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Economic crises and energy use

An input–output analysis of Catalonia’s 2008–2014 financial crisis

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Abstract

The impact of economic crises on an economy’s energy consumption, considering its sectorial interactions, remains an unexplored area. For this article, we investigated the structural sectorial relationships in energy terms before, during, and after Catalonia’s 2008–2014 financial crisis, using environmentally extended input–output analysis. We used three input–output tables from 2005, 2011, and 2014, for which we constructed and employed five vectors representing sectorial energy consumption (“natural gas,” “coal,” “petroleum,” “electricity,” and “biomass and waste”) for 41 economic sectors. We studied the evolution of backward and forward linkage coefficients in terms of energy, as well as key sectors over this period. Our findings reveal that most sectors, particularly energy-intensive ones, experienced a reduction in both backward and forward linkages. However, the relative importance of sectors in the Catalan economy remained relatively stable over the years, indicating a certain level of persistence in this indicator throughout the period, despite the economic crisis.

KEYWORDS

economic structure, energy use, environmentally extended input–output analysis, financial crisis, key sectors, satellite accounts

1 | INTRODUCTION

The global financial crisis of 2007–2009 was the most impactful economic crisis since the Great Depression (1929–1939) (Reinhart & Rogoff, 2009; Verick & Islam, 2010). The crisis triggered a significant global decline in economic activity (Claessens & Kose, 2013). In Spain, the crisis began a year later but had a heavy impact because of the housing bubble and poor previous supervision of the financial sector (Santos, 2017). It is usually known as the “2008–2014 Spanish financial crisis” or “the Great Recession in Spain” (Bentolila et al., 2012), and it changed the socioeconomic landscape in many respects. From an environmental or an ecological economics perspective, one of the understudied aspects of this (and other) economic crises is the effect on the use of natural resources—not only in terms of their direct use but also from a structural perspective, considering the long-term changes that crises trigger in consumption and productive structures and the implications of these crises on their use.

By using a variety of tools, scholars can assess the direct and indirect economic impacts of policies or shocks such as an economic crisis. One of the most popular among applied researchers are input–output (I–O) models that were later followed by the theoretical Arrow–Debreu model (Arrow & Debreu, 1954; Geanakoplos, 1989) and Walrasian equilibrium (Walras, 1954). These can reveal direct and indirect impacts at the sectoral level in terms of different macroeconomic indicators such as production, gross value added (GVA), jobs, or imports. They were first developed by

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Leontief (1941) as an abstract representation of the technology used by the productive sectors of an economy, specifying input requirements and other factors necessary to produce each good or service.

Some studies conducted in the 1970s related economic systems to natural systems and the environment. Isard et al. (1968) pioneered these types of studies by proposing a methodology based on I–O tables, mixing economic and environmental variables to offer more economic policy alternatives. It is worth mentioning the seminal contribution of Daly (1968), putting a particular emphasis on bringing together similarities between biology and economics, which helped open up this field. Other scholars (Alcántara & Padilla, 2009; Bullard & Herendeen, 1975; Casler & Wilbur, 1984; Chapman, 1974; Lenzen et al., 2004; Leontief, 1970; Leontief & Ford, 1972; Proops, 1988) subsequently made further developments to this approach, modeling different aspects of the relationships between the productive structure of an economy and the environment. Related to the I–O analysis, Rasmussen (1956) first developed the concept of “key” sectors, which are defined as having high multiplier effects on final demand and can be linked to environmental impacts or the use of resources such as different energy sources. For energy resources, for instance, “key” sectors are those which have more importance than others in driving the energy consumption of other productive branches and, in turn, in inducing other sectors to consume energy. These sectors have high values for both their forward linkages and their backward linkages in terms of I–O analysis, as we will define later (Alcántara, 1995).

Focusing on economic and financial crises and energy, some scholars have analyzed this relationship; however, few have studied it from an economic structural perspective. Yuan et al. (2010) analyzed the influence on energy consumption and economic growth of the global financial crisis of 2007–2009 and the resulting stimulus plan using an I–O analysis. The results showed that the fall of exports led to a decrease of 7.33% in gross domestic product (GDP) and a 9.21% drop in energy consumption. Roinioti and Koroneos (2017) performed a decomposition analysis of CO₂ emissions in Greece to assess changes in the contributions of different factors during the economic crisis in Greece (2008–2013). Bekhet and Yasmin (2014) used I–O analysis to study the influence of the crisis on Malaysia's energy consumption, finding that a decline in exports produced a 13% decrease in GDP and a 16% reduction in energy consumption. Additionally, they found that the stimulus plans reduced the effects of the crisis and increased economic growth and energy consumption by 1.83% and 4.62%, respectively, by adapting and using an I–O table from 2005 with 19 sectors for the analyses. Beyond their main focus, all these analyses are focused on countries rather than specific regions. This may show a lack of interest from scholars and national or supranational authorities, more interested in country-specific effects, but also to the difficulty to obtain subnational data to perform this kind of analyses.

We identified three specific research questions that we aimed to address in this study: How does a financial crisis impact a regional economy in terms of energy use? Does a financial crisis provoke changes in the energy consumption patterns of industries? How can we quantitatively measure these changes, considering their multi-industry and dynamic nature? To answer them, in our research, we study the impact of a financial crisis on direct and indirect energy use through energy I–O analysis and the concept of key sectors. Input–output analysis allows us to quantitatively assess changes in a multi-industry context by considering the relationships between industries. This approach enables us to evaluate changes not only within individual sectors but across all sectors, providing insight into how economic structures evolve. Additionally, environmentally extended I–O analysis methods are suitable to examine these changes in environmental terms, such as energy use. As detailed in Section 3, “key sectors” analysis, which is related to I–O methods, becomes essential for mapping the evolution of the economic structure in one direction or another. We analyze the case study of Catalonia during the 2008–2014 financial crisis by comparing the following three periods: precrisis (2005), midcrisis (2011), and postcrisis (2015). Catalonia represents around 20% of Spain's GDP and 16% of its population, making it one of the most economically dynamic regions in the country. This region was severely affected by the financial crisis of 2008–2014, as reported in several studies (Álvarez Cuccia, 2020; Gutiérrez and Delclòs, 2017). In 2008, Catalonia's GDP decreased by 0.9% compared to 2007, and in 2009, it fell by 4.4% compared to 2008. In contrast, Spain as a whole experienced a slightly more moderate decline (+0.9% in 2008 and –3.8% in 2009). Over the entire period, Catalonia's GDP dropped by 5.24%, and it registered an unemployment increase of 104% from January 2008 to December 2014.

There are some novel aspects of our research which we hope significantly contribute to the literature: First, we developed and reported a data development process from the beginning (raw source) to the end (when the data is ready to be used) for five different sectorial energy use vectors, not relying in external sources as usual in these studies, generating a reliable and homogeneous database. Second, unlike previous studies, we worked simultaneously with three different I–O tables, reflecting the actual productive structures under the different stages of the crisis, as well as five different energy products for each of these three periods, at a highly disaggregated industry level (41 sectors). The simultaneous analysis of three tables at different periods is novel and allowed us to observe the evolution of structural changes provided by I–O methods during that period. Third, we used a previously existing methodological instrument, like I–O analysis, and forward and backward linkages, to provide different results than the ones they were developed for, as we do not aim a simple impact analysis via simulation or a structural analysis of a region, but the impact of an economy-wide and real success on the structure of an economy. Finally, the results reported in this study are new in the literature, that is, there are no similar studies, as pointed out in the literature review conducted at the beginning of this section.

