of the network of projects and the network of entities created by the consortia affect the efficiency of the regional innovation system. Moreover, the average number of participations per entity is positively related to the regional average degree in the regional network as well as with the proportion of regional entities connected among them (connectivity). Thus, bigger participants contribute to a better integrated regional innovation system; therefore, large participants are key players who act as intermediaries between communities and supra-regional networks, as has already been demonstrated by previous works [61,62].

Fourth, considering both the efficacy and efficiency of the regional innovation systems, the heterogeneity of the nodes, attending to its attributes, should be considered. In this line, according previous works [9], in our study we have considered the performance of innovation systems. Our results show that higher education establishments and research centers occupy a prominent position within the innovation system, as established in the literature [63–65], showing higher centrality metrics in the SNA analysis and acting as enablers of knowledge exchange and collaboration, thus supporting the execution of the regional research policy goals. In this sense, the authors have already highlighted the relevance of ensuring the diversity of the nodes, considering the relevance of technology transfer between universities and research centers and the companies [9]. Moreover, the high level of centrality of universities has been appointed as a requirement for the market transfer of the research and innovation results [66,67].

Finally, like any other, this study has limitations. The empirical work is focused on the H2020 projects. Thus, on the one hand, further research should analyze FP7, the predecessor of H2020, as well as Horizon Europe, its successor, to assess the progress of the energy R&D ecosystem in these regions. On the other hand, non-European areas, such as Africa or South America, in which there are not similar collaborative research funding programs, or in which the participation data are not available, cannot benefit easily from the methods used in this study. It should be also considered that innovation activities outside H2020 have not been considered in this study, thus neglecting its contribution to the innovation system functioning. Furthermore, as three coal in transition regions from the same country have been considered, further work may be required to enlarge the scope of this study considering other regional challenges and geographical contexts.

5. Conclusions

Our work proposes relevant theoretical and practical contributions. From the theoretical perspective, the first group of contributions extends the literature on regional innovation systems in terms of their modelling and effectiveness, particularly for the coal in transition regions [68–70]. Thus, from our conceptualization, the innovation system consists of diverse nodes, both in terms of typology and geographic dispersion, interacting to collaborate and share information and knowledge. This modelling allows us to consider the effectiveness of the innovation system in terms of this network structure and properties, which, relying on the potential of the social network analysis, allows us to determine the ability to achieve the objectives of the research and development policy. Therefore, we indicated the convenience of conceiving the regional innovation system as a network of relationships between entities and projects to understand how the effectiveness of this innovation system at the regional level 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 metrics, both in terms of knowledge transfer and collaboration within the region, at the different technological trajectories.

The second group of theoretical contributions is rooted in regional innovation systems. While the regional studies emphasize the regional characteristics of the concentration of highly specialized skills and knowledge, institutions, related businesses and clients in a particular region [71–73], our work extends the regional innovation systems literature by pointing out that the correct evaluation of the research policy must analyze the topology and structural properties of the innovation systems' related networks in the region. First, the cohesion of the innovation systems allows an assessment of the viability of potential collaborations, transfer of information and knowledge, and geographic cohesion for the different technology and research fields. Second, the centrality metrics of the innovation system allow the evaluation of research policies in terms of competitiveness. Lastly, the connectivity of the network allows an analysis of the transversality between the different research programs as a way to promote synergistic effects between them.

This study has strong implications for management and research policymaking. First, the design of smart specialization strategies should focus on the strengths of the innovation systems existing in the region to avoid fragmentation, improving the collaboration between projects and entities and fostering transversal actions. Moreover, the involvement in these actions of the project coordinators, particularly universities and research centers, may be beneficial, as they are the most influential nodes of the network. Second, regional research policymakers may apply the proposed method and findings to their regions to evaluate the existing innovation system and consider it in the next generation of smart specialization strategies definition. European policymakers may consider these results to reshape the next FPs to foster the development of the smart specialization strategies of the European regions. In addition, regional and national policymakers may rely on this study to design regional support programs to facilitate the participation of their regional entities into European programs, to rely on their contribution to the promotion of regional innovation systems. Finally, individual participants may apply the results of this study to select their consortium partners to enhance their network position, thus improving their access to knowledge and research capabilities.

Regarding the case of the coal in transition regions, the consideration of the existing strengths and capacities, that in our empirical study have consistently been related to energy and resource efficiency, seems to be crucial for the effectiveness of the policy making. Furthermore, the prioritization of technology fields not supported by the innovation system, should be performed consciously and, in consequence, with the pertinent support mechanisms and institutional impulse to foster the evolution of the innovation systems towards these new priorities.

Furthermore, considering the EU decarbonization goals that particularly challenge some of its regions, the new Horizon Europe Programme that addresses the period 2021–2027, can consider the conclusions from this work to enhance the effectiveness of its institutional impulse. Moreover, the regional policies, and especially those related to the just transition in coal regions, can benefit from the analysis of the regional innovation systems to align their strategies for the upcoming RIS3.

Finally, the authors consider that, in this work, the regions have been considered as isolated innovation systems, but their connections and links with other innovation systems geographically located outside the regions should be studied in further research to determine their affection to the regional innovation systems performance. Furthermore, more empirical studies, targeting other regions, in other location, or presenting other challenges different from the coal transition, could be beneficial to enlarge the applicability of the obtained conclusions.

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References

1. Polido, A.; Pires, S.M.; Rodrigues, C.; Teles, F. Sustainable development discourse in Smart Specialization Strategies. *J. Clean. Prod.* **2019**, *240*, 118224. [CrossRef]
2. McCann, P.; Ortega-Argilés, R. Smart Specialization, Regional Growth and Applications to European Union Cohesion Policy. *Reg. Stud.* **2015**, *49*, 1291–1302. [CrossRef]
3. Oei, P.-Y.; Hermann, H.; Herpich, P.; Holtemöller, O.; Lünenbürger, B.; Schult, C. Coal phase-out in Germany—Implications and policies for affected regions. *Energy* **2020**, *196*, 117004. [CrossRef]
4. Ćetković, S.; Buzogány, A. Between markets, politics and path-dependence: Explaining the growth of solar and wind power in six Central and Eastern European countries. *Energy Policy* **2020**, *139*, 111325. [CrossRef]
5. Raźniak, P.; Dorocki, S.; Rachwał, T.; Winiarczyk-Raźniak, A. The Role of the Energy Sector in the Command and Control Function of Cities in Conditions of Sustainability Transitions. *Energies* **2021**, *14*, 7579. [CrossRef]
6. Raźniak, P.; Dorocki, S.; Rachwał, T.; Winiarczyk-Raźniak, A. Influence of Energy Sector Corporations on the Corporate Control Functions of Cities. *Int. J. Energy Econ. Policy* **2021**, *11*, 333–340. [CrossRef]
7. Heinisch, K.; Holtemöller, O.; Schult, C. Power generation and structural change: Quantifying economic effects of the coal phase-out in Germany. *Energy Econ.* **2020**, *95*, 105008. [CrossRef]
8. Brauers, H.; Oei, P.-Y. The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels. *Energy Policy* **2020**, *144*, 111621. [CrossRef]
9. De Arroyabe, J.C.F.; Schumann, M.; Sena, V.; Lucas, P. Understanding the network structure of agri-food FP7 projects: An approach to the effectiveness of innovation systems. *Technol. Forecast. Soc. Chang.* **2020**, *162*, 120372. [CrossRef]
10. Calvo-Gallardo, E.; Arranz, N.; de Arroyabe, J.C.F. Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives. *J. Clean. Prod.* **2021**, *298*, 126690. [CrossRef]
11. Di Cagno, D.; Fabrizi, A.; Meliciani, V.; Wanzenböck, I. The impact of relational spillovers from joint research projects on knowledge creation across European regions. *Technol. Forecast. Soc. Chang.* **2016**, *108*, 83–94. [CrossRef]
12. Mattes, J.; Huber, A.; Koehrsen, J. Energy transitions in small-scale regions—What we can learn from a regional innovation systems perspective. *Energy Policy* **2014**, *78*, 255–264. [CrossRef]
13. Maruccia, Y.; Solazzo, G.; Del Vecchio, P.; Passiante, G. Evidence from Network Analysis application to Innovation Systems and Quintuple Helix. *Technol. Forecast. Soc. Chang.* **2020**, *161*, 120306. [CrossRef]
14. Dehdarian, A.; Tucci, C.L. A complex network approach for analyzing early evolution of smart grid innovations in Europe. *Appl. Energy* **2021**, *298*, 117143. [CrossRef]
15. Sena, V.; Arranz, N.; Lucas, P.; Park, H.W.; de Arroyabe, J.C.F. "Editorial: Big Data and Network Analysis in National Innovation Systems (NIS)". *Technol. Forecast. Soc. Chang.* **2021**, *168*, 120790. [CrossRef]
16. Llopis, O.; D'Este, P.; Díaz-Faes, A.A. Connecting others: Does a tertius iungens orientation shape the relationship between research networks and innovation? *Res. Policy* **2021**, *50*, 104175. [CrossRef]
17. Falcone, P.M.; D'Alisa, G.; Germani, A.R.; Morone, P. When all seemed lost. A social network analysis of the waste-related environmental movement in Campania, Italy. *Politi- Geogr.* **2019**, *77*, 102114. [CrossRef]
18. Falcone, P.M.; De Rosa, S.P. Use of fuzzy cognitive maps to develop policy strategies for the optimization of municipal waste management: A case study of the land of fires (Italy). *Land Use Policy* **2020**, *96*, 104680. [CrossRef]
19. Yip, W.; To, S. Identification of stakeholder related barriers in sustainable manufacturing using Social Network Analysis. *Sustain. Prod. Consum.* **2021**, *27*, 1903–1917. [CrossRef]
20. Morone, P.; Falcone, P.M.; Tartiu, V.E. Food waste valorisation: Assessing the effectiveness of collaborative research networks through the lenses of a COST action. *J. Clean. Prod.* **2019**, *238*, 117868. [CrossRef]
21. Nunes, M.; Abreu, A.; Bagnjuk, J.; Tiedtke, J. Measuring project performance by applying social network analyses. *Int. J. Innov. Stud.* **2021**, *5*, 35–55. [CrossRef]
22. Sá, E.S.; de Pinho, J.C.M.R. Effect of entrepreneurial framework conditions on R&D transfer to new and growing firms: The case of European Union innovation-driven countries. *Technol. Forecast. Soc. Chang.* **2019**, *141*, 47–58.
23. De Juana-Espinosa, S.; Luján-Mora, S. Open government data portals in the European Union: Considerations, development, and expectations. *Technol. Forecast. Soc. Chang.* **2019**, *149*, 119769. [CrossRef]
24. Mignon, I.; Bergek, A. System- and actor-level challenges for diffusion of renewable electricity technologies: An in-ternational comparison. *J. Clean. Prod.* **2016**, *128*, 105–115. [CrossRef]
25. Asheim, B.T. Smart specialisation, innovation policy and regional innovation systems: What about new path development in less innovative regions? *Innov. Eur. J. Soc. Sci. Res.* **2019**, *32*, 8–25. [CrossRef]
26. Trippl, M.; Zukauskaite, E.; Healy, A. Shaping smart specialization: The role of place-specific factors in advanced, intermediate and less-developed European regions. *Reg. Stud.* **2019**, *54*, 1328–1340. [CrossRef]
27. Foray, D.; Goddard, J.; Goenaga Beldarrain, X.; Landabaso, M.; McCann, P.; Morgan, K.; Nauwelaers, C.; Ortega-Argiles, R. *Guide to Research and Innovation Strategies for Smart Specialisations (RIS 3)*; EU Commission, Publications Office of the European Union, Regional Policy: Luxembourg, 2012.
28. Cebolla, R.O.; Navas, C. Supporting hydrogen technologies deployment in EU regions and Member States: The Smart Specialisation Platform on Energy (S3PEnergy). *Int. J. Hydrog. Energy* **2019**, *44*, 19067–19079. [CrossRef]

