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RESEARCH

Enhancing regional resilience for energy price shocks: efficient gas use and upstream decarbonization

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Abstract
Resilience and competitiveness in relation to fossil energy dependencies is of increasing concern to industries and policy makers. We investigate to what extent the competitive position of industries in European regions are sensitive to changes in fossil fuel prices, and whether reductions in gas use along the value chain may increase resilience of regional industry. A new spatial revealed cost competition model based on the input–output price model is used and calibrated to multi-regional world input–output tables on an EU NUTS 2 level. We obtain elasticities of fossil fuel prices on revealed cost competitiveness and analyse how resilience can be enhanced by increasing efficiency and electrification in production. We show that European regions are resilient to global coal price increases, but are vulnerable to gas price shocks. The transition towards using less gas in production, by efficiency improvements or electrification, can reduce these gas price vulnerabilities. However, when competitors become more efficient instead, the vulnerability to such shocks may increase. Decarbonizing upstream sectors like electricity generation in the own region, own country or in Europe, can increase resilience of downstream industrial sectors in most European regions.

Keywords Competitiveness · Resilience · Fossil fuels · Energy efficiency · Industrial energy use · Economic input–output analysis · Global value chains · Decarbonization · Regional economy

1 Introduction

In recent years, there have been notable fluctuations in energy prices resulting in cost increases in energy-using firms. The Ukrainian-Russian conflict and the following spike in gas prices led to concerns regarding the dependency of economies on gas, especially given competitiveness of the European Union has already been under pressure due to low productivity growth and high energy costs (Chiacchio et al., 2023; European Commission, 2024). The gas market is sensitive to shocks and geopolitical tensions, increasing uncertainty regarding price developments (IEA, 2023). Due to specialization of regional economies in energy-intensive industries or production processes, increasing regional resilience to shocks is becoming an important policy objective to limit the potential damages from future shocks. Meanwhile, policies addressing industrial ecology, such as the transformation of the energy system may alter this sensitivity to fossil fuel prices. Regional resilience may then increase by altering energy consumption in industrial production and upstream sectors, related to Hoffman et al. (2014) and Esty and Porter (1998), discussing industrial ecology as a source of competitive advantage at the firm level. This paper therefore investigates the effect of rising energy prices on competitiveness of regional industries, and asks what strategies can be applied to enhance the resilience.

The impacts of energy price shocks on regional economies have been studied using historical data (Alexeev & Chih, 2021; Bohi & Powers, 1993), input–output price models (Miernyk, 1976a, b; Wang, 2022) and macroeconomic models (Aydın & Acar, 2011; Dong et al., 2020; Nguyen et al., 2024; Turco et al., 2023). This paper specifically studies regional competitiveness and its resilience, deviating from past measures of energy resilience (see, e.g., He et al.,

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2015, 2017, 2019; Sato et al., 2017), by introducing a model for revealed cost competition.

We develop a new model for revealed cost competition (RCC), which fully integrates an input–output price model into the model of revealed competition from Thissen et al. (2013). Subsequently, we derive the price elasticity of the RCC of industries in regions to changes in fossil fuel costs. This elasticity describes the region-specific competitive threats and opportunities (or resilience) for these industries. Furthermore, we examine the change in this elasticity that describes how technological advancements and substitutions among different energy types impact the resilience. This way, we gain insights into the intricate relationships between energy price fluctuations and competitive dynamics of technological advancements resulting in shifts in energy types at the regional and industry levels. The analysis is based on a multi-regional world input–output table at the EU NUTS 2 level, see Thissen et al. (2018), extended with energy accounts.

The results of this paper provide a deeper understanding of the competitive dynamics within regions, due to sectoral specialization of regions and competitive positions in global value chains (GVCs). We show that regions in Europe are resilient to global coal price increases, suggesting a low dependency on coal, whereas they are more vulnerable to natural gas price shocks in terms of their competitive position. The size of the total effect on the regional industrial competitiveness in the case of a global gas price shock is negative only in a few regions, due to a dependence on energy-intensive industries or reliance on gas in industrial processes. For example, regions in the Netherlands are vulnerable to global gas price shocks, due to dependency on gas in electricity generation and a historical pattern of gas intensity in production. Hamburg in Germany, due to a large chemical industry sector, is also negatively affected. Meanwhile, the traditional materials sector in the European regions, including basic metals production, is very competitive. In the case of a European end-user price shock in either gas or coal, all EU regions lose in terms of their competitiveness.