While the methodology followed is quite data demanding, there are ways to obtain it and consolidate it for Catalonia with high confidence from reliable sources as we will show later. This provides an interesting case of study for the research community as it is the first subnational study with these characteristics. This article continues as follows: Section 2 shows the data we used and the energy consumption vectors we built for natural gas, petroleum, coal, biowaste, and electricity, for three years: 2005, 2011, and 2014; Section 3 describes our methodology, based on envi-

ronmentally extended input–output analysis for the mentioned energy resources; Section 4 presents the main results of the research; and Section 5 concludes the article.

2 | DATA¹

2.1 | Data sources

I–O tables are a basic component in the construction of national accounting systems (NAS), as recognized by the United Nations Accounts Manual (SNA-93) and the European System of National and Regional Accounts 1995 (SEC-95). They allow approximation of the main macro-magnitudes that define an economy such as GDP, GVA, income generated (wages and gross surplus), and other various concepts to include aggregate demand of the economy: private consumption, public consumption, investment, and foreign demand. Statistical institutes estimate these concepts by establishing a balance between the total resources available to the economy and their uses. The table is a double-entry matrix of the economic relationships of an economy over a given period, usually a year.

The Statistical Institute of Catalonia (Idescat) publishes the I–O tables for Catalonia (TIOC). Tables are currently available for the years 2001, 2005, 2011, 2014, and 2016, with different new sectoral breakdowns. The methodological reference used for its preparation is the SEC-95. For this study, we used the 2005 (before the financial crisis), 2011 (middle of the crisis), and 2014 (after the crisis) tables. Because the tables have different sectorial aggregations, we uniformly adopted a classification of 41 industries across all of them. The European System of Accounts 2010 (ESA 2010) serves as the accounting framework of reference for the development of the tables, with the aim of providing a systematic and detailed description of an entire economy, its components, and its relationships with other economies. Tables are originally developed at basic prices and we maintained them at current prices. No inflation adjustment is needed for the purpose of this analysis, as all indicators constructed and used for comparisons are relative indicators of each year's economic structures, as we will show in Section 3.

In ESA 2010, two basic methods are presented for estimating the production coefficients of homogeneous branches: (1) The industry technology hypothesis, which assumes that the technology of branches by homogeneous activity does not differ from the technology of branches by main activity; (2) The product technology hypothesis, which assumes that each product has a characteristic technology, regardless of the type of unit that produces it. Both hypotheses have pros and cons (Miller & Blair, 2009). In this research we use the product technology hypothesis as Catalan I–O symmetric matrices are based on this assumption. Regarding the foreign sector, the Catalan I–O tables distinguish between imports and exports with the rest of Spain and the rest of the world. Since our analyses were conducted using “total” matrices, not just domestic ones, the indicators also include intermediate imports from both the rest of Spain and the rest of the world.

Environmental satellite data provided information at the sectoral level at the same disaggregation as the I–O tables. Satellite data can include pollutant emissions, energy use, or other resources within a homogeneous system compatible with the I–O table framework. Currently, regarding pollutant emissions in Catalonia, there are only the 2001 satellite accounts of atmospheric emissions (Alcántara et al., 2009); however, they are not relevant for our study because these accounts are for pollutant emissions, not energy use, and they comprise a different period. So, using a different methodology than the one used by these authors, we developed a matrix of different energy consumption vectors with the same aggregation level as the I–O tables for the relevant years of the analysis (2005, 2011, and 2014), which we detail in Section 2.3.

We used the following data sources to develop the energy satellite accounts for Catalonia: (1) Catalan energy balances from the Catalan Energy Institute (ICAEN)²; (2) statistics on energy consumption in the industrial sector (ECESI)³ also from the ICAEN; (3) electricity supply data from Endesa power supply company; and (4) EORA database (Lenzen et al., 2013) to reallocate energy consumption to specific sectors. This way we can use its energy accounts, having the table aligned with them. EORA is a multiregional I–O framework which includes inter-sectoral transfers, including trade, amongst 15,909 sectors across 190 countries, containing a complete time series for the period 1990–2021. It also includes satellite accounts with sectoral information on several resources such as energy use.

2.2 | Data homogenization and aggregations

The homogenization of the data structure was a key step in setting up a common framework for the sectoral disaggregation of both the economic and the energy data. The different data sources used to develop the I–O framework and the energy satellite accounts contain different levels of aggregation. The first task was to develop uniform sectorial aggregations with the highest possible sectorial detail while ensuring comparability between sources, as the Catalan I–O tables of 2001, 2005, and 2014 all have different aggregation levels. We finally fixed a total of 41 economic sectors.

To develop the energy accounts, we first had to align sectors of Catalan I–O tables with EORA tables. EORA data follow the International Standard Industrial Classification of All Economic Activities (ISIC) methodology (United Nations, 2008) for sectorization, while the Statistic Institute of Catalonia uses CCAE (Catalan Classification of Economic Activities in Catalan) codes, following the European Statistical classification of economic

activities in the European Community (NACE) classification system. Hence, a direct comparison between the Catalan and EORA I–O tables is not feasible. During the aggregation process we found that: (i) some sectors included in the Catalan classification system were missing in EORA, and (ii) EORA had more sectoral detail for some industries, like the extractive industries sector. A summary of the aggregations conducted to align the Catalan tables (which include CCAE classifications) with EORA I–O tables can be seen in [Appendix A](#).

2.3 | Development of energy satellite accounts for Catalonia

We needed to create the Catalan energy accounts for the years 2005, 2011, and 2014 because there were no energy satellite accounts that could be integrated into Catalonia's input–output framework. We used energy balances from the ICAEN⁴ as a main source, and we employed other supplementary data sources to distribute energy consumptions between the 41 economic sectors included in the Catalan I–O tables.

We were able to develop sectorial energy consumption vectors for the following five groups of energy products (41 sectors, years 2005, 2011, and 2014):

- Natural gas.
- Petroleum: aggregate of petroleum derivatives such as petroleum, liquified petroleum gas (LPG), gasoline, diesel, kerosene, fuel oil, etc.
- Coal.
- Biomass and waste.
- Electricity: This primary source includes all types of electricity generated from electricity generation with renewable energies to generation with fossil fuels.

Catalan energy balances provide information for these energy products but at very high levels of aggregation for just five major sectors: households, transport, primary sector, industry, and services. Therefore, we used additional information to break them down and obtain information for the 41 sectors of interest. For primary and tertiary sectors, we used information from EORA environmentally extended I–O tables, while for the secondary sector (industries), we could rely on other specific Catalan sources like ECESI or the power supply company Endesa, the main supplier in Catalonia. We extracted electricity consumption for all sectors from Endesa. This data comes from the consumers' side, so we were unable to disaggregate it between renewable and non-renewable sources. This has implications in terms of CO₂ emissions, but not absolute energy consumption. Although this is not the focus of this research, this aspect can be important for energy and climate policy implications, or for further research on this topic.