29. Truffer, B.; Coenen, L. Environmental Innovation and Sustainability Transitions in Regional Studies. *Reg. Stud.* **2012**, *46*, 1–21. [CrossRef]
30. Heiligenberg, H.A.V.D.; Heimeriks, G.J.; Hekkert, M.P.; van Oort, F.G. A habitat for sustainability experiments: Success factors for innovations in their local and regional contexts. *J. Clean. Prod.* **2017**, *169*, 204–215. [CrossRef]
31. Arnone, M.; Cavallaro, C. The Challenge of a Place-and Network-based Approach to Development in Italian Regions. *Procedia—Soc. Behav. Sci.* **2016**, *223*, 31–36. [CrossRef]
32. Dahesh, M.B.; Tabarsa, G.; Zandieh, M.; Hamidizadeh, M. Reviewing the intellectual structure and evolution of the innovation systems approach: A social network analysis. *Technol. Soc.* **2020**, *63*, 101399. [CrossRef]
33. Cha, J.M. A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the Powder River Basin. *Energy Res. Soc. Sci.* **2020**, *69*, 101657. [CrossRef]
34. Scott, M.; Powells, G. Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. *Energy Res. Soc. Sci.* **2019**, *61*, 101346. [CrossRef]
35. Skoczkowski, T.; Bielecki, S.; Kochański, M.; Korczak, K. Climate-change induced uncertainties, risks and opportunities for the coal-based region of Silesia: Stakeholders' perspectives. *Environ. Innov. Societal Trans.* **2020**, *35*, 460–481. [CrossRef]
36. Spencer, T.; Colombier, M.; Sartor, O.; Garg, A.; Tiwari, V.; Burton, J.; Caetano, T.; Green, F.; Teng, F.; Wiseman, J. The 1.5 °C target and coal sector transition: At the limits of societal feasibility. *Clim. Policy* **2017**, *18*, 335–351. [CrossRef]
37. Evans, G.; Phelan, L. Transition to a post-carbon society: Linking environmental justice and just transition discourses. *Energy Policy* **2016**, *99*, 329–339. [CrossRef]
38. Cherp, A.; Vinichenko, V.; Jewell, J.; Brutschin, E.; Sovacool, B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.* **2018**, *37*, 175–190. [CrossRef]
39. Markard, J.; Raven, R.; Truffer, B. Sustainability transitions: An emerging field of research and its prospects. *Res. Policy* **2012**, *41*, 955–967. [CrossRef]
40. Fuenfschilling, L.; Truffer, B. The structuration of socio-technical regimes—Conceptual foundations from institutional theory. *Res. Policy* **2014**, *43*, 772–791. [CrossRef]
41. Platform on Coal and Carbon-Intensive Regions. Terms of Reference. Available online: https://ec.europa.eu/energy/sites/default/files/crit_tor_fin.pdf (accessed on 4 January 2021).
42. Instituto Nacional de Estadística. Data Corresponding to 2018. Available online: https://www.ine.es/dyngs/INEbase/listaoperaciones.htm (accessed on 10 December 2021).
43. Estadística Minera de España. Plan Estadístico Nacional. Instituto Nacional de Estadística. 2010–2018. Available online: https://energia.gob.es/mineria/Estadistica/Paginas/Consulta.aspx (accessed on 10 December 2021).
44. Estrategia de Transición Justa. *Plan de Acción Urgente para Comarcas de Carbón y Centrales en Cierre*; Instituto para la Transicion Justa; Ministerio para la Transición Ecológica y el Reto Demográfico: Madrid, Spain, 2020; ETJ: 665-20-016-5.
45. Open Processes for the Establishment of Fair Transition Agreements in the Spanish Coal in Transition Regions. Available online: https://www.transicionjusta.gob.es/Convenios_transicion_justa/procesos_en_marcha-ides-idweb.asp (accessed on 10 December 2021).
46. Wasserman, S.; Faust, K. *Social Network Analysis: Methods and Applications*; Cambridge University Press: Cambridge, UK, 1999.
47. Gulati, R. Does familiarity breed trust? The implications of repeated ties for contractual choice in alliances. *Acad. Manag. J.* **1995**, *38*, 85–112.
48. Arranz, N.; Arroyabe, M.F.; Schumann, M. The role of NPOs and international actors in the national innovation system: A network-based approach. *Technol. Forecast. Soc. Chang.* **2020**, *159*, 120183. [CrossRef]
49. Grewal, R.; Lilien, G.L.; Mallapragada, G. Location, Location, Location: How Network Embeddedness Affects Project Success in Open Source Systems. *Manag. Sci.* **2006**, *52*, 1043–1056. [CrossRef]
50. Enkel, E.; Gassmann, O.; Chesbrough, H. Open R&D and open innovation: Exploring the phenomenon. *R&D Manag.* **2009**, *39*, 311–316. [CrossRef]
51. Huang, Q.; Liu, H.; Zhong, X. The impact of transactive memory systems on team performance. *Inf. Technol. People* **2013**, *26*, 191–212. [CrossRef]
52. Kang, M.J.; Hwang, J. Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector. *Energy Policy* **2016**, *96*, 471–490. [CrossRef]
53. Muñiz, A.S.G.; Cuervo, M.R.V. Exploring research networks in Information and Communication Technologies for energy efficiency: An empirical analysis of the 7th Framework Programme. *J. Clean. Prod.* **2018**, *198*, 1133–1143. [CrossRef]
54. Hekkert, M.; Suurs, R.; Negro, S.; Kuhlmann, S.; Smits, R. Functions of innovation systems: A new approach for analysing technological change. *Technol. Forecast. Soc. Chang.* **2007**, *74*, 413–432. [CrossRef]
55. Papaioannou, T.; Wield, D.; Chataway, J. Knowledge ecologies and ecosystems? An empirically grounded reflection on recent developments in innovation systems theory. In Proceedings of the 6th International Triple Helix Conference on University-Government-Industry Relations, Singapore, 16–17 May 2007.
56. De Noni, I.; Ganzaroli, A.; Pilotti, L. Spawning exaptive opportunities in European regions: The missing link in the smart specialization framework. *Res. Policy* **2021**, *50*, 104265. [CrossRef]

57. Radosevic, S. Assessing EU Smart Specialization Policy in a Comparative Perspective. In *Advances in the Theory and Practice of Smart Specialization*; Radosevic, S., Curaj, A., Gheorghiu, R., Andreescu, L., Wade, I., Eds.; Elsevier; Academic Press: Cambridge, MA, USA, 2017; pp. 1–36. [CrossRef]
58. Min, S.; Kim, J.; Sawng, Y.-W. The effect of innovation network size and public R&D investment on regional innovation efficiency. *Technol. Forecast. Soc. Chang.* **2020**, *155*, 119998. [CrossRef]
59. Jun, S.-P.; Lee, J.-S.; Lee, J. Method of improving the performance of public-private innovation networks by linking heterogeneous DBs: Prediction using ensemble and PPDM models. *Technol. Forecast. Soc. Chang.* **2020**, *161*, 120258. [CrossRef]
60. Thomas, V.J.; Sharma, S.; Jain, S.K. Using patents and publications to assess R&D efficiency in the states of the USA. *World Pat. Inf.* **2011**, *33*, 4–10. [CrossRef]
61. Richter, R.; Christmann, G.B. On the role of key players in rural social innovation processes. *J. Rural Stud.* **2021**. [CrossRef]
62. Cahoon, S.; Pateman, H.; Chen, S.-L. Regional port authorities: Leading players in innovation networks? *J. Transp. Geogr.* **2012**, *27*, 66–75. [CrossRef]
63. Bukhari, E.; Dabic, M.; Shifrer, D.; Daim, T.; Meissner, D. Entrepreneurial university: The relationship between smart specialization innovation strategies and university-region collaboration. *Technol. Soc.* **2021**, *65*, 101560. [CrossRef]
64. Sedlacek, S. The role of universities in fostering sustainable development at the regional level. *J. Clean. Prod.* **2013**, *48*, 74–84. [CrossRef]
65. Bramwell, A.; Wolfe, D.A. Universities and regional economic development: The entrepreneurial University of Waterloo. *Res. Policy* **2008**, *37*, 1175–1187. [CrossRef]
66. Kastrinos, N.; Weber, K.M. Sustainable development goals in the research and innovation policy of the European Union. *Technol. Forecast. Soc. Chang.* **2020**, *157*, 120056. [CrossRef]
67. Jaekel, M.; Wallin, A.; Isomursu, M. Guiding Networked Innovation Projects Towards Commercial Success—a Case Study of an EU Innovation Programme with Implications for Targeted Open Innovation. *J. Knowl. Econ.* **2015**, *6*, 625–639. [CrossRef]
68. Kashani, E.S.; Roshani, S. Evolution of innovation system literature: Intellectual bases and emerging trends. *Technol. Forecast. Soc. Chang.* **2019**, *146*, 68–80. [CrossRef]
69. Kapetaniou, C.; Samdanis, M.; Lee, S.H. Innovation policies of Cyprus during the global economic crisis: Aligning financial institutions with National Innovation System. *Technol. Forecast. Soc. Chang.* **2018**, *133*, 29–40. [CrossRef]
70. Lundvall, B.-Å. *Innovation System Research and Policy Where It Came from and where It might Go*; Globelics Working Paper Series 2007-01, Globelics—Global Network for Economics of Learning, Innovation, and Competence Building Systems; Aalborg University, Department of Business and Management: Aalborg, Denmark, 2007.
71. Barrutia, J.M.; Echebarria, C.; Apaolaza-Ibáñez, V.; Hartmann, P. Informal and Formal Sources of Knowledge as Drivers of Regional Innovation: Digging a Little Further into Complexity. *Environ. Plan. A: Econ. Space* **2014**, *46*, 414–432. [CrossRef]
72. Oerlemans, L.; Meeus, M. Do organizational and spatial proximity impact on firm performance? *Reg. Stud.* **2005**, *39*, 89–104. [CrossRef]
73. Cooke, P.; Clifton, N.; Oleaga, M. Social capital, firm embeddedness and regional development. *Reg. Stud.* **2005**, *39*, 1065–1077. [CrossRef]

5.4. Preventing Internal COVID-19 Outbreaks within Businesses and Institutions: A Methodology Based on Social Networks Analysis for Supporting Occupational Health and Safety Services Decision Making

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Preventing Internal COVID-19 Outbreaks within Businesses and Institutions: A Methodology Based on Social Networks Analysis for Supporting Occupational Health and Safety Services Decision Making

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Abstract: This study aims at developing and demonstrating in a real case study a methodology for supporting Occupational Health and Safety Services in the design and assessment of preventive measures to reduce the risks of COVID-19 outbreaks within their entities. The proposed methodology applies the concepts from Social Network Analysis (SNA) to the current challenge of preventing risks of contagion of viruses like SARS-COV-2 among employees. For this purpose, the authors consider a network of employees whose interaction is caused by triggers, which are defined as common circumstances between two workers that may result in contagion, like sharing an office or participating in the same management board. The network cohesion is then evaluated, and those core nodes, which are the most significant contributors to its integration, are identified to be addressed in the design of the preventive measures. The impact of the designed preventive measures on the networks' cohesion is assessed for its prioritization and further deployment. The methodology has been demonstrated in a real case, a Spanish Research Center, providing promising results in a quick and easy manner. The objective insights provided by its application were demonstrated as very valuable for the Occupational Health and Safety Services in the design and evaluation of the set of preventing measures to be implemented before the return of the employees to the facilities after the Spanish confinement period. The current COVID-19 outbreak brings the need to develop tools and methods to support businesses and institutions in the use of SNA for preventing outbreaks among their employees. Although some literature does exist in the field of SNA application in epidemiology, its adaptation for extensive use by the Occupational and Health Services is still a challenge.

Keywords: COVID-19; SARS-COV-2; coronavirus; workers; risk; preventive measures; decision making; infection prevention; protection; job shift; epidemiology; public health; social network analysis

1. Introduction

In 2020, the whole world is struggling against the SARS-COV-2 coronavirus pandemic. Public Health authorities have implemented isolation policies to reduce the loss of human lives, restricting, among others, all the non-essential economic activities. Thus, in addition to the sanitary effects, the virus will have a substantial impact on worldwide economies. A reduction of global economic growth by 2.0% per month of the outbreak is expected, while global trade could also fall between

13% and 32% [1]. Although the full economic impact will not be known until the crisis ends, it will strongly depend on how safe the economic activities reactivation at the workplaces is developed after the lockdown to prevent further outbreaks.