Additionally, we examine how decarbonization can present opportunities for these regions to reduce their sensitivity and enhance their resilience for gas price shocks. Efficiency improvements in the use of gas or electrification in the production process of industrial products in the own region always increases resilience to future price shocks. At the same time, the results show that if your competitors become more efficient in the use of gas (e.g., get closer to the technological frontier), you become relatively more dependent and thus this negatively affects your competitive resilience. It is therefore important to avoid staying behind in such improvements to limit negative effects of future price shocks. We find that increasing the efficiency of the use of gas in electricity generation and oil refinery and cokes production within the same region, country or in Europe, can increase resilience for the low- and medium-tech industry in most European regions.

The paper is structured as follows. In Sect. 2 an overview of the literature is provided and various concepts used are defined. In Sect. 3 the model is presented. In Sect. 4 the data used for the analysis are described. Sect. 5 presents the price elasticities and decarbonization effects. Finally, in Sect. 6, we conclude.

2 Literature review

2.1 Related literature

Historically, rising energy prices are found to drive economic recessions, inflation and unemployment (see, e.g., Davis & Haltiwanger, 2001). Meanwhile, in a long-term analysis of the U.K., van de Ven and Fouquet (2017) show that vulnerability and resilience of an economy may adjust over time, and depend on the types of energy the economy is relying on most. Past studies focused on energy price shocks and resilience use a range of methodologies: input–output price models, historical data and econometric methods, or computable general equilibrium (CGE) models.

During the oil crisis in 1973, the regional economic effects in the U.S. of changing energy prices depended on the energy-intensity of regions (Miernyk, 1976a, b; Polenske, 1979). Using a cost-push price model to investigate the cost pass-through and changes in value-added per region from the energy price changes between 1967 and 1974, energy-consuming regions experienced a shift in the inter-regional terms of trade, having to pay more for the products they are importing. Similarly, Bohi and Powers (1993) used historical regional data on mining employment and industrial energy consumption in the U.S. during the oil crisis to assess short-term fluctuations due to energy price shocks. In a state-level analysis of the U.S. using panel data for 1975–2018, Alexeev and Chih (2021) find a significant effect on economic growth of states, with large heterogeneity in the different effects for exporters and importers. Using historical data, the economic impacts can be studied after the actual price shock occurred (see also Lin & Song, 2024; Wang, 2022).

Besides using historical panel data or time series, input–output price models are often used to study fossil fuel cost change effects on regional economic outcomes. They are especially useful to estimate the ex-ante impact of a cost change and are able to provide an idea of the structure of the regional economy and the pass-through of the increased prices on other sectors through trade networks. An alternative method is to use a macro-economic general equilibrium model, where firms are able to substitute between inputs as prices change (see, e.g., Aydın & Acar, 2011; Dong et al., 2020; Nguyen et al., 2024; Turco et al., 2023).

More recently, the effect of rising oil, gas, and coal prices on competitiveness is studied, measured in terms of exports, imports, or value-added on a national or supranational level. Capros et al. (2016) investigate competitiveness effects in the EU of increases in gas and electricity prices using a general equilibrium model, where competitiveness is measured based on changes in imports and exports. They find that energy-intensive sectors that are more exposed to foreign competition, such as chemicals and nonferrous metals, are more negatively affected in terms of competitiveness. Valadkhani and Mitchell (2002) study petrol price increases in Australia using a modified input–output price model and investigate resilience to such shocks. Comparing the analysis for 1977–1978 with the same analysis for 1996–1997 shows that the Australian economy has become less sensitive to fossil fuel price shocks.