2.3.1 | Industries

ECESI surveys provide information on the consumption of petroleum, coke, coal, fuel oil, diesel, LPG, natural gas, forest biomass, biogas, solar thermal energy, non-renewable waste, and renewable waste for the different industrial sectors (from CCAE 05 to 32). In this case we just adapted the data of the different energy sources to match CCAEs used by the energy vectors developed at the industrial level. To check the alignment between energy use data of the ECESI surveys and the energy balances from the ICAEN, a comparison of total consumption per energy source was conducted showing less than 1% difference between both data sets. These results were used to assume that the disaggregation data offered by ECESI surveys correctly reflects the reality of the different industrial sectors energy use.

Endesa is the main power supply company in Catalonia, representing around 96% of all supply excluding self-consumption. We disaggregated data from Endesa following the CNAE national classification system (Spanish classification), equivalent to the Catalan CCAE classification. We proceeded to aggregate the data at the same level as in the I–O matrix (41 sectors). Then, we projected this sectorial consumption to the remaining 4% of electricity consumption supplied by power supply companies other than Endesa. This electricity consumption was later compared with the Catalan energy balances to identify potential discrepancies, finding that the difference between the sources was just below 2%.

2.3.2 | Primary and tertiary sectors

We first extracted the energy consumption data for primary and tertiary sectors—that is, those not included in the industry or the transport sectors—from the information provided by the Catalan energy balances and then reallocated them using the EORA I–O framework. We took as a reference the Spanish table from the EORA framework, including both the I–O table and the energy accounts for the economic sectors of Spain that EORA covers. We previously adapted the sectors of Spain included in EORA to the 41 sectors we could ultimately consolidate in the Catalan tables. Then, to allocate the energy consumption for each primary and tertiary sector to the Catalan tables, we compared the economic production

for each specific sector between the Spanish economy and the Catalan economy as well as energy consumption, obtaining weights for the 41 aggregated sectors. Then, we used the Catalan energy balances published by ICAEN to multiply total primary and tertiary energy use to the weights, obtaining a proxy of the energy consumption realized by the different sectors included in the Catalan matrices. We applied this approach to all energy vectors described at the beginning of this section except for electricity, which we extracted from Endesa data following the same approach as the one followed for industries. With this approach, we assumed that Spanish and Catalan energy use have a similar sectorial structure and that production functions of both regions use a similar technology, which in our view is reasonable, considering that Catalonia represented the 20% of Spanish GDP in 2023.⁵

2.3.3 | Transport

We obtained Spanish energy consumption data from the Spanish Observatory of Logistics and Transport for energy consumption for different types of transport,⁶ including maritime, land, and air transport. This information helped us define the energy use per source and transport mode (land, maritime, and air). Then we applied the percentages recommended by transport experts from the Energy Management Division of the ICAEN: 43% of consumption is considered private (domestic), and the remaining 57% for the land transport sector itself, while for air and maritime transport, private consumption could be considered negligible. To generate the energy vectors for the different transport sectors (CCAEE 49 to 51), we employed (1) the distribution of energy use per sector; and the (2) the previously established non-domestic energy use split, which guided the disaggregation of the transport sector aggregate from the Catalan energy balances provided by the ICAEN.⁷ Besides, to ensure the regional energy vector coherence with the national energy vector, we extracted the 2006 energy vector of the Spanish economy from the Spanish National Statistics Institute (INE).⁸ This data was subsequently recalculated for the Catalan economy by factoring in the region's economic weight. Finally, we compared the results with the 2005 Catalan energy vector generated, to find that they just differed by 3.04%.

3 | METHODOLOGY

3.1 | Input–output analysis

The simplified Leontief's production model makes the following assumptions: (i) each sector produces only one product; (ii) there are the same number of product suppliers and product users; (iii) technical coefficients are constant, representing the quantity of a commodity expressed in monetary units to produce one unit of another commodity; and (iv) there is exogeneity in alterations of the final demand or values added. A change in one of them will allow us to obtain the economic impact in terms of total production of the economy, both direct and indirect.

The row relationships within the I–O table can be symbolically represented as follows:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad (1)$$

where x_{ij} is the economic flow from sector i (supplier) to sector j (user); x_i is the total production of sector i ; y_i is the total final demand of sector i ; and $i, j = 1, 2, \dots, n$, is the number of sectors considered. This system of equations shows the total production of a sector as the sum of its intermediate demands plus final demand. The production of each sector requires fixed quantities of intermediate products supplied by other sectors and primary inputs. Therefore, the initial proportions of factors used by the sectors are invariable. The technical coefficients for intermediate products are defined as follows:

$$a_{ij} = x_{ij} / x_j \quad (2)$$

The model can also be expressed as:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad (3)$$

This can be summarized as:

$$x = Ax + y \quad (4)$$

Or, by rearranging terms:

$$x = (I - A)^{-1}y \quad (5)$$

The solution presented by this equation is the new production that the different sectors assume when final demand changes.

3.2 | The energy input-output analysis

Given the sectoral supply and demand of goods of an economy, the final energy use will depend both on the energy use of the different sectors across the economy and on its technological structure as defined by I–O relationships. We can adapt the fundamental equation of the Leontief model to reflect energy flows in analogy with economic flows. Specifically, the total energy use of an economic sector depends on the relationships among all sectors of the economy. The fundamental assumptions of the original Leontief model are the same, but they are now interpreted within the context of energy use: (i) each sector uses a certain amount of energy to produce a single product; (ii) technical coefficients of energy use are constant: analogous to the technical coefficients, a technical coefficient of energy use is the amount of energy used directly by a sector to produce a good or service for another sector, in relation to the total direct energy use of the first; and (iii) there is exogeneity in the alterations of the final demand or the values added. Such an alteration allows us to obtain a measure of impact in terms of total energy use of the economy, both direct and indirect.

It is possible to develop an indicator of direct energy use per unit produced or energy intensity (E), which is defined as the direct energy use of each sector (e) per monetary unit produced directly by the sector (x), which is expressed as a column vector in which each element responds to the expression. This indicator is expressed in quantity of energy use per monetary unit, usually in tons/€:

$$E = \frac{e}{x} \quad (6)$$

Additionally, from Equations (7) and (8), the following expression can be obtained:

$$e = E(I - A)^{-1}y \quad (7)$$

Equation (9) is the formula for estimating direct and indirect energy consumption (e) of an economic system based on changes in consumption patterns (y).

3.3 | The “key” sectors in the consumption of energy

Returning to Equation (9), we calculated the “key” sectors in the consumption of energy (Rasmussen, 1956). We can call F to the linear operator that transforms any increase in final demand into an increase in the energy use vector.

$$F = E(I - A)^{-1} \quad (8)$$

If we premultiply the matrix F by u' , a unit row vector of the appropriate dimension:

$$f' = u'F \quad (9)$$

where f' is the vector ($1 \times n$) of total unitary energy use, direct and indirect, generated by a unit of final demand. Thus, f' expresses the multiplier effect of energy use driven by the expansion of the different components of the final demand. This is known in the literature as *backward linkages* (Hirschman, 1958). On the other hand, we can obtain the next expression:

$$f^* = Fu \quad (10)$$

TABLE 1 Determination of key sectors in the consumption of energy.

	$\mu_j < 1$	$\mu_j > 1$
$\delta_j > 1$	A) Relevant sectors from the perspective of the demand of other sectors.	B) Key sectors push and are pushed to consume energy.
$\delta_j < 1$	C) Sectors of little relevance.	D) Relevant sectors from the perspective of final demand.