Workplaces have a role in disease transmission, with a substantial impact on public health [2]. As an example, in Singapore, among the first 25 locally transmitted COVID-19 cases, 17 of them (68%) were probably related to occupational exposure outside hospitals [3]. The workers' exposure to infection has been considered a key factor for containing the risk of COVID-19 infection also in the United States, where at least 18% of the total number of workers are expected to be exposed to COVID-19 at their workplaces at least once per month [4]. The interest of preventing sickness presenteeism at work, which was already an emerging concern of the organizations [5], is now one of their primary key challenges, highlighted by the fact of the asymptomatic COVID-19 cases contagion capacity, the silent spreaders.

In the context of the global COVID-19 pandemic, companies and institutions all over the world, supported by their Occupational Health Services, are trying to find the best ways to reorganize their activity to minimize the contagion risk among their employees, so as to protect their health and prevent internal SARS-COV-2 outbreaks. The rules and guidelines provided by the Health Authorities, as well as the organizational measures recently proposed by different authors [6], are the starting point, but they do not consider customized measures to be implemented at each entity attending to its activity, organization, and business particularities.

The employees of an entity interact among them, constituting a social network in which their contacts are driven by the work organization, the entity structures, the management procedures, or the people habits. This social network, through which COVID-19 could be spread, can be represented by a graph [7], that may be constructed relying on the data from the Enterprise Resources Planners (ERP) of the companies. Social Network Analysis (SNA) studies the underlying conditions of such social networks to identify patterns of interaction between the network's actors to understand their connections and the implications of their relationships [8]. There is an opportunity for applying SNA to the social network constituted by the employees of an entity to identify those critical nodes in which preventive measures may have the biggest impact in reducing the risk of contagion among employees.

Therefore, a methodology for guiding the design and evaluation of tailor-made preventive measures to contain internal outbreaks within each entity is still a gap that can be covered by the application of the Social Networks Analysis (SNA) techniques. This paper aims at covering this gap, also providing the results from a real demonstration case of this methodology applied in a Spanish Research Center.

2. Methodology

2.1. Concept and Approach

This paper addresses the gap in the application of SNA for preventing internal outbreaks within workplaces, providing a methodology to support Occupational Health and Safety Services in the design and selection of preventive measures ready to reduce the risk of outbreaks. To achieve this goal, the authors conceptualize how the employees of a company interact among them, forming a network in which outbreaks may be triggered by many factors or circumstances, such as sharing an office space, or participating in the same management board. Considering that the SARS-COV-2 is spread not only by direct contact between individuals, but also by fomites [9], a 2-mode network is required.

In this 2-mode network, every employee is tied to those triggers that may imply a close contact with another employee. As an example, these triggers may be working at the same office, participating in the same management body, sharing a collective transport, or collaborating in a given project. The 2-mode network composed of employees and triggers can be transformed into two 1-mode networks, one of the employees and one of the triggers. In the network of employees, the employees are the nodes, which are connected among them by shared triggers. In the network triggers, the nodes are the triggers, which are linked by those employees that participate in both. Both 1-mode networks are weighted considering a tie as strong as the number of links between the two connected nodes.

An analysis of both 1-mode networks can be performed with a twofold approach, on the one hand identifying the employees' network cohesion, which is related to the overall outbreak risk and, on the other hand, detecting those nodes, either employees or triggers, that are the most significant contributors to the network integration, thus with the highest probability to foster internal outbreaks. The identification of these critical nodes will support the design of different high impact sets of preventive measures.

The evaluation of the effect of the different sets of measures designed, as separating spaces, telework assignment to critical employees, management bodies virtualization, elimination of collective transports, etc., is then developed to select those actions with the most significant contribution to decreasing the risk of contagion, thus, the employees' network cohesion.

This paper aims to propose a quick methodology for designing and prioritizing actions able to minimize the risks of outbreaks within workplaces, also providing a simple example for its illustration, together with a real case of a given entity, with anonymized actual data.

2.2. Background

The social network approach has been used in epidemiology since 1985 [10]. In the last decade, SNA has become of great interest [11,12] due to two main advantages [13]: Firstly, a network provides a representation of the social contacts between individuals that are known to significantly influence the disease spread [14,15], and secondly, the analysis of the network structure itself supports the design of efficient plans of intervention or awareness [16]. Usually, each node of the network represents an individual, but also may represent groups or even locations, and it is described by a vector of attributes to understand the network dynamics. Two main types of contacts can be considered in the network construction, depending on the virus transmission paths: Personal contacts and geographical contacts. Indeed, in the case of SARS, with similar transmission paths to SARS-COV-2, it was demonstrated how the use of geographical contacts in the network construction provided valuable results [17], as its inclusion highlighted the network properties affecting the disease transmission. In this paper, a wider concept of the geographical location is proposed, considering all the triggers that may cause a close contact.

Several studies have assessed the relation of the properties of the networks—cohesion metrics—and its nodes—centrality metrics—with the infection dynamics in large populations [18]. Considering that although transmission tends to occur more rapidly in small-world networks, the final outbreak size tends to be smaller in these cases [18], so maybe for this reason, no focus has been placed at the population forming a business or an organization. Nevertheless, the relevance of the network properties in the outbreak spread in small networks has already been demonstrated [19].

The application of SNA in epidemiology has relied on tools designed to support Public Health Authorities [20–22] that provide simulations of the disease spread over time in large populations from urban to international levels.

Some studies on healthcare workers' occupational health have been conducted regarding the prevention of infectious diseases, but they represent only 13% of a sample of 402 papers published between 1992 and 2019 on this matter. Besides, most of them are surveillance studies [23]. The authors have not identified any study addressing the use of SNA for the support of Occupational Health and Safety Services in the prevention of outbreaks within workplaces.

3. Process

This paper proposes a five steps methodology to identify and evaluate preventative measures within the entities based on the use of Social Network Analysis. It is an iterative methodology in which, once guidance on the design of those preventive measures with the most significant impact is given, an evaluation of the resulting situation is performed to assess the achieved effects and to identify possible additional measures to implement. Figure 1 presents an overview of the methodology, including the key points of each step together with their relations. In the following subsections, each step is defined together with a simple example to illustrate the proposed methodology.

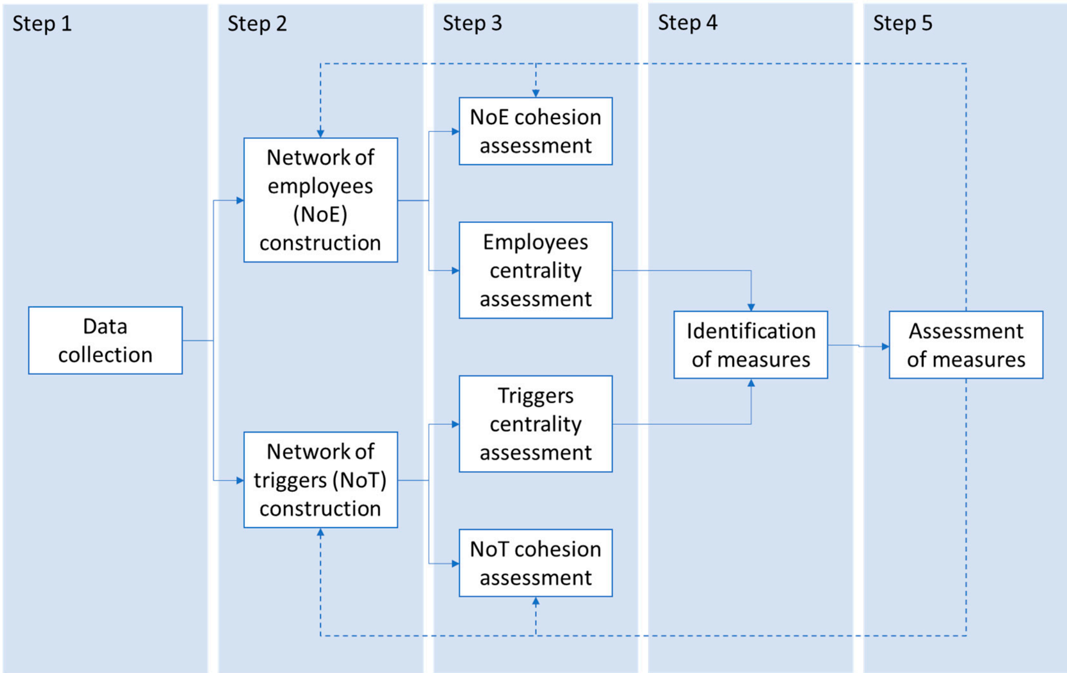

Figure 1. Overview of the proposed methodology.

3.1. Step 1: Data Collection

The main objective of this step is to collect, from the entity management systems or Enterprise Resource Planning (ERP), the nodes that will compose the network, employees and triggers, together with their connections. Firstly, all the people that constitute the entity population should be identified, including, in addition to the direct employees, all the external in-house persons. Secondly, all the triggers that are documented should be identified. Considering that a trigger is a common circumstance shared between two or more employees that can kick-off an outbreak, each company should identify those that are registered in their systems. As an example, some trigger categories that usually exist in the ERPs, and that can be easily extracted are:

- Permanent locations: Employees in shared offices will have close contact daily, so the permanent location of the employee is one of the key factors.
- Work shifts or other established time slots in which employees share spaces, like meals or coffee breaks, if they are scheduled.
- Locations with access: Those employees having access rights to a given part of the facilities, e.g., laboratories, warehouses, lockers' rooms, etc., may be in close contact and spread the virus from one part of the entity to another.
- Structural or functional areas or groups: Employees in the same organizational area usually are more prone to interact.
- Participation in projects: Employees participating in the same project will be more likely to work together, thus, having contacts.
- Management bodies: People that participate in the same management bodies are usually connected as they participate in meetings, etc.
- Company transport means: Some companies provide collective transports to their employees that may be a focus for contagion.

There is a non-exhaustive list, and it should be completed and revised for each entity attending to their specificities and available data.

With all the collected data, it is possible to construct an affiliation matrix in which each employee is tied to those triggers that affect him or her. Employees are placed in rows, and triggers in columns. In Table 1, a simple affiliation matrix is presented for an illustrative purpose of the methodology.

Table 1. Affiliation matrix.

	Board 3	Bus	Office H	Office I	Project A
E1	0	1	0	0	1
E2	1	1	0	0	0
E3	0	1	1	0	1
E4	0	0	1	0	1
E5	1	1	1	1	0
E6	1	0	0	1	0
E7	0	0	1	1	0
E8	0	0	0	1	0

3.2. Step 2: Networks Construction

The affiliation matrix is a representation of a 2-mode network, in which the nodes "employees" are tied with the nodes "triggers". Figure 2 represents the 2-mode network coming from the affiliation matrix presented in Table 1. Affiliation matrix.

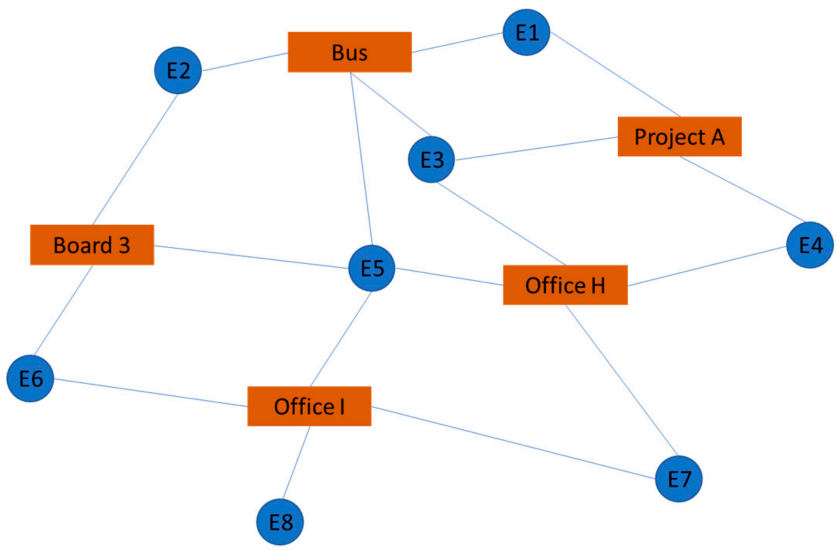

Figure 2. Mode network in which employees (circles) are tied to triggers (squares).