Similarly, various studies have investigated the effect of climate policy or carbon prices on competitiveness (see Dechezleprêtre & Sato, 2017, for a review). For example, Ward et al. (2019) investigate competitiveness after a worldwide carbon tax.

Regional economies are more specialized in terms of their production structure compared to national economies, and therefore can be more vulnerable to energy price shocks. Various studies have described and quantified energy resilience on a regional level (Exner et al., 2016; He et al., 2015, 2017, 2019). Meanwhile, resilience of regions could increase as renewable energy markets are more geographically dispersed (see, e.g., Bridge et al., 2013; Scholten et al., 2020; IRENA, 2019; van de Ven & Fouquet, 2017). However, studying regional effects of an increasing market share of renewables is complicated due to data limitations (Jenniches, 2018). One example of including renewables in an input–output methodology is Többen (2017), who studies the regional effects of the promotion of renewable energy policy in Germany. In our analysis, we implicitly consider efficiency and electrification and investigate the effect on regional competitive resilience, as industrial ecology could affect the competitiveness of firms (Esty & Porter, 1998; Hoffman et al., 2014).

2.2 Competitiveness and resilience

Within our framework, a region's *competitiveness* is defined by the concept of revealed competition, which is based on the trade network of regions in global product markets (Thissen et al., 2013). This is a spatial interpretation of competition, where suppliers from specific regions sell their products on sales markets in other regions. Consequently, competition occurs between suppliers from distinct regions on these sales markets. This measure was previously applied to analyze the impact of Brexit (Thissen et al., 2020).

This concept differs from competitiveness measures based on the Balassa index (Balassa, 1965), which assesses a country's competitiveness based on its specialization in industries measured by gross exports compared to other countries. Other measures, such as the one proposed by Timmer et al. (2013), replace gross exports with global value chain (GVC) income to account for the overestimation of competitiveness caused by imported intermediates. By incorporating GVC income, the index shifts the focus from export share to a country's contribution to international global value chains. This is an improvement over export-based indices that fail to consider the modern organization of production processes, which involves numerous small value-adding activities required to produce a final manufacturing product. Los et al. (2016) utilize this index to examine the competitiveness of EU regions, and both Timmer et al. (2013) and Los et al. (2016) argue that countries with a high concentration of value-added activities in specific production processes within GVCs are more competitive than others.

While Balassa-based indices concentrate on the outcome of the competitive process, the revealed competition measure utilized in this analysis centers on how cost changes may affect the competitive position of industries in regions. These concepts are not directly comparable and rely on distinct assumptions. For instance, whereas GVCs analyses rely on static value chains with competition in end products, the concept of revealed competition is focused on the competition within the value chain where distinct firms in distinct locations compete to be a part of the value chain. In other words, the revealed competition concept involves both intermediate and final products. Furthermore, the concept of revealed competition is focused on spatial markets where competition occurs on regional and product-specific spatial scales, whereas GVC analyses consider solely a global market with local suppliers participating in global competition. An analysis of different Balassa-based concepts of competitiveness would give additional insights into resilience, but given the large difference in conceptualization and modeling, it is beyond the scope of this paper.

The measure of revealed competitiveness is used to study the regional *resilience* of industries. As described by Scott (2013); Martin (2012) and Meerow and Newell (2015) competitiveness is a long-run, path-dependency phenomenon, whereas resilience relates to the short-run ability of regional economies to bounce back from a shock (also referred to as 'equilibrium resilience'). A different way of looking at resilience is 'evolutionary resilience' or 'ecological resilience': the shock allows the region to move towards a new equilibrium, realizing new growth paths, or 'bounce forward' (Boschma, 2014; Martin, 2012; Meerow & Newell, 2015). Based on a biblometric review, Meerow and Newell (2015) conclude that quantifications of characteristics of resilience are scarce.

Resilience to fossil fuel supply shocks and decarbonization have been addressed and quantified in terms of energy resilience by Binder et al. (2017), Exner et al. (2016), Erker et al. (2017), Gatto and Drago (2020) Qian et al. (2023), Roege et al. (2014) and specifically by He et al. (2017, 2019), He et al. (2015) (quantifying energy import resilience) and Sato et al. (2017) using input–output modelling. However, these studies focus on supply shocks and the ability of the system to satisfy energy demand, and no studies have applied an input–output price model to investigate the effect on competitiveness of energy users (industrial sectors).