Note: Based on Alcántara and Padilla (2009).

in which f^* is a vector ($n \times 1$) resulting from the sum by rows of the matrix F above. This corresponds to what the literature calls *forward linkages*. Finally, we can construct a relative coefficient for both backward and forward linkages:

$$\mu_j = \frac{f'_{gi}}{\sum_i f'_{gi}} n \quad (11)$$

$$\delta_j = \frac{f^*_{gi}}{\sum_i f^*_{gi}} n \quad (12)$$

where n is the number of sectors of the I–O matrix, μ_j are relative pull coefficients, and δ_j are relative push coefficients. Following the values obtained by each sector of an economy, we can classify them into four groups: (1) key sectors with values higher than 1 in both relative pull coefficients and relative push coefficients, so they are relevant in pushing other sectors and being pushed by other sectors to consume energy; (2) sectors of little relevance where both coefficients have values lower than 1; (3) relevant sectors from the perspective of the demand of other sectors in which relative pull coefficients are lower than 1, but relative push coefficients are higher than 1, so they increase their energy consumption more than other sectors when the latter increase their final demand; and (4) relevant sectors from the perspective of their final demand: relative pull coefficients are higher than 1, but relative push coefficients are lower than 1, so other sectors increase energy consumption when they see their final demand increase more than when other sectors see their final demand increase.

Table 1 shows the relative importance in a scatterplot of each industry of pushing and being pushed to use energy in an economic system.

4 | RESULTS

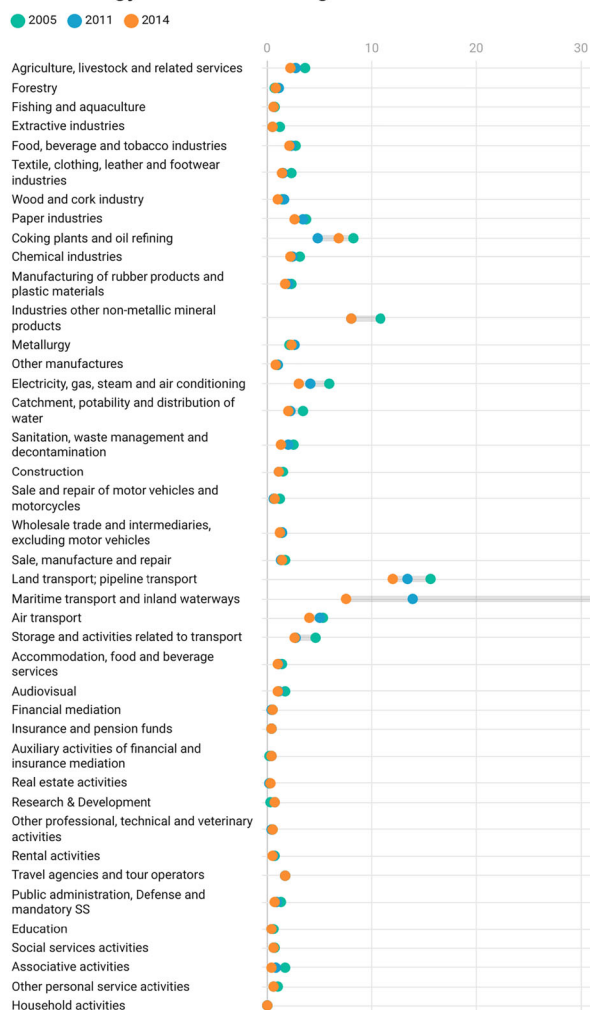
4.1 | Analysis of backward and forward linkage coefficients

First, we assessed the obtained backward and forward linkages in Catalonia for energy consumption. In other words, we measured how different sectors influence energy use in other sectors given interindustry flow dynamics. As shown, the backward energy linkage of a sector quantifies its capacity to encourage other sectors to increase energy consumption after a rise in its final demand, while the forward energy linkage of a sector represents the ability of all economic sectors to induce that specific sector to consume energy, following an increase in the final demand of all sectors.

In Figure 1 we can observe both indicators for each sector during the analysis period for total energy use (the sum of all energy sources). One important general result is that on average, both backward and forward linkages declined during the whole period, particularly during the first period of the economic crisis (2005–2011), with an average annual change of -4.96% for backward linkages and -5.02% for forward linkages. During the second period of the economic crisis (2011–2014), they experienced an average annual change of -4.70% and -4.60% , respectively. These results mean that globally, after the crisis, economic sectors reduced their potential to induce energy use in the economic structure. As previously explained, sectors with linkages greater than 1 are considered to have a relevant effect on energy consumption. The high reduction in both backward and forward linkages of the *maritime transport and inland waterways* sector is noteworthy. Other sectors with high linkages also experienced reductions in both linkages such as *land transport*, *pipeline transport*, *industries other nonmetallic mineral products*, or *electricity, gas, steam, and air conditioning*. All of these are energy-intensive sectors. Another relevant sector in energy use like *coking plants and oil refining* reduced its linkages at first (2011) and then rebounded in 2014; however, coefficients in 2014 remained lower than in 2005. These results suggest an absolute reduction of the importance of energy-intensive sectors in inducing other sectors to consume energy during the period of analysis.

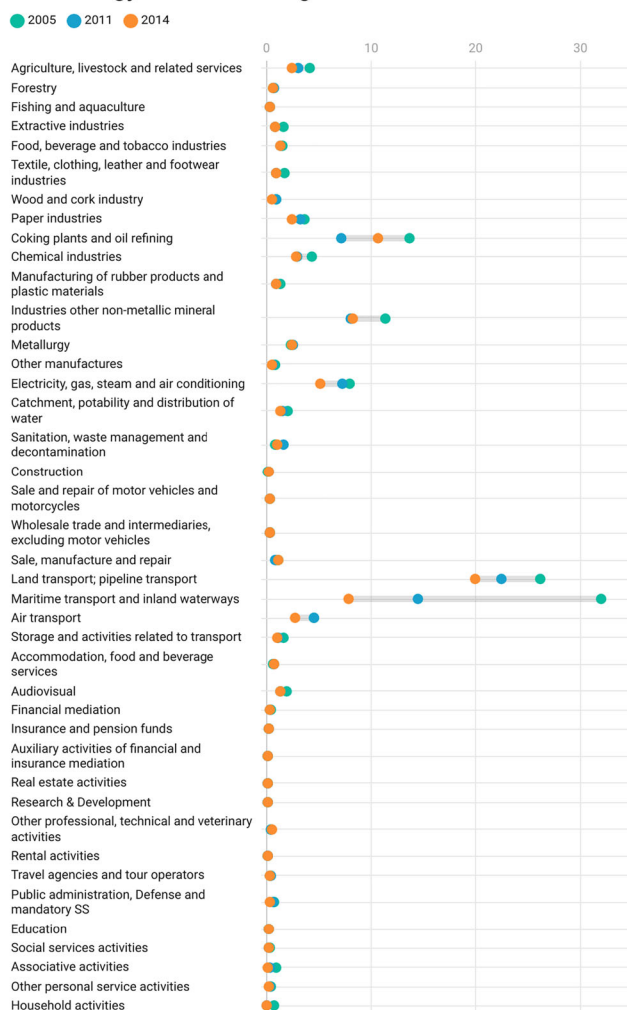
If we account for the whole period 2005–2014, only five sectors increased their backward linkages of total energy consumption: *research and development*, *metallurgy*, *forestry*, *auxiliary activities of financial and insurance mediation*, and *real estate activities*. Only six sectors increased their forward linkages: *metallurgy*; *sanitation, waste management, and decontamination*; *construction*; *accommodation, food, and beverage services*; other

Total energy - Backward linkages



Created with Datawrapper

Total energy - Forward linkages



Created with Datawrapper

FIGURE 1 Total energy consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

professional, technical, and veterinary activities; and travel agencies and tour operators. All these increases were low, ranging from 0.03 to 0.43 points. The remaining economic sectors reduced their linkages ranging from 0.01 to 24.30 points.