This 2-mode network can be transformed into two different 1-mode networks, one constituted by the employees and one constituted by the triggers. In the first case, the employees will appear as nodes, and they will be linked by a tie that will be weighted depending on the common triggers shared by them. In the second case, the triggers will appear as nodes, and they will be linked by a tie that will be weighted depending on the common employees shared by these triggers.

The network of employees is represented in Figure 3.

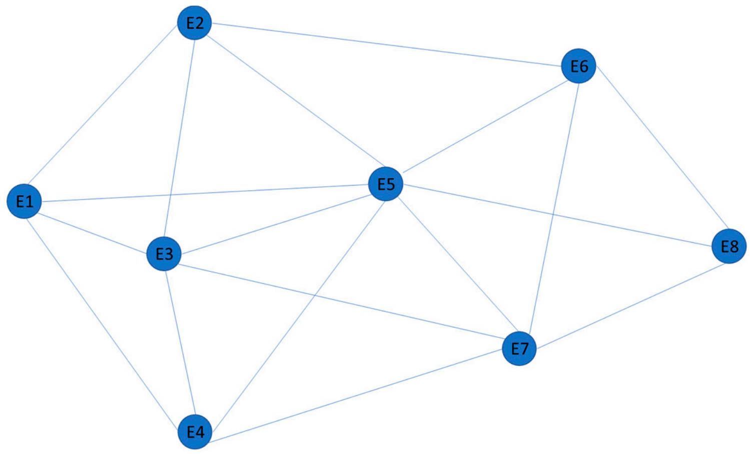

Figure 3. Network of employees.

This network is weighted depending on the number of triggers in which each pair of employees participates. The matrix of weights is presented in Table 2, and they represent a measure of how strongly linked two employees are, and thus how likely the virus may be transmitted between them, thus spreading an outbreak.

Table 2. Matrix of weighted ties between employees.

id	E1	E2	E3	E4	E5	E6	E7	E8
E1	2	1	2	1	1	0	0	0
E2	1	2	1	0	2	1	0	0
E3	2	1	3	2	2	0	1	0
E4	1	0	2	2	1	0	1	0
E5	1	2	2	1	4	2	2	1
E6	0	1	0	0	2	2	1	1
E7	0	0	1	1	2	1	2	1
E8	0	0	0	0	1	1	1	1

This matrix may already be used to trace the contagion chains if a case of COVID-19 is detected. As an example, if employee E2 tests positive for the virus, the prevention systems may test employee E5 firstly, as he or she holds the most significant risk of being also infected.

In addition to the network of employees, the network of triggers can be depicted. It is presented in Figure 4.

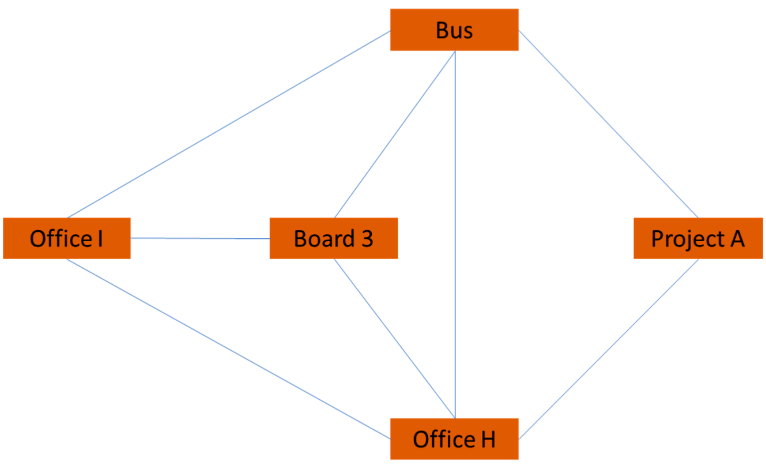

Figure 4. Network of triggers.

This network is also weighted depending on the number of employees that participate in each pair of triggers. The weights are presented in the matrix presented in Table 3, and they represent a measure of how strongly linked two triggers are, and thus how easily the virus may be transmitted between triggers, thus spreading an outbreak.

Table 3. Matrix of triggers weighted.

	Board 3	Bus	Office H	Office I	Project A
Board 3	3	2	1	2	0
Bus	2	4	2	1	2
Office H	1	2	4	2	2
Office I	2	1	2	4	0
Project A	0	2	2	0	3

3.3. Step 3: Networks Assessment

Networks can be assessed with a twofold perspective. From one side, the overall network characteristics can be assessed, most of them related to its cohesion. From the other, the role that each node plays within the network contributing to its overall cohesion, and thus to the virus spread, can be assessed.

In general, the cohesion metrics of the network of employees will provide a reference value to assess how the different measures taken on the nodes influenced these values; thus, contributing to lowering the outbreak risks. The absolute values of these network metrics are not so representative, as they are strongly influenced by the quantity of data, mainly triggers that can be extracted from the entity information systems. They should serve as a reference to compare the effect of the different preventative measures that are considered in the assessment.

The main cohesion metrics to be calculated from the network of employees are:

- Average Degree: It represents the number of ties per node, so how many other people are tied, on average, to an employee. The lower this rate, the better for reducing the contagion risk.
- H-Index: The largest number "h", such that there are "h" nodes with a degree (number of connections to other nodes) of at least "h". It gives an approximation of the number of super-spreaders, so it is related to the speed that a possible outbreak may have. The lower this rate, the better for reducing the contagion risk.
- Density: It calculates the rate of actual ties between the maximum potential ties in the network. So, it represents the number of tied employees divided by the maximum number of possible connections. The lower this rate, the better for reducing the contagion risk.
- Fragmentation: It gives the proportion of pairs of employees that are unreachable among them. The higher this rate, the better for reducing the contagion risk.
- Compactness: Calculated as the average of all the reciprocal distances between employees, it gives an idea of the overall tendency of employees to stay in proximity. The lower this rate, the better for reducing the contagion risk.

In Table 4, the calculated cohesion metrics of the network of employees in the baseline scenario are presented.

Table 4. Cohesion metrics from the baseline scenario network of employees.

Average Degree	H-Index	Density	Fragmentation	Compactness
4.5	4	0.64	0	0.82

Once the cohesion metrics of the overall network of employees are calculated for the baseline scenario, then the centrality metrics of the nodes of both 1-mode networks, triggers, and employees should be calculated to identify those critical spots to which preventative actions should be directed. The proposed metrics have already demonstrated their representativeness for identifying high-risk individuals in previous studies [18].

For both networks, the following centrality measures should be calculated for each node, either a trigger or an employee:

- Degree: It represents the number of nodes to which a given node is connected. The nodes with the higher rates are the ones more likely to spread an outbreak.
- Eigenvector: It gives a measure of the influence of a node within a network. Relative scores are given to all the network nodes considering their connections, then considering that the nodes connected to the high-scoring nodes are those with the most significant influence. The nodes with the higher rates are the ones more likely to spread an outbreak.
- Betweenness: It measures the number of times that a node is part of a geodesic path between all the reachable pairs of nodes. The nodes with the higher rates are the ones more likely to spread an outbreak.
- DwFrag: It represents the geodesic distance-weighted of the network fragmentation when the considered node is removed. The nodes with the higher rates are the ones more likely to spread an outbreak.

These centrality metrics have been calculated for each node and are presented in Table 5.

Table 5. Centrality measures of the network of employees in the baseline scenario.

Employee	Degree	Eigenvector	Between	DwFrag
E1	5.000	0.458	0.333	0.239
E2	5.000	0.484	0.833	0.239
E3	8.000	0.745	1.000	0.261
E4	5.000	0.462	0.333	0.239
E5	11.000	1.000	4.833	0.312
E6	5.000	0.431	0.833	0.239
E7	6.000	0.516	1.833	0.261
E8	3.000	0.229	0.000	0.217

Looking at the centrality measures of the network of employees, it is remarkable how E3 and E5 are the core of the network, being high contributors to the network cohesion. In particular, the employee that may have the most significant influence on the virus spreading is E5 (highest score on Eigenvector), while the one that serves as the unique connector between employees, and thus the one with more capacity to serve as a barrier for outbreaks, is E3 (highest score in betweenness). The measures of Degree and DwFrag are in line with the previous conclusions, so actions involving these two employees may be the ones with the most significant impact.

If the network of triggers centrality measures, presented in Table 6, are reviewed, it is noticeable how sharing the space at Office H is the condition that may have the most significant impact on the virus spreading among employees, followed closely by using the entity bus. Besides, both conditions are the ones with the highest scores of betweenness, DwFrag and Degree, so the measures with the highest impact should be directed to these two events.

Table 6. Centrality measures of the network of triggers in the baseline scenario.

Trigger	Degree	Eigenvector	Between	DwFrag
Board 3	5.000	0.704	0.000	0.389
Bus	7.000	0.987	1.000	0.444
Office H	7.000	1.000	1.000	0.444
Office I	5.000	0.799	0.000	0.389
Project A	4.000	0.612	0.000	0.333

As a summary, at this step, the cohesion metrics of the network of employees should be assessed to serve as a reference for the ulterior measurement of the impacts of the different possible preventive measures. Additionally, the centrality metrics of each node at both networks, employees, and triggers should be calculated to guide the definition of the preventive measure, whose identification will take place in the following step of the methodology.

3.4. Step 4: Preventive Measures Design

Starting from the centrality measures of the different nodes, a selection of those nodes with the highest contribution to the network's integration should be made. Then, all the possible actions to reduce their influence should be assessed considering the entity particularities, which may highly differ from one entity to another.

On the one hand, regarding those employees with the highest impact, four main lines of action may be considered. Firstly, to reduce their presence and interaction with other employees to increment their social distance (not using collective transport, participating virtually in project meetings, establishing a separate office space or, the most strict, teleworking). Secondly, to establish a close follow up of their health conditions (e.g., increasing test frequency). Lastly, to increase their level of Individual Protection Equipment (masks, screens, suits, etc.).

On the other hand, regarding the triggers, the actions will mainly depend on the triggers' nature. For spaces, splits through compartmentalization or distance augmentation between employees may be an option, together with enhanced access restrictions to some places. Additionally, an intensification of the disinfection measures in those spaces with the highest impact should be considered. Regarding turns, augmenting the number of turns or moving employees from one turn to another could be considered. Collective transport may be substituted by individual ones that may be subsidized to the employee. Regarding internal meetings, those related to management boards or projects that may have the most significant influence could be virtualized. All in all, each entity should carefully assess all the possible available means to reduce the effect of those triggers or employees that may have the most significant impact on the virus spread.

Following our previous example, let us suppose that the entity detects two possible sets of measures that may be implemented:

- Option A: E3 goes to telework, and E5 is moved from Office H to an individual office.
- Option B: The bus is eliminated, and Office H is split into two parts using screen walls.

Each of these options will configure a different network, as it is presented in Figure 5, which will be assessed in the next step of the method.