In our study, we therefore provide a novel method to study resilience of competitiveness of the industrial sector of regions. We investigate whether decarbonization can be a way to increase the resilience of regions in a quantitative manner. In the first part of the analysis, a change of the regional competitiveness informs us about the 'equilibrium resilience' of a region. In the second step, decarbonization scenarios indicate a different equilibrium where the resilience may be smaller or larger: decarbonization may help a region to 'bounce back' after the shock and thus increase resilience. Important to note, however, is that the underlying mechanisms or dynamics from moving from one equilibrium to another are not endogenous in our framework.

3 Model

We combine the model for revealed competition developed in Thissen et al. (2013) with an input–output price model. This is comparable to the price competition model used in Thissen et al. (2020), however, here we fully integrate both models into one new model for revealed cost competition (RCC). This integration allows us to directly analyze the effect of, for instance, policies or technological changes on the cost competitiveness of industries in specific regions.

The model is used for a two-step analysis, presented in Fig. 1: First, we study the effect of a change in the fossil fuel costs on the region-sector-specific RCC, which is reflected in a price elasticity in our model. This shows to what extent a sector in a region experiences a cost increase for its products and compares it to the cost increase of important competitors. This price elasticity reflects the resilience in terms of the competitive position of this sector in this region for these costs or prices in the baseline situation. This follows the methodology of using marginal prices in a revealed competition model also used by Thissen et al. (2020) to determine the effect of tariffs due to Brexit.

Second, we study the effect of decarbonization on regional resilience. Here, we use a novel approach of studying marginal changes on the technological coefficients, which refer to the required intermediate products in production. This can be seen as investigating slight adjustments in the production structure of firms. Using the previous method of studying the resilience to fossil fuel costs changes, we compare different adjustments in production structure (or equilibria) and the change in competitiveness of the region-sector informs us of the new 'equilibrium resilience'. Comparing the baseline with the decarbonization outcomes informs us of the *enhanced resilience* due to decarbonization. This is explained in more detail in Sect. 3.2.

3.1 Measuring regional revealed cost competitiveness

The model for regional cost competitiveness (RCC) uses the revealed *spatial* competition concept from Thissen et al. (2020) to determine the relative cost change effect of a price change for an industry in a region relative to its revealed competitors. This measure of revealed cost competitiveness takes into account value chain linkages and the competitive position of the region on various product markets. Changes in prices are compared to the price changes of the most important competitors, and this is reflected in the revealed cost competitiveness measure.

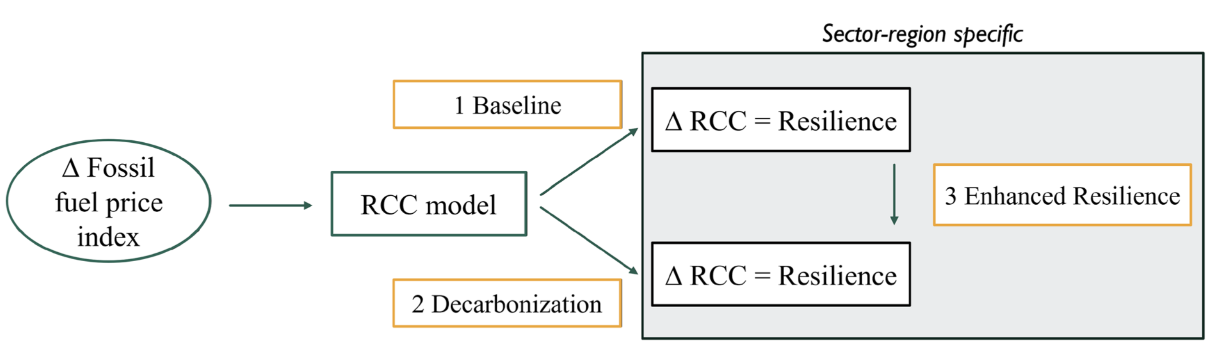

Fig. 1 A graphical representation of the analysis. The Δ represents a change in the specified variable.