Figure 2 shows the same analysis for natural gas consumption. In this case, we also observe that on average, both backward and forward linkages declined over the whole period, but to a lesser extent. For the period 2005–2011, we observed an average annual change of -1.92% for backward linkages and -1.93% for forward linkages, while for the period 2011–2014, we saw an average annual change of -2.95% and -3.15% , respectively. Again, after the crisis, economic sectors globally reduced their potential to induce gas natural consumption into the rest of the economic structure. Important reductions in backward and forward linkages can be seen in sectors such as *paper industries*; *textile, clothing, leather, and footwear industries*; *chemical industries*; and *industries other nonmetallic mineral products*. These are sectors with an intensive direct use of natural gas.

We noted that 13 sectors increased their backward linkages during this period with increases ranging from 0.01 to 0.12 points, while the rest of the sectors reduced their linkages ranging from 0.01 to 0.35 points. Conversely, 25 sectors increased their backward linkages, with increases ranging from 0.01 to 0.10 points, and the rest decreased with absolute variations from -0.01 to -0.76 . So, for natural gas, there were no significant absolute variations in coefficients during the economic crisis period.

Coal consumption in Catalonia is low compared with the other analyzed energy sources and is concentrated in specific sectors, seeing global reduction during the crisis period (see Figure 3). In this case, we noted an average increase for the first period of the crisis (2005–2011): 2.47% for both backward linkages and forward linkages, and decreases for the second period of the crisis (2005–2011) of -5.39% and -4.38% , respectively. The overall lowest increase was experienced by the sector *metallurgy*, although there was a higher increase in 2011, and the highest increase was for *industries other than nonmetallic mineral products*. However, most sectors were not affected by coal linkages.

Natural gas - Backward linkages



Natural gas - Forward linkages



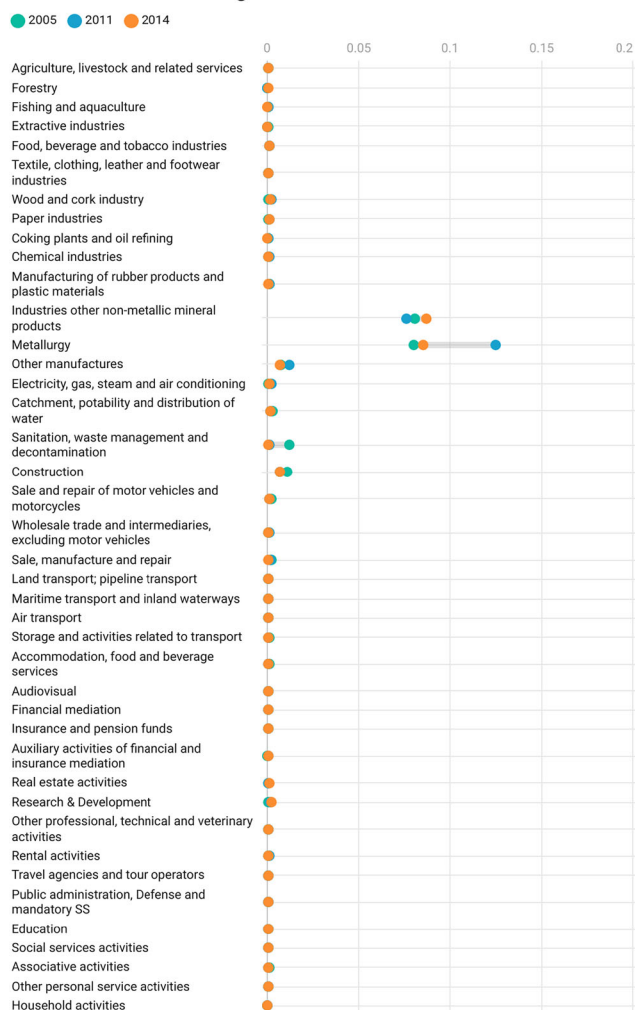
FIGURE 2 Natural gas consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

Petroleum (Figure 4) is the most important consumed energy source in Catalonia's different economic sectors, and it saw important decreases in average backward and forward linkages. Specifically, there was an average annual change of -6.29% for backward linkages and -5.56% for forward linkages for the first period 2005–2011, and an average annual change of -6.30% for backward linkages and -5.47% for forward linkages in the second period of 2011–2014. We also observe that again, after the crisis, economic sectors reduced their potential to induce petroleum consumption in the rest of the economy.

The most important reductions in backward and forward linkages were maritime transport and inland waterways; land transport, pipeline transport; electricity, gas, steam, and air conditioning; and coking plants and oil refining with different intensities. Some sectors with intensive petroleum usage are direct producers that exhibited the declining importance of petroleum during the crisis in relation to the precrisis period. In this context, only five sectors increased their backward linkages: travel agencies and tour operators, research and development, real estate activities, auxiliary activities of financial and insurance mediation, and forestry, with absolute variations ranging from 0.04 to 0.19. Remarkably, for petroleum, no single sector increased its forward linkages. Absolute reductions ranged from -0.03 to -24.23 for backward linkages and -0.01 to -24.25 for forward linkages.

Regarding electricity (Figure 5), both backward and forward linkages were more dispersed than other energy sources, reaching some level of linkage in most sectors. On average, both coefficients went down during the economic crisis, with an annual average variation of -3.04% (for backward linkages) and -3.42% (for forward linkages) during the period 2005–2011 and -3.42% and -2.34% , respectively, during the period 2011–2014. The potential impact of sectors in triggering other sectors to consume electricity was reduced, but below that of the remaining energy sources on average, as shown in the analysis of total energy consumption (Figure 1). The sectors experiencing higher coefficient reduction in absolute terms during the crisis were *associative activities*; *catchment, potability, and distribution of water*; *storage and activities related to transport*; and *electricity, gas*,

Coal - Backward linkages



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Coal - Forward linkages



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FIGURE 3 Coal consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

steam, and air conditioning. Eight sectors increased their backward linkages with absolute variations ranging from 0.01 to 0.14. In contrast, six sectors increased their forward linkages ranging from 0.02 to 0.27 in absolute variations.

Finally, biomass and waste energy (Figure 6) showed important differences between the two periods analyzed. In the first period (2005–2011), there was an average annual increase of 35.59% for backward linkages and 35.56% for forward linkages for the period 2005–2011, and an average annual reduction of –8.20% for backward linkages and –8.16% for forward linkages for the period 2011–2014. Therefore, there was a global increase in both coefficients during the whole period. Three sectors stood out above the rest in terms of variations: *wood and cork industry*, which experienced the higher reduction in absolute terms; and on the other side, *industries other nonmetallic mineral products*, and *land transport; pipeline transport* showed the higher increase in absolute terms. The sector *wood and cork industry* is the only one that showed reduced backward and forward linkage coefficients during the whole period.