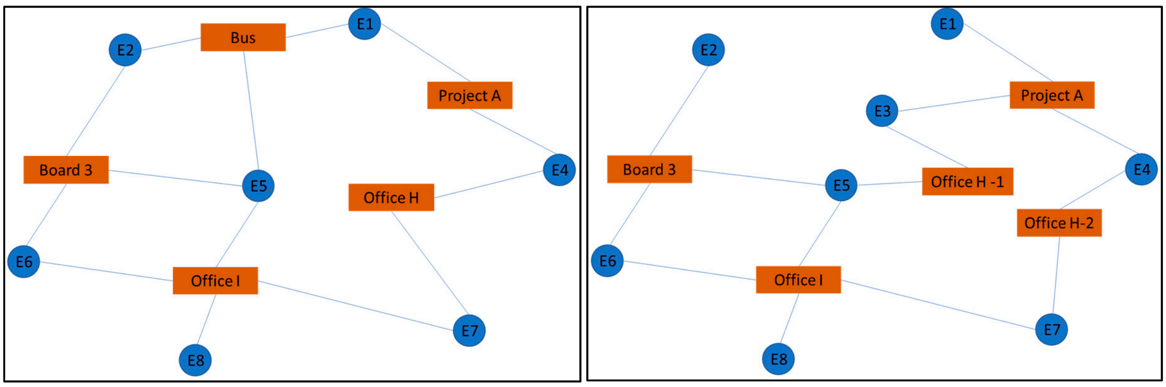

Figure 5. Option A Network on the left and Option B network on the right.

3.5. Step 5: Assessment of the Preventive Measures

Once that the effect of the preventive measures has been reflected in the networks, the process of constructing the 1-mode network of employees for the options considered and then calculating the cohesion measures should be followed. In Table 7, the different metrics for each of the two options are presented, together with baseline situation ones.

Table 7. Assessment of the network of employees' cohesion metrics for the different preventive options.

Cohesion Metrics	Baseline Situation	Option A	Option B
Average Degree	4.5	3	3.25
H-Index	4	3	3
Density	0.64	0.43	0.46
Fragmentation	0	0.25	0
Compactness	0.82	0.59	0.71

An overview of the cohesion metrics shows how both options improve the ratios compared to the baseline situation. Nevertheless, Option A shows a better performance than Option B, reaching a fragmentation level of 0.25 and lowering the compactness up to 0.59. So, from an SNA point of view, Option A (telework for E3 and an individual office for E5) has a higher impact on preventing an internal outbreak than Option B.

At that point, an iterative process should start, proposing new complementary measures over Option A, which may be identified by looking to the centrality metrics of the newly generated networks. This way, the iteration process should continue until the managers find a set of actions that is suitable for the company's operations. For sure, the results from the proposed SNA methodology should be considered together with other variables, like costs of the proposed measures, deployment easiness, or implementation time.

4. Real Case Example

The proposed methodology has been developed and already applied in a Spanish Research Center, CIRCE Foundation-Research Center for Energy Resources and Consumption-, considering actual data.

4.1. Step 1: Data Collection

This center is composed of 204 people, including employees and external in-house persons. In the ERP, seven categories of triggers have been identified, ready to be exported, involving a total of 105 different triggers. The 204 employees have 1266 ties to the 105 triggers. The distribution of triggers between categories together with the number of ties between employees and trigger categories is presented in Table 8.

Table 8. Categories of triggers and number of triggers per category at the research center.

Trigger Category	Number of Triggers	Number of Ties to this Category
Structural area	3	185
Research or management groups	12	201
Office locations (open spaces or rooms)	23	194
Locations with restricted access (laboratories or warehouses)	3	77
Management bodies	2	24
Project teams	58	577
Collective shared transport (shared cars)	4	8

4.2. Step 2: Networks Construction

The 2-mode network, constructed using the software UCINET [24], can be plotted, as it is presented in Figure 6.

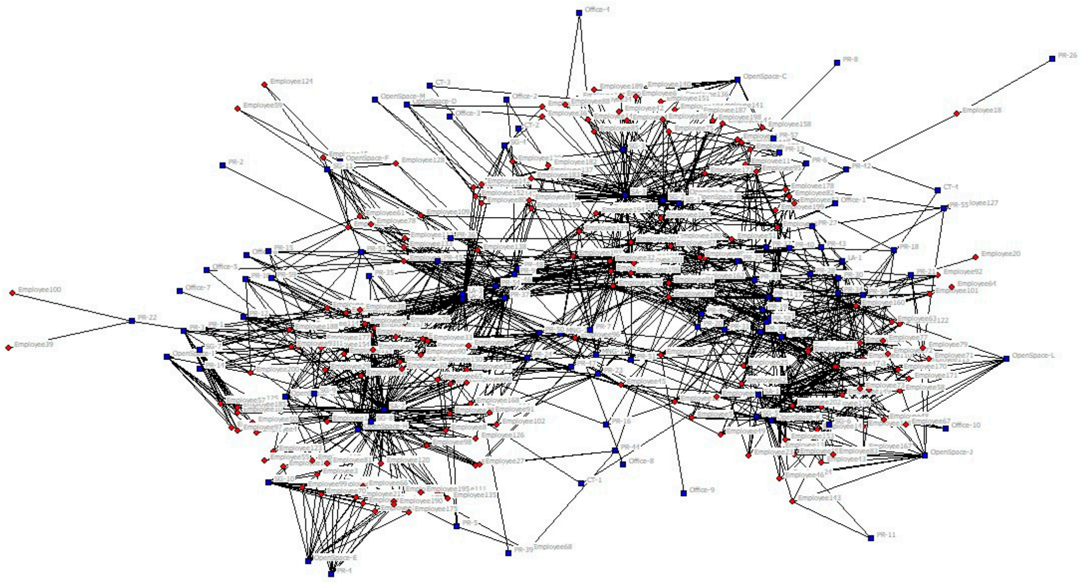

Figure 6. Graph of the 2-Mode network constructed for the Research Center.

4.3. Step 3: Networks Assessment

From this 2-mode network, the network of triggers and the network of employees can be deducted. The cohesion measures from the network of employees are presented in Table 9.

Table 9. Cohesion measures of the research center network of employees.

Average Degree	H-Index	Density	Fragmentation	Compactness
77.83	79	0.38	0	0.69

Regarding the centrality values of the Triggers network, the items from each category with the highest scores at the metrics Degree, Eigenvector, Between, and DwFrag have been identified. They are presented in Table 10.

Table 10. Most critical triggers at each category considering the four centrality metrics.

Trigger Category	Degree	Eigenvector	Between	DwFrag
Structural area				
SA-2	353	1	253.89	0.025
SA-3	391	0.91	328.73	0.029
Research or management groups				
SG-2	165	0.37	44.62	0.022
SG-1	149	0.31	38.54	0.022
SG-8	138	0.43	28.50	0.019
SG-3	67	0.17	38.92	0.018
Office locations (open spaces or rooms)				
OpenSpace-H	112	0.35	11.04	0.018
OpenSpace-B	134	0.31	26.14	0.021
OpenSpace-A	117	0.24	21.89	0.020
OpenSpace-K	111	0.18	4.17	0.019
Locations with restricted access (laboratories or warehouses)				
LA-3	343	0.91	444.53	0.029
Management bodies				
MNG-2	174	0.35	175.10	0.024
Project teams				
PR-37	276	0,67	223,58	0,026
PR-42	28	0,05	104,08	0,028
Collective shared transport (shared cars)				
CT-2	28	0,05	7,48	0,018
CT-1	22	0,04	15,62	0,018

Besides, the centrality measures of the nodes of the network of employees have been calculated. Table 11 present the most critical employees that have been identified considering the top-5 scores at each of the four centrality measures considered.

Table 11. Most critical employees considering the four centrality metrics.

Employee ID	Degree	Eigenvector	Between	DwFrag
Employee 203	350	1.00	340.79	0.012
Employee 129	323	0.95	344.05	0.012
Employee 32	331	0.89	338.76	0.012
Employee 37	346	0.86	302.82	0.011
Employee 94	323	0.85	330.24	0.012
Employee 74	312	0.81	499.49	0.013
Employee 96	296	0.72	2799.34	0.038
Employee 31	205	0.53	441.83	0.022

4.4. Step 4 and 5: Preventive Measures Design and Assessment

Considering the operations particularities of the research center and the centrality metrics obtained, the following set of six measures were initially designed:

1. Measure 1: Employees 74 and 94 will telework.
2. Measure 2: Employee 31 will telework, except for developing tests at the laboratory, where he will maintain the access.
3. Measure 3: Open Space B will be divided into two parts, with different entrance and exit access.
4. Measure 4: The access to laboratory LA-3 will be restricted to employees 129, 32, 37, and 96.
5. Measure 5: The management body MNG-2 will only have virtual meetings.
6. Measure 6: The projects PR-37 and PR-42 will only have virtual meetings.

In Table 12, the cohesion metrics of the baseline scenario, together with the initial set of measures, are presented.

Table 12. Comparison of the network of employees' cohesion metrics for the baseline and new situation scenario.

	Average Degree	H-Index	Density	Fragmentation	Compactness
Baseline scenario	77.83	79	0.38	0	0.69
Initial set of measures	72.84	75	0.36	0.03	0.66
Improvement	6.4%	5.1%	5.3%	N/A	4.3%

Although the proposed measures seem to improve all the values, a reinforced set of measures was designed to improve the prevention of outbreaks further. For this purpose, after a new calculation of the centrality metrics, different sets of measures where designed and assessed. Finally, the following set of seven additional measures was added to the previous one:

- Measure 1: Employee 203 will telework.
- Measure 2: Employees 26, 38, and 53 will telework, except for developing tests at the laboratory, where they will maintain access.
- Measure 3: Employees taken part in the management bodies will not attend any project meeting, participating only virtually.
- Measure 4: Access to LA-3 will only be permitted for the essential employees and restricted to visitors, thus only allowing Employees 2, 9, 30, 31, 33, 38, 65, 69, 76, 90, 117, 147, 150, 155, and 177.
- Measure 5: Access to LA-2 will only be permitted for the essential employees, thus only allowing Employees 69, 147, 150, 161, and 177.

- Measure 6: OpenSpace H will also be divided into two zones as was done in OpenSpace B.
- Measure 7: Projects PR-46, PR-50, PR-24, PR-9, PR-29, PR-41, and PR-54 will only have virtual meetings.

The calculations of the network of employees' cohesion measures that may be achieved by the set of reinforced measures are presented in Table 13. It can be seen how the final measures have a substantial effect on the cohesion metrics of the network.

Table 13. Comparison of the cohesion network considering two different sets of measures.

	Average Degree	H-Index	Density	Fragmentation	Compactness
Baseline scenario	77.83	79	0.38	0	0.69
Initial set of measures	72.84	75	0.36	0.03	0.66
Set of reinforced measures	58.94	68	0.29	0.04	0.62
Improvement achieved by the set of reinforced measures	24%	14%	24%	N/A	10%

In addition to these measures directly affecting the composition of the network, additional preventive measures are appointed by the networks metrics, like reinforcing the disinfection of OpenSpace-A and OpenSpace-K, as well as specific awareness campaigns for the employees belonging to the groups SG-2, SG-1, SG-8, and SG-3, which are the biggest contributors to the high metrics of the structural areas SA-2 and SA-3. Finally, tests of those employees with the highest centralities score may contribute to early detection of those cases with the highest probability of kicking-off an internal outbreak.

Although some of the preventive measures designed were intuitive, many other critical employees or triggers have been detected using the proposed methodology. Once identified, they seem reasonable considering the entity operations, but it could be almost impossible to identify all of them with an intuitive approach.

5. Discussion

In order to cope with the COVID-19 pandemic, general recommendations have been given to prevent COVID-19 in the workplaces considering different risk levels and targeting organizational, environmental, and individual measures [6,25]. These measures can be reinforced with additional tailor-made preventive interventions relying on the company data able to represent the social network of employees. The proposed methodology contributes to developing a kind of precision-medicine approach in the field of preventive healthcare, which is of an increasing interest in recent years [26,27].

SNA is a powerful tool to extract knowledge from massive and unstructured data [28] related to social networks. In recent years, SNA involving two-mode networks has been successfully used at country-level to model and analyze outbreaks [29]. Similarly, the methodology proposed in this paper of applying SNA in workplaces for reducing risks of contagion has revealed significant insights regarding cross-correlations between contagion triggers and workers, including non-intuitive ones. The concept of reducing the cohesion metrics of the network by acting on those nodes—triggers or employees—with the highest centrality metrics, has been illustrated and demonstrated with actual data in a real case study: A medium-size Spanish research center.