The principle of revealed competition takes into account the size of the sales market and the overlap of regions in those sales markets (for example, Dutch and German regions exporting to the same region in France). It determines the extent to which an industry in a region will sell the same product as an industry from another region in all the sales markets it sells its products. Simultaneously, the measure used also takes into account the size of the production within a region and thus the dependence of the regional economy on this particular product market. Thus, the final measure of regional competitiveness ($RC_{i,r,r'}$) is given by:

$$RC_{i,r,r'} = \sum_{r''} s_{i,r,r''} m_{i,r',r''}, \tag{1}$$

where i indicates a product and r and r' the various regions. The regional competition of product i between region r and r' is given by the product of the sales market share ($s_{i,r,r''}$) of region r for product i in region r'' times the market share ($m_{i,r',r''}$) of this product i in region r' exporting to region r''. We define the market share:

$$m_{i,r,r'} = \frac{x_{i,r,r'}}{\sum_{r'} x_{i,r,r'}}. \tag{2}$$

Thus, for the market share for product i between region r and r', we look at the production (given by $x_{i,r,r'}$) of good i in region r that is going to region r', over the total 'foreign' demand for this good produced in region r. The weighting of sales markets by the market share ensures that competition between industries from two regions is not symmetric.

The sales market share is computed as:

$$s_{i,r,r'} = \frac{x_{i,r,r'}}{\sum_{r} x_{i,r,r'}}. \tag{3}$$

The market share of an industry in a region represents its sales as a share of size of the market (the total sales in that market) in the denominator. This implies that we sum up the production of good i that is being consumed in region r' over all regions that it may be coming from. Thus, this is the total size of the sales market of good i in region r'. We compute the share by considering the amount of products i that is produced in region r that is being sold in region r' over the total size of the sales market. Therefore, if the sales market share is large, this implies that the production of good i from region r is very dominant in region r'.

The regional cost competitiveness considers how a change in the price level ($p_{i,r'}$) for a product or region affects the regional competitiveness through GVCs, in combination with the own-price effect. This results in:

$$RCC_{i,r} = \frac{\sum_{r'} p_{i,r'} \sum_{r''} s_{i,r,r''} m_{i,r',r''}}{p_{i,r}}. \tag{4}$$

This measure considers a full pass-through of price increases along the value chain.

3.2 The revealed cost competition model

The revealed cost competition model combines the revealed cost competition measure from Eq. 4 with the input–output price model (see Miller & Blair, 2009). For the base year index prices, the system of equations looks like:

$$p_{i,r} = \sum_{j,r'} p_{j,r'} a_{j,r',i,r} + v_{i,r}, \tag{5}$$

where $v_{i,r} = \frac{va_{i,r}}{x_{i,r}}$, the cost of production factor inputs per unit of output. Thus, changes in input prices lead to changes in sectoral unit costs through fixed technical coefficients, $a_{j,r',i,r}$. The input–output price model assumes a homogeneous index price (relative to the base year price) for region- and sector-specific goods ($p_{i,r}$), based on their value usage by other sectors across regions. The model therefore accounts for regional price variations and even specific prices related to region and sector of usage, if these exist in the base year of the analysis.

To compute the effect of price changes on the $RCC_{i,r}$, we maximize the RCC for a specific industry i in a region r, Eq. 4, subject to Eq. 5. The detailed formulation of the optimization problem is described in the Supplementary Information S3. This non-linear programming technique provides marginal values on fossil fuel prices which can be interpreted as price elasticities of the competitiveness, here interpreted as a measure of resilience of the competitive position[1]:

$$\eta^{p}_{i,r} = \frac{\partial RCC_{i,r}}{\partial v_{j,r}} \frac{v_{j,r}}{RCC_{i,r}}. \tag{6}$$