4.2 | Analysis of relative coefficients

The relative coefficients of a sector show its position in terms of the importance of its total consumption relative to the rest of the sectors within an economy (see equations 11 and 12), and they therefore have a different interpretation than absolute coefficients. They are used to identify the key sectors of an economy and construct the relative coefficients matrix illustrated in Table 1. In our analysis, we focused on relative pull and relative push coefficients. We explored the relative linkages for the five energy product categories for which we have developed energy accounts for Catalonia, plus a total energy consumption category that represents a sum of all the other sources. As previously stated, the energy sources

Petroleum - Backward linkages



Petroleum - Forward linkages



FIGURE 4 Petroleum consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

assessed are natural gas, petroleum, coal, electricity, and biomass and waste. Figure 7 shows the evolution of relative pull and push coefficients for 2005, 2011, and 2014 for each sector and energy product, following the same scheme developed in the matrix shown in Table 1. The key sectors of the Catalan economy for a specific year of analysis (the ones with relative pull and push coefficients higher than 1) are in the upper right box of the figures. We displayed the names for these key sectors in the same figure. The dimension of the dots is an approximate representation of the total sum of both coefficients. For more details on this classification for all sectors, energy products, and years, see Appendix C.

Most key sectors in 2005 remained key sectors in 2011 and 2014, with changes in the values of the coefficients. However, some less relevant sectors have become key during the economic crisis, while some key sectors have become less relevant. If we focus on total energy consumption, the sectors *industries other nonmetallic mineral products* and *metallurgy* became key in 2011 and remained so until 2014. For natural gas consumption, *manufacturing of rubber products and plastic materials* ceased being a key sector in 2011 and 2014, and the sector *audiovisuals*, which was a key sector in 2005 and 2011, stopped being a key sector in 2014. For coal, the same sectors considered key in 2005, *industries other nonmetallic mineral products* and *metallurgy*, were also key in 2011 and 2014. For petroleum consumption, *electricity, gas, steam and air conditioning*, one of the key sectors in 2005 and 2011, stopped being key in 2014, and the others remained key with different values. For electricity consumption, the sectors *textile, clothing, leather, and footwear industries* and *associative activities*, which were key in 2005, stopped being key in 2005 and 2014. The sector *sanitation, waste management, and decontamination* was not key in 2005, became key in 2011, but again stopped being key in 2014. The sector *public administration, defense, and mandatory SS*, which was key in 2005 and 2011, stopped being key in 2014. Finally, for biomass and waste, the sectors *food, beverage, and tobacco industries*, *paper industries*, and *audiovisuals*, which were key in 2005, stopped being key in 2011 and 2014. In general, we observed a reduction in the number of key sectors for all energy products. If we link these coefficients with economic activity, it is interesting to see how, for example, the sector *maritime transport and inland waterways* exhibits a significant contraction in absolute and not so high in relative coefficients from

Electricity - Backward linkages



Electricity - Forward linkages



FIGURE 5 Electricity consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

2005 to 2014, while at the level of maritime activity, this change is nonexistent or even the reverse. Total freight transport (in tons) in the Ports of Barcelona and Tarragona, which are the most important ports in Catalonia, was 74,823 in 2005; 74,526 in 2011; and 77,085 in 2014. Container transit (in million twenty-foot equivalent units [TEUs]) was 2080 (2005), 2239 (2011), and 2041 (2014).⁹

5 | DISCUSSION

In general terms, our analysis suggests that changes observed in backward and forward linkages coefficients (coefficients in absolute terms) have not been transferred to the determination of the relative importance of each sector within the Catalan economic structure, showing some persistence in relative sectorial importance over time. If we focus, for instance, on total energy consumption, we observe that some energy-intensive sectors like *maritime transport and inland waterways*; *land transport, pipeline transport*; *industries other than nonmetallic mineral products*; and *electricity, gas, steam, and air conditioning* showed significant reductions in their backward and forward linkages. Despite this reduction, they all were key sectors before the crisis and continued to be key sectors after the crisis. Something similar happens when we break down energy consumption by energy sources, with some exceptions.

There are important economic and environmental consequences derived from the results obtained in this research. If we analyze the results from a global perspective rather than detailing the results of each specific economic sector provided in the results section, we can point out some observations. First, although the economic crisis may have changed the economic structure in terms like changes of the relative importance of specific economic activities, as we can observe from most recent I–O tables, this effect may not have translated into energy use structure. Indeed,

Biomass and waste - Backward linkages



Biomass and waste - Forward linkages



FIGURE 6 Biomass and waste electricity consumption: Backward and forward linkage coefficients for Catalonia 2005, 2011, and 2015.

absolute energy use has changed during the period, but not that much if we put the focus on structural interrelationships, as shown by the calculated indicators. Second, this aspect is relevant for policy making, in the sense that it shows certain resilience and/or adaptation of the economic structures when considering energy resources use. Energy and climate policies focused on reducing energy use in absolute terms can be useful, but a wiser environmental policy targeting key sectors in energy consumption can weight better the effects not just of economic crises but also different stages of the economic cycle. That is, direct energy use is usually reduced in periods of contraction of the economic activity, but key sectors might not change—or change differently. In this scenario, certain policies should keep focusing on them despite relaxing their objectives. Third, and related to previous considerations, it is important to track those sectors particularly sensitive to changes in economic cycle. This research provides key insights on this for a relevant crisis period, but further research, considering other regions and periods, which have experienced different economic stages would help draw scenarios and capture the whole picture. Fourth, beyond energy use, decarbonization is also imperative and not aligned with energy use due to renewables and other environmental impacts that cause greenhouse gas emissions. This is why, although useful, results and conclusions drawn from this research are more adequate for energy policies than for climate policies.

From a strict public policy assessment point of view, this research shows alternative paths to use a traditional tool, such as input–output analysis, to obtain a better knowledge of the use of energy carried out by the different agents of a regional economy during an event. From an economic policy perspective, understanding the dynamic interplay between economies and natural resources, such as energy, is crucial. Traditional analyses often provide static snapshots of energy use, but economies are complex systems with evolving relationships with their environment. As economic conditions change, so too does their interaction with natural resources. Economies impact the environment, but structural natural resources use also impacts on economies. Therefore, it is essential to integrate economic with environmental policies to address these evolving dynamics effec-