The proposed methodology has resulted to abstract the structure and dynamics of the relations between the employees and to identify those critical workers or triggers to which preventive measures should be addressed to achieve the highest impacts. The demonstration of the proposed methodology has provided relevant non-intuitive information: Spaces with the highest risk, people with the greatest potential to spread the virus, meetings or projects serving as a driver for the virus to move around the organization, etc. Interventions addressing these critical nodes have been designed to resume the center activity in a safer way.

6. Conclusions and Future Perspectives

It has been seen how SNA may be a complementary tool contributing to the design and selection of tailor-made preventing measures for reducing the risk of internal outbreaks in companies and institutions of the human-to-human transmitted virus, like SARS-COV-2. An easy to follow methodology, ready to be adapted to each entity information system and particularity has been defined. This methodology provides quick results that should be interpreted by specialists on Occupational Health and Safety with basic training on SNA focused on those concepts involved in the methodology.

Although valuable results for guiding the design and definition of preventative measures are achieved, the methodology is limited by many aspects that have not been considered. The two main aspects that could be further integrated into the analysis are the power of the triggers and the employee's likelihood of spreading the virus. Additionally, the effects of a potential contagion on each employee, i.e., the vulnerability of the employee or cohabitation with vulnerable people, could be a crucial point to incorporate into the methodology.

The possibility of assigning attributes to the nodes is seen as the most promising solution for overcoming the limitations established. For the triggers, attributes regarding their power could be evaluated for each category. As an example, a shared location with enlarged space between people, which is disinfected daily, is less likely to be a contagion trigger than the same location crowded and without regular disinfection. The development of indicators and its evaluation for standardized circumstances for each trigger category will be key for the assignation of attributes to the trigger nodes.

Regarding the employees, attributes regarding their likelihood of spreading the virus could be considered. As an example, if they already overcame the disease and are now immune, their likelihood of contagion should be lowered. Additionally, data related to the employee residential address, like the number of cases in his or her postcode, may also be considered. Finally, the health conditions of the employee regarding its vulnerability, as well as the social ones, like his or her cohabitation with vulnerable people, could be an interesting point to consider. Nevertheless, the collection and use of this information are regulated by personal data protection laws, which may hamper its utilization.

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References

1. Jackson, J.K.; Weiss, M.A.; Schwarzenberg, A.B.; Nelson, R. *Global Economic Effects of COVID-19, Updated May 1, 2020*; Congressional Research Service: Washington, WA, USA, 2020; R46270.
2. Edwards, C.H.; Tomba, G.S.; de Blasio, B.F. Influenza in workplaces: Transmission, workers' adherence to sick leave advice and European sick leave recommendations. *Eur. J. Public Health* **2016**, *26*, 478–485. [CrossRef] [PubMed]
3. Koh, D. Occupational risks for COVID-19 infection. *Occup. Med.* **2020**, *70*, 3–5. [CrossRef] [PubMed]
4. Baker, M.G.; Peckham, T.K.; Seixas, N.S. Estimating the burden of United States workers exposed to infection or disease: A key factor in containing risk of COVID-19 infection. *PLoS ONE* **2020**, *15*, e0232452. [CrossRef] [PubMed]
5. Kinman, G. Sickness presentism at work: Prevalence, costs and management. *Br. Med Bull.* **2019**, *129*, 69–78. [CrossRef] [PubMed]
6. Cirrincione, L.; Plescia, F.; Ledda, C.; Rapisarda, V.; Martorana, D.; Moldovan, R.E.; Theodoridou, K.; Cannizzaro, E. COVID-19 Pandemic: Prevention and Protection Measures to Be Adopted at the Workplace. *Sustainability* **2020**, *12*, 3603. [CrossRef]

7. Wasserman, S.; Faust, K. *Social Network Analysis: Methods and Applications*; Cambridge University Press: Cambridge, UK, 1994; ISBN 0-521-38269-6.
8. Tabassum, S.; Pereira, F.; Fernandes, S.; Gama, J. Social network analysis: An overview. *Wiley Interdiscip. Rev. Data Min. Knowl. Discov.* **2018**, *8*, e1256. [CrossRef]
9. Peng, X.; Xu, X.; Li, Y.; Cheng, L.; Zhou, X.; Ren, B. Transmission routes of 2019-nCoV and controls in dental practice. *Int. J. Oral Sci.* **2020**, *12*, 1–6. [CrossRef] [PubMed]
10. Klovdahl, A.S. Social networks and the spread of infectious diseases: The AIDS example. *Soc. Sci. Med.* **1985**, *21*, 1203–1216. [CrossRef]
11. Mahmoud, A. Modeling community containment for pandemic influenza: A letter report. In *Committee on Modeling Community Containment for Pandemic Influenza, Institute of Medicine*; The National Academies Press: Washington, DC, USA, 2006.
12. Périssé, A.R.S.; Nery, J.A.D.C. The relevance of social network analysis on the epidemiology and prevention of sexually transmitted diseases. *Cadernos de Saúde Pública* **2007**, *23*, S361–S369.
13. Stattner, E.; Vidot, N. Social network analysis in epidemiology: Current trends and perspectives. In Proceedings of the 2011 Fifth International Conference on Research Challenges in Information Science, Gosier, Guadeloupe, 19–21 May 2011; pp. 1–11.
14. Newman, M.E. The structure and function of complex networks. *SIAM Rev.* **2003**, *45*, 167–256. [CrossRef]
15. Rosenberg, D.; Moseley, K.; Kahn, R.; Kissinger, P.; Rice, J.; Kendall, C.; Farley, T.A. Networks of persons with syphilis and at risk for syphilis in Louisiana: Evidence of core transmitters. *Sex. Transm. Dis.* **1999**, *26*, 108–114. [CrossRef] [PubMed]
16. Christakis, N.A.; Fowler, J.H. Social network sensors for early detection of contagious outbreaks. *PLoS ONE* **2010**, *5*, 0012948. [CrossRef] [PubMed]
17. Chen, Y.D.; Tseng, C.; King, C.C.; Wu, T.S.J.; Chen, H. Incorporating geographical contacts into social network analysis for contact tracing in epidemiology: A study on Taiwan SARS data. In Proceedings of the 2nd NSF Workshop on Intelligence and Security Informatics, New Brunswick, NJ, USA, 22 May 2007; Springer: Berlin/Heidelberg, Germany, 2007; pp. 23–36.
18. Christley, R.M.; Pinchbeck, G.L.; Bowers, R.G.; Clancy, D.; French, N.P.; Bennett, R.; Turner, J. Infection in social networks: Using network analysis to identify high-risk individuals. *Am. J. Epidemiol.* **2005**, *162*, 1024–1031. [CrossRef] [PubMed]
19. Britton, T. Epidemic models on social networks–with inference. *arXiv* **2019**, arXiv:1908.05517. [CrossRef]
20. Adams, A.L.; Koopman, J.S.; Chick, S.E.; Yu, P.J. GERMS: An epidemiologic simulation tool for studying geographic and social effects on infection transmission. In Proceedings of the WSC'99. 1999 Winter Simulation Conference Proceedings. 'Simulation-A Bridge to the Future' (Cat. No. 99CH37038), Phoenix, AZ, USA, 5–8 December 1999; Volume 2, pp. 1549–1556.
21. Barrett, C.L.; Bisset, K.R.; Eubank, S.G.; Feng, X.; Marathe, M.V. EpiSimdemics: An efficient algorithm for simulating the spread of infectious disease over large realistic social networks. In Proceedings of the 2008 ACM/IEEE Conference on Supercomputing, Austin, TX, USA, November 2008; pp. 1–12.
22. Eubank, S. Scalable, efficient epidemiological simulation. In Proceedings of the 2002 ACM symposium on Applied computing, New York, NY, USA, March 2002; ACM Digital Library: New York, NY, USA, 2002; pp. 139–145.
23. Zhu, B.; Fan, H.; Xie, B.; Su, R.; Zhou, C.; He, J. Mapping the Scientific Research on Healthcare Workers' Occupational Health: A Bibliometric and Social Network Analysis. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2625. [CrossRef] [PubMed]
24. Borgatti, S.P.; Everett, M.G.; Freeman, L.C. *Ucinet 6 for Windows: Software for Social Network Analysis*; Analytic Technologies: Harvard, MA, USA, 2002.
25. Pradhan, D.; Biswasroy, P.; Ghosh, G.; Rath, G. A Review of Current Interventions for COVID-19 Prevention. *Arch. Med. Res.* **2020**. [CrossRef] [PubMed]
26. Guinazu, M.; Cortés, V.; Ibáñez, C.; Velasquez, J. Employing online social networks in precision-medicine approach using information fusion predictive model to improve substance use surveillance: A lesson from Twitter and marijuana consumption. *Inf. Fusion* **2019**, 55. [CrossRef]
27. Woolliscroft, J. Chapter 12—Precision medicine. In *Implementing Biomedical Innovations into Health, Education, and Practice*; Academic Press: Cambridge, MA, USA, 2020. [CrossRef]

28. Niewiadomska-Szynkiewicz, E. Application of Social Network Analysis to the Investigation of Interpersonal Connections. *J. Telecommun. Inf. Technol.* **2012**, *2*, 81–89.
29. An, F.; Gao, X.; Guan, J.; Huang, S.; Liu, Q. Modeling the interdependent network based on two-mode networks. *Phys. A Stat. Mech. Its Appl.* **2017**, *483*, 57–67. [CrossRef]

6. Conclusiones obtenidas

Las conclusiones obtenidas contribuyen a la literatura relativa a las redes y sistemas de innovación, incluyendo apuntes particulares sobre el sector energético. A continuación, se detallan las conclusiones obtenidas organizadas según la publicación a la que corresponden.

- En el trabajo Calvo-Gallardo et al. (2021) se analiza el Sistema de Innovación de la UE y su impacto en la consecución de los objetivos europeos en materia de innovación y energética. Para ello, se asume que los consorcios de investigación son el principal mecanismo de la UE para el desarrollo de estas políticas, los cuales forman redes de relaciones entre proyectos y socios que, a su vez, conforman el sistema de innovación europeo.

  Desde una perspectiva teórica, el *primer grupo de contribuciones* de este trabajo amplía la literatura sobre los sistemas de innovación en cuanto a su modelado y efectividad. Los hallazgos indican la conveniencia de concebir los sistemas de innovación como redes de relaciones entre entidades y proyectos. De esta manera, se puede entender cómo la efectividad de los sistemas de innovación se relaciona con los atributos de los nodos, así como su posición dentro de la red. Además, el estudio revela cómo las propiedades estructurales de la red varían en cada área tecnológica, afectando la centralidad y la cohesión, tanto en términos de transferencia de conocimiento como de conexión geográfica entre países. El *segundo grupo de aportes teóricos* afecta a las políticas de investigación y desarrollo energético. Una correcta evaluación de la política energética debe analizar la topología y propiedades estructurales de la red. En primer lugar, la cohesión de los sistemas de innovación permite evaluar la viabilidad de colaboraciones potenciales, la transferencia de información y conocimiento y la cohesión geográfica. En segundo lugar, las métricas de centralidad del sistema de innovación permiten evaluar las políticas energéticas en términos de competitividad. Por último, la conectividad de la red permite analizar la transversalidad entre los diferentes programas de investigación como forma de identificar y promover efectos sinérgicos entre ellos.

  Este estudio tiene relevantes **implicaciones para la gestión y la formulación de políticas de innovación**. *En primer lugar*, los Programas Marco se enfrentan al reto de aumentar la cohesión de las actividades relacionadas con la Eficiencia y Ahorro Energético para evitar la actual fragmentación. Esto se puede conseguir a través de la mejora en la colaboración entre proyectos y acciones transversales, así como implicando a los coordinadores del proyecto, en particular a los centros de investigación, ya que se muestran como los nodos más influyentes de la red. Asimismo, se debe prestar especial atención a mejorar la colaboración entre países con diferentes niveles de desempeño para buscar beneficios recíprocos. Por otro lado, todas las medidas propuestas que apunten a una mayor cohesión de las redes deben evaluarse cuidadosamente para evitar promover un ecosistema de I+D cerrado, lo que tendría efectos perniciosos. Por tanto, los criterios de cohesión de la red deben equilibrarse con la competitividad abierta en I+D. *En segundo lugar,* los formuladores de políticas y los participantes en los programas de financiación pueden aplicar el método y los hallazgos propuestos en este estudio. Los responsables políticos europeos pueden considerar estos resultados para diseñar los próximos Programas Marco de manera que contribuyan al logro de los objetivos de la ERA y el SET-Plan. Además, el diseño de políticas nacional puede basarse en este estudio para configurar programas de apoyo para facilitar la participación de las entidades nacionales en los sistemas de innovación internacionales. Finalmente, los participantes individuales pueden aplicar los resultados de este estudio para seleccionar a sus socios del consorcio para mejorar su posición en la red y, por lo tanto, mejorar su acceso al conocimiento y las capacidades de investigación.