To study the effect of efficiency and electrification on resilience to fossil fuel price shocks, we use a novel approach using marginal changes of the technological coefficients and combine this with our previously computed sensitivity or price elasticity of resilience of the competitive position. As explained in Fig. 1, the change in the technological coefficients reflects moving towards decarbonization in production, and therefore the extent to which a fossil fuel price increase affects the sector's competitiveness may be different. Compared to the baseline situation, with this method we can now evaluate whether resilience for such price shocks increases or decreases, after adjusting the production structure due to decarbonization. The change in resilience is

[1] Technically, we model the price increase as a percentage change in the value-added component of the price, or the returns to fossil fuels.

therefore computed by evaluating the change in the price elasticity with respect to the technological coefficient $a_{j,r',i,r}$:

$$\sigma_{j,r',i,r} = \frac{\partial \eta^{p}_{i,r}}{\partial a_{j,r',i,r}} a_{j,r',i,r}, \tag{7}$$

where we define $\sigma_{j,r',i,r}$ as a semi-elasticity, such that we can interpret it as a percentage change in the use of a good in production.

By adding constraints on how the technological coefficients are allowed to change, we consider two scenarios focused on reducing the dependency on natural gas: first, an increase in the overall use of gas efficiency of the production process, simply reflected by Eq. 7 and evaluating the impact of a percentage decrease of a specific $a_{j,r',i,r}$ which refers to gas or coal use in a sector for a specific region. Second, in an electrification scenario, the use of a gas can only be substituted for electricity from the own region, which implies that a percentage decrease of $a_{gas,r',i,r}$ results in an increase of $a_{electricity,r',i,r}$. We can both evaluate these decarbonization adjustments in the production for the sector-region we are studying the competitiveness for, or, alternatively and perhaps more interesting, we can also evaluate upstream adjustments in production and evaluate the competitiveness of downstream sectors (e.g. study $RCC_{j,r'''}$ after adjustments in $a_{gas,r',i,r}$). It is important to note here that we do not take into account the dynamics of this transformation of the production process and only provide a comparative static analysis.

4 Data

We create detailed supply and use tables (SUTs), and a multi-regional input–output (MRIO) table, by disaggregating the regional EU NUTS 2 level SUTs for 2017 from Thissen et al. (2026) to isolate fossil fuels as separate products. These highly detailed trade-linked SUTs include 64 countries and one 'rest of the world' region and distinguish 56 economic activities (NACE) or sectors and 63 products (CPA classification).

The rows of the original SUTs are split up, where these disaggregated SUTs by design sum up to the original tables and are fully balanced. We make use of various detailed data sources, such as the IEA World Energy Balances database, SUTs of the U.S. and Japan, BACI trade flow data, and regional structural business statistics from Eurostat. A description of the method applied is presented in the supplementary information S2. We aggregate the resulting product-by-product MRIO table to the products: agriculture, traditional materials, high-tech industry, low- and medium-tech industry, chemical industry, oil refinery and cokes production, coal, oil, gas, electricity, other energy, private services, public services and transport, see the Supplementary Information SI2. The table is aggregated to the NUTS 2 regions within a country (included countries: Austria, Belgium, Germany, Denmark, Spain, France, The Netherlands, Italy, Poland and Portugal), other countries in the EU and the various countries in the rest of the world[2]. Using this method, the resulting MRIO table contains industry-region-specific energy intensities in production and regional-level trade flows.

Figure 2 shows the direct fossil energy use per product on the horizontal axis, and the total energy use throughout the value chain on the vertical axis. Each data point represents a product-region combination. The chemical industry and traditional materials industry products are most fossil-intensive. However, while substantial direct energy consumption is a necessary condition for sensitivity to price shocks, it alone is not sufficient to have a significant impact on cost competitiveness. To have a substantial effect on cost competitiveness, it is also crucial for an industry to demonstrate differences in energy usage compared to its competitors.

5 Results

First, we present price elasticities of the revealed cost competitiveness in the baseline. We study a global price increase for gas and coal, and a European tax or price increase on the use of these energy sources in products. Second, we analyze how these price elasticities are affected by changes in the energy use, e.g. whether resilience increases or decreases when production is decarbonizing.