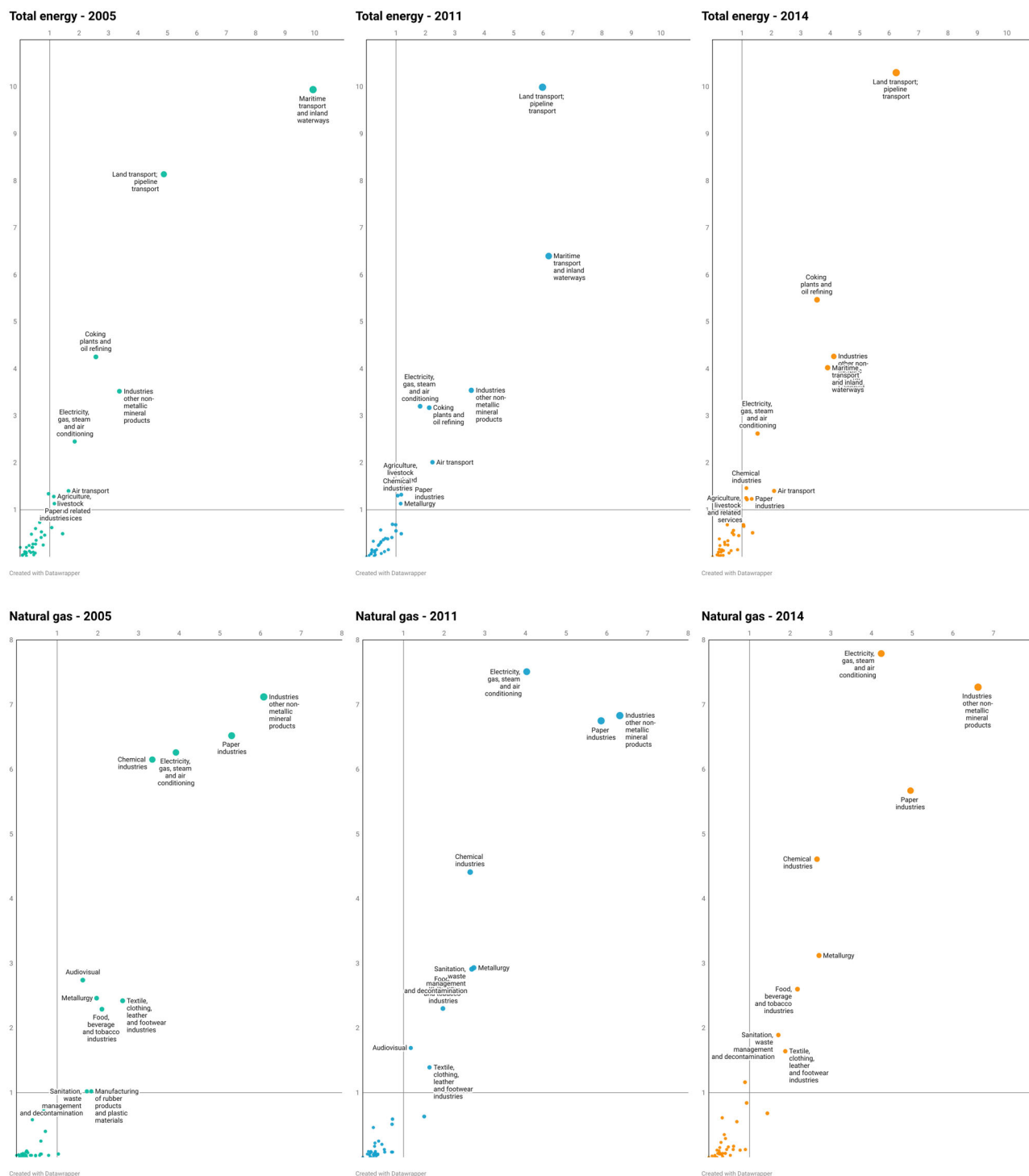


FIGURE 7 Key sectors matrices for the consumption of energy for different energy categories in Catalonia 2005, 2011, and 2014.

tively. This is why complex methodologies should also be introduced in public administrations to advance toward net-zero or sustainable societies. From an industrial policy perspective, it is crucial to understand the structural use of different industries and how it evolves with economic events or changes in order to strengthen or try to not boost sectors that are misaligned with natural resource use strategies. Finally, from an energy or natural resources policy perspective, this kind of analysis provides essential information to elaborate adequate policy strategies, plans, or programs without only relying on conjunctural analyses which often lack the complexity needed to fully understand inter-agent relationships. From an academic perspective, beyond all the mentioned technical particularities, we show we can extend traditional simulation methodologies and find other uses for them, to extract interesting and useful results.



FIGURE 7 Continued

From the results of this research, we can assume it is difficult to change the relative importance of economic sectors in energy consumption because despite the economic crisis and other events that took place during the period they have not changed in Catalonia. However, more evidence is necessary at this point to support this hypothesis. Modifying this relative importance is important for decarbonization of economies, to give less importance in energy terms to those sectors with more final consumption potential, and the other way around. It is also important to point out that a different disaggregation of the economic sectors would provide the same results for the aggregate but could provide small changes within the economic activities included in each sector. This is another aspect that should be explored in further research. To contextualize these results, it is important to highlight that there are some aspects from input-output methodologies that affect the results and are worth discussing: (1) technolog-