Por último, como cualquier otro, este estudio tiene limitaciones. El estudio empírico se centra en los proyectos de Energía del Séptimo Programa Marco (FP7) financiados bajo un Esquema de Proyecto Colaborativo; por lo tanto, futuras investigaciones deberían analizar Horizon 2020, el sucesor del FP7, lo que permitiría evaluar la evolución del ecosistema de I+D en energía. Además, los trabajos posteriores deberían centrarse en la necesidad de establecer valores de referencia para determinar los niveles de cohesión y centralidad más convenientes para cada área de investigación, considerando los diferentes tipos de actores y la cooperación transnacional.

- En el trabajo Calvo-Gallardo et al. (2022a) se estudia la evolución del sistema de innovación energético europeo entre los periodos 2007-2013 y 2014-2020, así como su respuesta a los cambios políticos que planteaba el programa de financiación H2020, correspondiente al segundo periodo, frente a su antecesor FP7, correspondiente al segundo periodo.

  Desde el punto de vista teórico, *la primera contribución* de este estudio amplía trabajos previos en la literatura de innovación, particularmente en lo que respecta a la comprensión de la capacidad de respuesta de los sistemas de innovación frente a cambios resultantes del impulso institucional que generan los programas de financiación de la innovación. Primero, proporciona evidencia empírica de cómo la composición (heterogeneidad de los nodos) y la estructura de la red (cohesión, centralidad y conectividad) de entidades y relaciones que subyacen al sistema de innovación evolucionaron entre dos Programas Marco (FP7 y H2020) en función de los objetivos perseguidos por cada uno. En segundo lugar, este estudio contribuye a ampliar el conocimiento en el campo de la evolución y dinámica de los sistemas de innovación. Así, la comparación entre los dos periodos correspondientes a las dos FP permite un análisis de la dinámica del sistema de innovación mediante Análisis de Redes Sociales a partir de la evolución de las propiedades de la red. Los resultados indican que las propiedades del sistema completo, evaluadas mediante métricas de cohesión, evolucionaron de manera más suave, impulsadas por cambios más pronunciados en las propiedades de los nodos, que se evaluaron mediante métricas de centralidad. En tercer lugar, este estudio contribuye a evaluar la eficacia de los sistemas de innovación al considerar la relevancia de la heterogeneidad de los socios en términos de tipo de actividad y ubicación geográfica. Así, la identificación y caracterización de la evolución de las entidades que contribuyen a la cohesión de todo el sistema, apoyándose en métricas de centralidad y sus atributos, posibilitan la consideración de los nodos como parte activa de la red. Esto puede proporcionar la dinámica y los cambios en las propiedades de cohesión de todo el sistema y, en consecuencia, en su desempeño general. Finalmente, en línea con estudios previos, el análisis de redes sociales ha demostrado ser una herramienta valiosa para evaluar la evolución de los sistemas de innovación complejos y evaluar la dinámica general sin perder la perspectiva de la entidad y proporcionando información complementaria desde las perspectivas del sistema y del nodo. La *segunda contribución* se sitúa dentro de la teoría de impulso institucional, ampliando la literatura existente al proporcionar información sobre cómo el impulso institucional de los programas de financiación pública a la investigación afecta al desarrollo de nuevas tecnologías energéticas. Los resultados muestran que la red de relaciones desarrollada a través del impulso institucional tiene un impacto relevante en el desarrollo de nuevas tecnologías. Por tanto, se puede concluir que, además del impacto directo en las entidades participantes, genera un efecto indirecto a través de la generación de una red de relaciones acorde a los objetivos perseguidos, indicando así la eficiencia de los programas marco en el impulso de la innovación. La *tercera aportación teórica* se enmarca en el contexto de los Programas Marco de la UE, en el que se ha producido un desarrollo asimétrico de las diferentes áreas de investigación. Por lo tanto, la evaluación y comparación de las métricas de cohesión y centralidad de cada subgrafo tecnológico permiten evaluar la efectividad de las trayectorias tecnológicas y el desarrollo de cada área de investigación.

Las implicaciones para la **formulación de políticas** que se derivan de estos resultados son relevantes, ya que proporcionan la base para comprender cómo los objetivos de la política de innovación pueden lograrse mediante cambios en el impulso institucional capaces de impulsar el sistema de innovación hacia el logro de estos objetivos. *En primer lugar*, la evaluación de las topologías de red existentes y sus propiedades estructurales, seguida de un diseño de los cambios más convenientes para el logro de los objetivos, puede proporcionar una buena base para la formulación de políticas. *En segundo lugar*, la participación de las entidades más influyentes y su contribución a los cambios buscados puede impulsar el sistema de innovación hacia el logro de nuevas metas. Por lo tanto, el monitoreo continuo de las entidades que tienen la mayor influencia en la red y trabajar para lograr su involucración en los cambios deseados puede allanar el camino para la implementación exitosa de nuevas políticas. *En tercer lugar*, los cambios en el impulso institucional y los programas de financiación son efectivos para gestionar la evolución de las diferentes tecnologías. Aunque la Eficiencia y el Ahorro Energético siguen siendo uno de los retos clave, se han conseguido algunas mejoras en la cohesión de sus redes asociadas, así como en la consecución de la apertura de algunas tecnologías que antes estaban cerradas y restringidas a unas pocas entidades. Además, desde la perspectiva de las entidades participantes, los resultados del seguimiento de la dinámica de los sistemas de innovación brindan información valiosa sobre la evaluación de las tendencias relacionadas con la tecnología, la identificación de actores clave y la consideración de los objetivos y el contexto de las políticas. Esta información es útil para la evaluación de inversiones, opciones tecnológicas y desarrollo de alianzas.

Este estudio tiene algunas limitaciones. La investigación empírica se centra en el campo de la energía, que es un sector regulado. Por lo tanto, algunas de sus particularidades pueden dificultar la replicación de los resultados en sistemas de innovación correspondientes a otros sectores. De este modo, se necesita más investigación para abordar más y diferentes sectores o programas de investigación. Finalmente, se necesita más estudios para determinar el equilibrio más conveniente entre la inercia y la dinámica, tanto en la topología como en las propiedades de las redes, para lograr sistemas de innovación más eficientes.

- En el trabajo Calvo-el al. (2022b) se aborda la relación entre las políticas de especialización regionales y las características de las redes de los sistemas de innovación regionales, con el objetivo de analizar cómo diseñar mejor estas políticas teniendo en cuenta las características de los sistemas de innovación. El trabajo se particulariza en las regiones intensivas en carbón, en concreto en las españolas, que actualmente afrontan el reto de desarrollar nuevas sendas económicas bajas en carbono.

  Desde la **perspectiva teórica**, el *primer grupo de contribuciones* amplía la literatura sobre los sistemas regionales de innovación en términos de su modelado y efectividad, particularmente en regiones del carbón en transición. Se establece la conveniencia de concebir el sistema de innovación regional como una red de relaciones entre entidades y proyectos para entender cómo su efectividad se relaciona tanto con características de cohesión de la red y subredes temáticas, como con los atributos de los nodos y su posición dentro de la red. Además, el estudio revelaa cómo las propiedades estructurales de la red varían en cada área de investigación, afectando las métricas de centralidad y cohesión, tanto en términos de transferencia de conocimiento como de colaboración dentro de la región, en las diferentes trayectorias tecnológicas.

El *segundo grupo de aportes teóricos* tiene su origen en los sistemas regionales de innovación. Mientras que la literatura enfatiza como características regionales la concentración de habilidades y conocimientos altamente especializados, instituciones, negocios relacionados y clientes en una región particular, nuestro trabajo amplía la literatura al señalar que la correcta la evaluación de la política de investigación debe analizar la topología y las propiedades estructurales de las redes relacionadas de los sistemas de innovación en la región. En primer lugar, la cohesión de los sistemas de innovación permite evaluar la viabilidad de posibles colaboraciones, transferencia de información y conocimiento, y cohesión geográfica para los diferentes campos tecnológicos y de investigación. En segundo lugar, las métricas de centralidad del sistema de innovación permiten evaluar las políticas de investigación en términos de competitividad. Por último, la conectividad de la red permite analizar la transversalidad entre los diferentes programas de investigación como forma de promover efectos sinérgicos entre ellos.

Este estudio tiene **implicaciones relevantes para la gestión y la formulación de políticas de investigación regionales**. *En primer lugar*, el diseño de estrategias de especialización inteligente debe centrarse en las fortalezas de los sistemas de innovación existentes en la región para evitar la fragmentación, mejorando la colaboración entre proyectos y entidades y fomentando acciones transversales. Además, la implicación en estas acciones de los coordinadores de proyectos, en particular de universidades y centros de investigación, puede ser beneficiosa, ya que son los nodos más influyentes de la red. *En segundo lugar*, los formuladores de políticas de investigación regionales pueden aplicar el método propuesto y los hallazgos a sus regiones para evaluar el sistema de innovación existente y considerarlo en la próxima generación de definición de estrategias de especialización inteligente. Los responsables políticos europeos pueden considerar estos resultados para remodelar los próximos Programa Marco para fomentar el desarrollo de las estrategias de especialización inteligente de las regiones europeas. Finalmente, los participantes individuales pueden aplicar los resultados de este estudio para seleccionar a sus socios del consorcio para mejorar su posición en la red, mejorando así su acceso al conocimiento y las capacidades de investigación. *En tercer lugar*, en cuanto al caso del carbón en las regiones en transición, la consideración de las fortalezas y capacidades existentes, que en nuestro estudio empírico se han relacionado consistentemente con la eficiencia energética y de recursos, parece ser crucial para la efectividad de la formulación de políticas. Asimismo, la priorización de campos tecnológicos no soportados por el sistema de innovación debe realizarse de manera consciente y, en consecuencia, con los mecanismos de apoyo y el impulso institucional pertinentes para propiciar la evolución de los sistemas de innovación hacia estas nuevas prioridades.

Además, considerando los objetivos de descarbonización de la UE que desafían particularmente a algunas de sus regiones, el nuevo Programa Horizonte Europa que aborda el período 2021-2027, puede considerar las conclusiones de este trabajo para mejorar la efectividad de su impulso institucional. Además, las políticas regionales, y especialmente las relacionadas con la transición justa en las regiones carboníferas, pueden beneficiarse del análisis de los sistemas regionales de innovación para alinear sus estrategias para la próxima RIS3.

Finalmente, en este trabajo, las regiones han sido consideradas como sistemas de innovación aislados, pero sus conexiones y vínculos con otros sistemas de innovación, ubicados geográficamente fuera de las regiones, deberían ser estudiados en futuras investigaciones para determinar su influencia en el rendimiento de los sistemas regionales de innovación. Además, más estudios empíricos, dirigidos a otras regiones, en otras ubicaciones, o que presenten otros desafíos diferentes a la transición del carbón, podrían ser beneficiosos para ampliar la aplicabilidad de las conclusiones obtenidas.