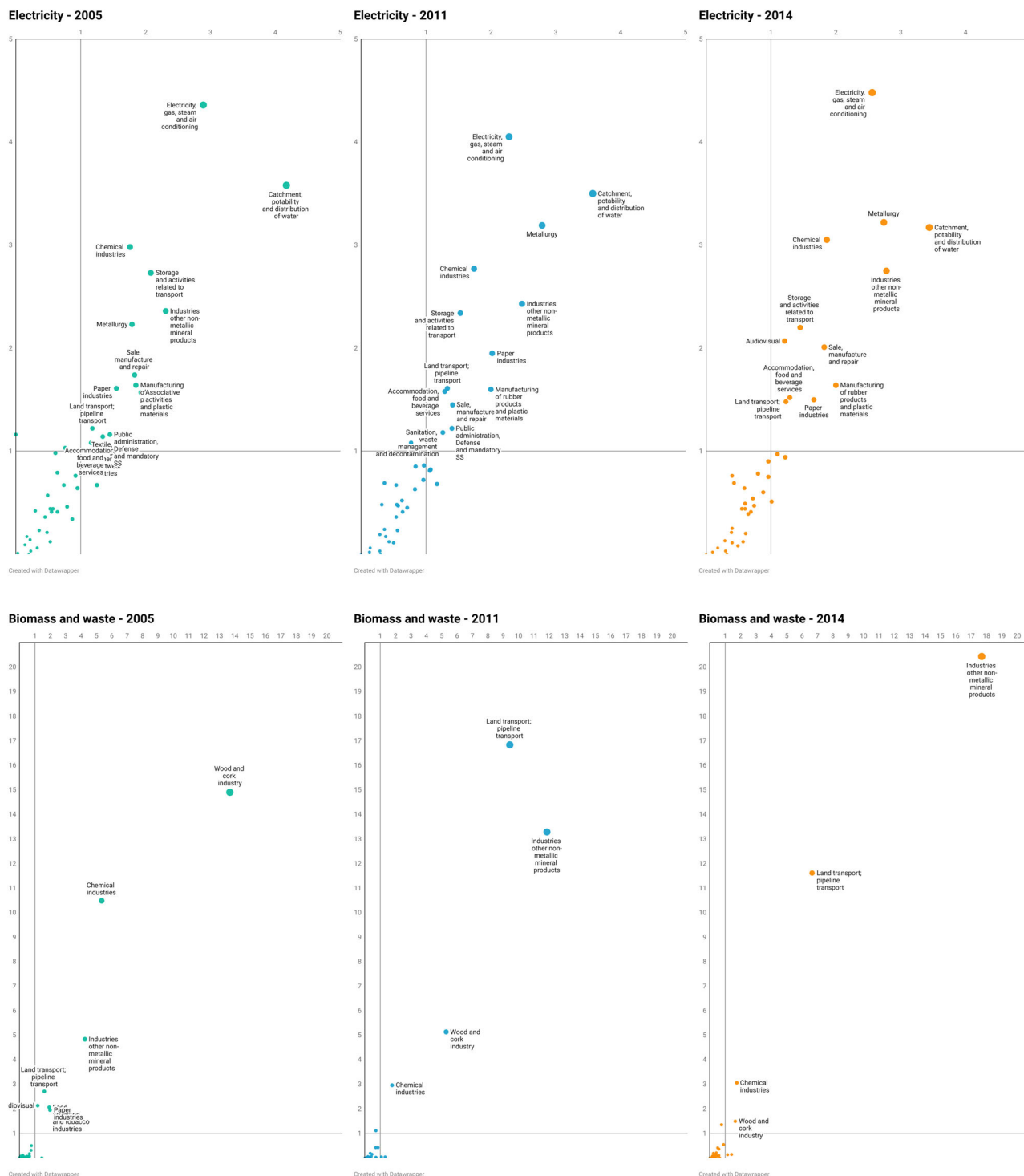


FIGURE 7 Continued

ical change plays a significant role in input–output models by influencing how industries interact within an economy and how resources are utilized; (2) relative prices influence the economic relationships and interdependencies between different sectors within an economy, by determining input costs, influencing production decisions, shaping interindustry relationships, affecting trade and specialization, impacts on inflation and economic policy, sectoral shifts, and structural changes.

The objective and approach of this study is novel, with no similar studies found in the literature. However, related studies mentioned earlier in this article reveal similarities which are worth exploring. Previous studies we have identified on the global financial crisis and energy consumption from an I–O perspective have mainly been based on obtaining different kinds of outcomes. For instance, Yuan et al. (2010) focused their study on the

impact of the 2007–2008 global financial crisis and a 4 trillion Yuan (\$586 billion) stimulus plan in China, in terms of changes in exports, imports, and economic growth, using a single I–O table. As they did not consider or calculate structural indicators/changes, as we do along periods, our results and conclusions are not comparable. Also, Bekhet and Yasmin (2014) used I–O analysis to assess the impact of the same crisis on trade and energy consumption in Malaysia, as well as the impact of a stimulus plan launched by the government. Similarly, they did not analyze the structural energy consumption during the crisis period, so we cannot compare our results with theirs. On the other hand, Roinioti and Koroneos (2017) research was focused on using a decomposition technique to identify the driving forces of CO₂ emissions in Greece. Their study covered two subperiods (2003–2008 and 2008–2013) to assess changes in the contribution of the examined factors during the same economic crisis we study. In relation to our study, they found that “the structural effect” contributed to the decrease of CO₂ emissions in the industry and construction, agriculture and transport sectors over the period 2003–2013, and CO₂ emissions increase in the energy and service sectors, as a sign of their increased share in the Greek GDP. Using the key sectors (total) energy consumption methodology for Catalonia, we find for these sectors there are no relevant structural changes, but their study considers CO₂ emissions, while we use different energy sources.

6 | CONCLUSIONS

There is some uncertainty regarding the effect of specific economic crises on structural energy consumption along the economic structure and their interactions. In this article, we shared the structural relationships in energy terms before, during, and after an economic crisis using the case study of Catalonia during the 2008–2014 financial crisis and environmentally extended input–output analysis methodology. The use of five different energy resources is observed along three input–output tables for different years. These sources are as follows: natural gas, coal, petroleum, electricity, and biomass and waste. Total energy has also been considered as an additional source that adds up all the other energy sources. We studied the evolution of linkage coefficients and key sectors, and beyond the interest level of the results in merely descriptive terms, some important conclusions can be drawn from the static and dynamic analysis we performed.

Because there are no sectoral energy accounts for Catalonia, we built the energy vectors using different sources and applying homogeneity with the input–output framework of Catalonia using detail for 41 sectors. Sectoral energy consumption has globally dropped for all vectors. This drop has been higher in energy-intensive sectors than in others, although there are some nuances depending on the sector and energy source analyzed.

The backward and forward linkage analysis shows that most economic sectors have reduced their potential to induce energy use in the economic structure after the economic crisis. At the same time, they also show that economic sectors are generally less susceptible to others in terms of consuming energy. This has probably been the effect of different causes occurring during this period, but at an economic structural level, the economic crisis may have had an important role in shaping a new energy consumption structure.

Both backward and forward linkage coefficients (coefficients in absolute terms) experienced important changes for some sectors, but in general these changes did not translate into important changes in the relative importance of each sector within the Catalan economic structure. We illustrated this by analyzing the key sectors analysis performed, where the relative importance of each sector within the economic structure is analyzed with the dynamic sequence proportioned by the energy input–output analysis of the three years of interest. This persistence in the relative importance of sectors over the studied time frame can point to a structural problem that policymakers working on energy policies should be aware of.

From a policymaking perspective, our study suggests some important policy implications, beyond the importance of using economic structural indicators with techniques like input–output analysis, our results highlight the importance of considering not just absolute indicators in shaping energy strategies, plans, or programs, but also relative indicators providing essential information to understand the use of energy carried out by an economic structure. Additionally, analyses through different time frames helps with understanding the dynamics of sectoral energy use through different economic events or economic stages like an economic crisis and can therefore consequently redefine economic and energy policies.

Future studies should look more deeply into the causes and consequences of this persistence in the relative importance of sectors despite their volatile absolute importance, as well as contemplate strategies to modify undesirable situations. The consideration of other periods, regions, and methodologies would also consolidate the interpretation of energy input–output analyses through dynamic frameworks. Also, the consideration of the Catalan economy within the contexts of the Spanish, European, and global economies, as well as analyzing the I–O tables and associated indicators by breaking down interregional and international trade, would provide valuable insights for evaluating a structural response to a crisis. This analysis could reveal the extent to which sectors replaced domestic production with imports or redirected their production toward non-domestic markets, with such structural changes potentially impacting energy consumption. Finally, if it is difficult to change the relative importance of these sectors, particularly those considered key, their decarbonization becomes more important for fighting climate change.

AUTHOR CONTRIBUTIONS

Jaume Freire-González: conceptualized the study; contributed to the methodology; performed formal analyses; supervised the study; and wrote the original draft. **Oliver Canosa:** conceptualized the study; conducted data curation; performed formal analyses; and wrote parts of the document.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Notes

¹ Readers who wish to avoid the detailed discussion on data-related challenges in the analyzed case can skip Sections 2.2 and 2.3.

² https://icaen.gencat.cat/ca/energia/estadistiques/resultats/anuals/balanc_energetic/

³ <https://icaen.gencat.cat/ca/energia/estadistiques/resultats/sectorials/ecesi/index.html>

⁴ The energy balance of Catalonia shows the production and consumption of primary energy, consumption in the transformation in electricity generation and in refineries and olefins plants, energy consumption specific to the sector, losses in energy transport and distribution, and non-energy consumption as well as final consumption by sector and energy source.

⁵ <https://www.idescat.cat/indicadors/?id=ue&n=10130&t=201300&lang=en&col=1>

⁶ <https://apps.fomento.gob.es/BDOTLE/visorBDpop.aspx?i=314>

⁷ https://icaen.gencat.cat/ca/energia/estadistiques/resultats/anuals/balanc_energetic/

⁸ <https://www.ine.es/jaxi/Datos.htm?path=/t26/p067/p02/energia/a2006/10/&file=01002.px>

⁹ <https://www.idescat.cat/indicadors/?id=anuals&n=10512&t=201400&lang=en>

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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