- En el trabajo Calvo et al. (2020), se ha concluido cómo el análisis de redes sociales puede ser una herramienta complementaria para el diseño y selección de medidas preventivas capaces de reducir el riesgo de brotes internos en empresas e instituciones para virus de transmisión persona a persona, como el SARS-COV-2. Para ello se ha propuesto una metodología sencilla y fácilmente adaptable a los sistemas de información de cada entidad. La metodología proporciona resultados rápidos que deben ser interpretados por especialistas en Seguridad y Salud en el Trabajo con formación básica en análisis de redes sociales. El análisis de redes sociales se ha demostrado como una herramienta muy valiosa para extraer conocimiento de datos masivos y no estructurados. Estas técnicas se han utilizado recientemente con éxito a nivel de país para modelar y analizar brotes epidemiológicos. De manera similar, la metodología propuesta en este documento enfocada a los lugares de trabajo ha revelado importantes conocimientos sobre las relaciones cruzadas entre los factores desencadenantes del contagio y los trabajadores, incluidas muchas no intuitivas. El concepto de reducir las métricas de cohesión de la red actuando sobre aquellos nodos, disparadores o empleados, con las métricas de centralidad más altas, se ha ilustrado y demostrado en un caso de estudio real, mostrando su alta efectividad. La metodología propuesta ha resultado en abstraer la estructura y dinámica de las relaciones entre los empleados e identificar aquellos trabajadores críticos o desencadenantes a los que se deben dirigir las medidas preventivas para lograr los mayores impactos. La demostración de la metodología propuesta ha proporcionado información relevante no intuitiva: espacios de mayor riesgo, personas con mayor potencial de propagación del virus, reuniones o proyectos que sirven de motor para que el virus se mueva por la organización, etc. Intervenciones que abordan estos nodos críticos han sido diseñados para retomar la actividad del centro de forma más segura.

Si bien mediante la metodología propuesta se logran resultados valiosos para orientar el diseño y definición de medidas preventivas, ésta se encuentra limitada por muchos aspectos que no han sido considerados. Los dos aspectos principales que podrían integrarse aún más en el análisis son el poder de los factores desencadenantes y la probabilidad de que una persona propague el virus. Adicionalmente, los efectos de un potencial contagio en cada empleado, es decir, la vulnerabilidad del empleado o la convivencia con personas vulnerables, podría ser un punto crucial a incorporar en la metodología. La posibilidad de asignar atributos a los nodos se ve como la solución más prometedora para superar las limitaciones establecidas.

7. Summary and conclusions of the published papers

This section presents the four abstracts of the published papers.

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

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.

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

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.

7.3. Contribution of the Horizon2020 Program to the Research and Innovation Strategies for Smart Specialization in Coal Regions in Transition: The Spanish Case

This work aims to assess how regional innovation systems support research and innovation smart specialization strategies (RIS3) in coal intensive regions. Although many authors have analyzed energy transition paths for the European coal regions, no study has assessed how the network properties of their innovation systems are aligned with the priorities identified in their RIS3. This work fills this gap, relying on social network analysis (SNA) to assess innovation systems' underlying networks, considering the active role of their nodes, thus, contributing to the innovation systems literature in the areas of modelling, simulation and performance evaluation. Within this work, regional innovation systems are modelled as research networks. These networks are promoted by the consortia funded by the European H2020 program. The assessment of the topology and properties of these networks enables the evaluation of the functioning of the innovation system, its technological strengths, as well as the key players involved. Based on these results, the characteristics of the innovation systems are compared to the priorities established by the RIS3. Three Spanish coal intensive regions (Aragón, Asturias and Castilla y León) are considered as use cases in this study. The obtained results indicate that, in some cases, the technological strengths of the regional innovation systems are not considered in the identification of the RIS3 priorities, while some RIS3 priorities are not supported by the innovation system. Considering these results, this paper proposes recommendations for regional and European policymakers, as well as for participants in the European research programs.

7.4.Preventing Internal COVID-19 Outbreaks within Businesses and Institutions: A Methodology Based on Social Networks Analysis for Supporting Occupational Health and Safety Services Decision Making

This study aims at developing and demonstrating in a real case study a methodology for supporting Occupational Health and Safety Services in the design and assessment of preventive measures to reduce the risks of COVID-19 outbreaks within their entities. The proposed methodology applies the concepts from Social Network Analysis (SNA) to the current challenge of preventing risks of contagion of viruses like SARS-COV-2 among employees. For this purpose, the authors consider a network of employees whose interaction is caused by triggers, which are defined as common circumstances between two workers that may result in contagion, like sharing an office or participating in the same management board. The network cohesion is then evaluated, and those core nodes, which are the most significant contributors to its integration, are identified to be addressed in the design of the preventive measures. The impact of the designed preventive measures on the networks' cohesion is assessed for its prioritization and further deployment. The methodology has been demonstrated in a real case, a Spanish Research Center, providing promising results in a quick and easy manner. The objective insights provided by its application were demonstrated as very valuable for the Occupational Health and Safety Services in the design and evaluation of the set of preventing measures to be implemented before the return of the employees to the facilities after the Spanish confinement period. The current COVID-19 outbreak brings the need to develop tools and methods to support businesses and institutions in the use of SNA for preventing outbreaks among their employees. Although some literature does exist in the field of SNA application in epidemiology, its adaptation for extensive use by the Occupational and Health Services is still a challenge.

8. Otras aportaciones derivadas de la tesis doctoral

La metodología desarrollada en el trabajo Calvo-Gallardo et al. (2020) para la prevención de brotes de COVID-19 se implementó en una aplicación web para su uso en empresas. El desarrollo se realizó en conjunto entre Fundación CIRCE (centro de investigación de la doctoranda) y la empresa Más Allá de la Tecnología S.L. (CIF 52.189.679-B), estando la relación regulada por un acuerdo de colaboración entre ambas entidades firmado el 2 de julio de 2020. Para la herramienta se eligió la marca comercial SafeBack2Work que fue a su vez registrada en la oficina española de patentes y marcas con el número de solicitud M4074007. La herramienta está disponible en la página web: https://safeback2work.com/

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9. Informes sobre factor de impacto y quartiles de las publicaciones

A continuación, se listan las referencias de los cuatro artículos de revista publicados en el marco de la tesis doctoral.

- Elena Calvo-Gallardo, Nieves Arranz, Juan Carlos Fernández de Arroyabe. Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives. Journal of Cleaner Production. Volume 298. 2021. 126690. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2021.126690.
- Elena Calvo-Gallardo, Nieves Arranz, Juan Carlos Fernandez de Arroyabe. Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to H2020. Journal of Cleaner Production. Volume 340. 2022. 130810. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2022.130810.
- Calvo-Gallardo, E.; Arranz, N.; Fernandez de Arroyabe, J.C. Contribution of the Horizon2020 Program to the Research and Innovation Strategies for Smart Specialization in Coal Regions in Transition: The Spanish Case. *Sustainability* **2022**, *14*, 2065. https://doi.org/10.3390/su14042065
- Calvo Gallardo, E.; Fernandez de Arroyabe, J.C.; Arranz, N. Preventing Internal COVID-19 Outbreaks within Businesses and Institutions: A Methodology Based on Social Networks Analysis for Supporting Occupational Health and Safety Services Decision Making. *Sustainability* **2020**, *12*, 4655. https://doi.org/10.3390/su12114655

Los artículos han sido publicados en las revistas Journal of Cleaner Production, de la editorial Elsevier, y Sustainability de la editorial MDPI (Multidiciplinary Digital Publishing Institute). A continuación, se presentan los datos relativos a factor de impacto y quartiles de ambas revistas.

Journal of Cleaner Production

Scopus coverage years: from 1993 to Present

Publisher: Elsevier

ISSN: 0959-6526 E-ISSN: 1879-1786

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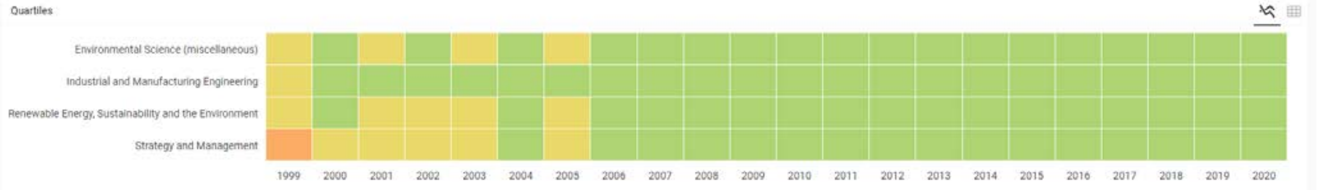
Business, Management and Accounting — Strategy and Management	#7/440	98th
Environmental Science — General Environmental Science	#4/220	98th
Engineering		



Research Area – Journal of Cleaner Production	Quartile 2020
Environmental Science (miscellaneous)	Q1
Industrial and Manufacturing Engineering	Q1
Renewable Energy, Sustainability and the Environment	Q1
Strategy and Management	Q1

Sustainability

Open Access

Scopus coverage years: from 2009 to Present

Publisher: Multidisciplinary Digital Publishing Institute (MDPI)

ISSN: 2071-1050

Subject area: Social Sciences: Geography, Planning and Development; Environmental Science: Environmental Science (miscellaneous); Environmental Science: Management, Monitoring, Policy and Law; Energy: Energy Engineering and Power Technology; View all

Source type: Journal

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CiteScore 2020: 3.9

SJR 2020: 0.612

SNIP 2020: 1.242

CiteScore | CiteScore rank & trend | Scopus content coverage

CiteScore 2020

3.9 = 97.894 Citations 2017 - 2020 / 24.902 Documents 2017 - 2020

Calculated on 05 May, 2021

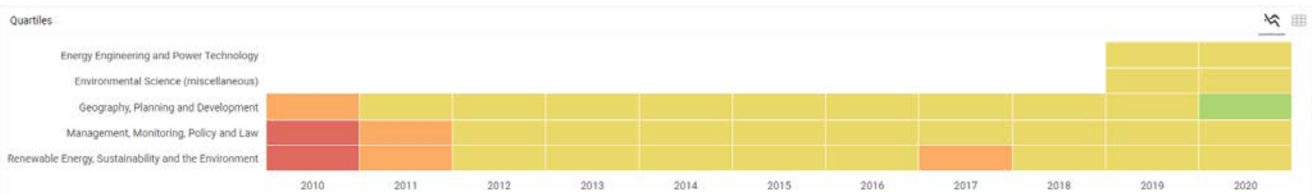
CiteScoreTracker 2021

4.8 = 173.425 Citations to date / 36.473 Documents to date

Last updated on 05 January, 2022 • Updated monthly

CiteScore rank 2020

Category	Rank	Percentile
Social Sciences – Geography, Planning and Development	#110/704	84th
Environmental Science – Environmental Science (miscellaneous)	#18/104	83rd
Environmental Science		



Research Area - Sustainability	Quartile 2020
Engineering and Power Technology	Q2
Environmental Science (miscellaneous)	Q2
Geography, Planning and Development	Q1
Management, Monitoring, Policy and Law	Q2
Renewable Energy, Sustainability and the Environment	Q2

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10. Principales referencias

Las referencias utilizadas en el desarrollo de la tesis se detallan en cada uno de los cuatro artículos desarrollados y recogidos en la Sección 5 de este documento:

- Elena Calvo-Gallardo, Nieves Arranz, Juan Carlos Fernández de Arroyabe. Analysis of the European energy innovation system: Contribution of the Framework Programmes to the EU policy objectives. Journal of Cleaner Production. Volume 298. 2021. 126690. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2021.126690.
- Elena Calvo-Gallardo, Nieves Arranz, Juan Carlos Fernandez de Arroyabe. Innovation systems' response to changes in the institutional impulse: Analysis of the evolution of the European energy innovation system from FP7 to H2020. Journal of Cleaner Production. Volume 340. 2022a. 130810. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2022.130810.
- Calvo-Gallardo, E.; Arranz, N.; Fernandez de Arroyabe, J.C. Contribution of the Horizon2020 Program to the Research and Innovation Strategies for Smart Specialization in Coal Regions in Transition: The Spanish Case. Sustainability, 2022b, 14, 2065. https://doi.org/10.3390/su14042065
- Calvo Gallardo, E.; Fernandez de Arroyabe, J.C.; Arranz, N. Preventing Internal COVID-19 Outbreaks within Businesses and Institutions: A Methodology Based on Social Networks Analysis for Supporting Occupational Health and Safety Services Decision Making, Sustainability, 2020, *12*, 4655. https://doi.org/10.3390/su12114655