5.1 Global price shock

In the model, the sensitivity of a specific industry to a change in the gas or coal price is directly influenced by its energy intensity in production, plotted in Fig. 2. Industries that heavily rely on energy will have their total production costs significantly affected by changing energy prices, creating conditions for substantial effects on cost competitiveness. The type of energy and the regions from which it is obtained are also crucial factors influencing the sensitivity of cost competitiveness. When a particular industry in a region utilizes a specific energy type obtained from a certain region, while its competitors employ different energy types or sources, the price competitiveness of that industry

[2] The regional aggregation used includes the regions/countries: all European countries, NUTS 2 regions ITC4 (Lombardia), FR10 (Île-de-France), UKI (London), Russia, Saudi-Arabia, U.S., China, India, Japan, rest of the world. The product and regional aggregations are chosen such that important industrial sub-sectors can be distinguished and tractability is maintained when solving the model with the regional EU NUTS 2 level.

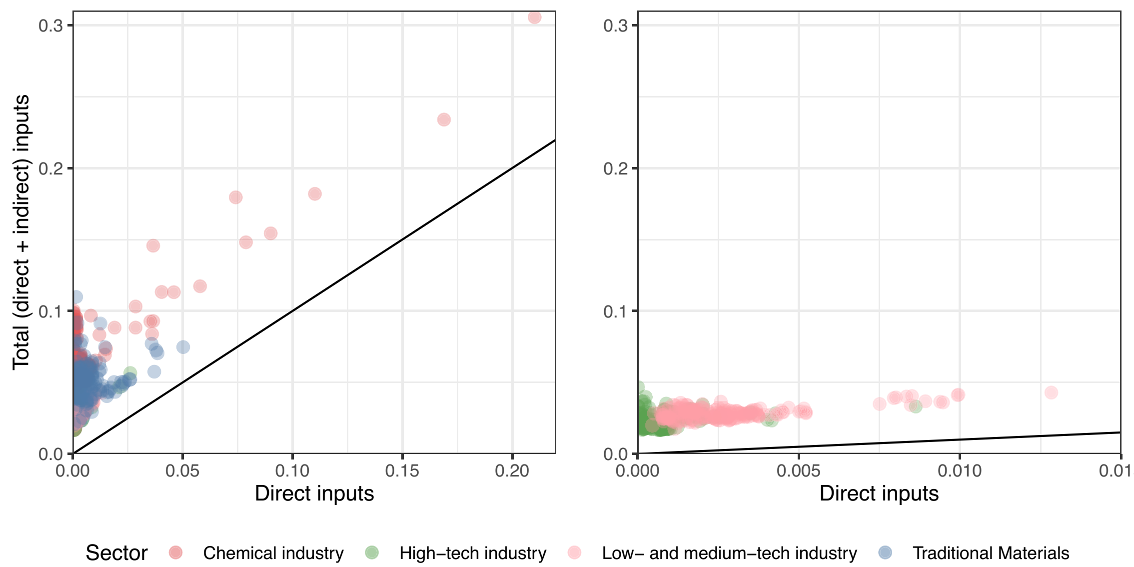

Fig. 2 Fossil inputs in production per sector (in Euros per 1 Euro of production). Underlying data for this figure are available in Supplementary Information SI5. The resulting direct use of fossil energy per NUTS 2 region per sector plotted against the total use of fossil energy throughout the value chain. In the left panel, all sectors are included. In the right panel, only the sectors high- and low- and medium-technology industry are shown. A 45° line is included in both figures. In the Supplementary Information SI1 file, additional plots for separately coal and gas are included.

becomes highly sensitive to the price of the specific energy type it relies on and its specific source.

The effect of a global price increase of coal or gas on the RCC of industries is heterogeneous but follows a strong sectoral pattern, as shown in Fig. 3. With a global price increase, the price change is independent of the regional source. The observed effects are therefore attributed to differences in usage type or production efficiency. A negative price elasticity implies that an increase in the global gas or coal price decreases the competitive position of the industry

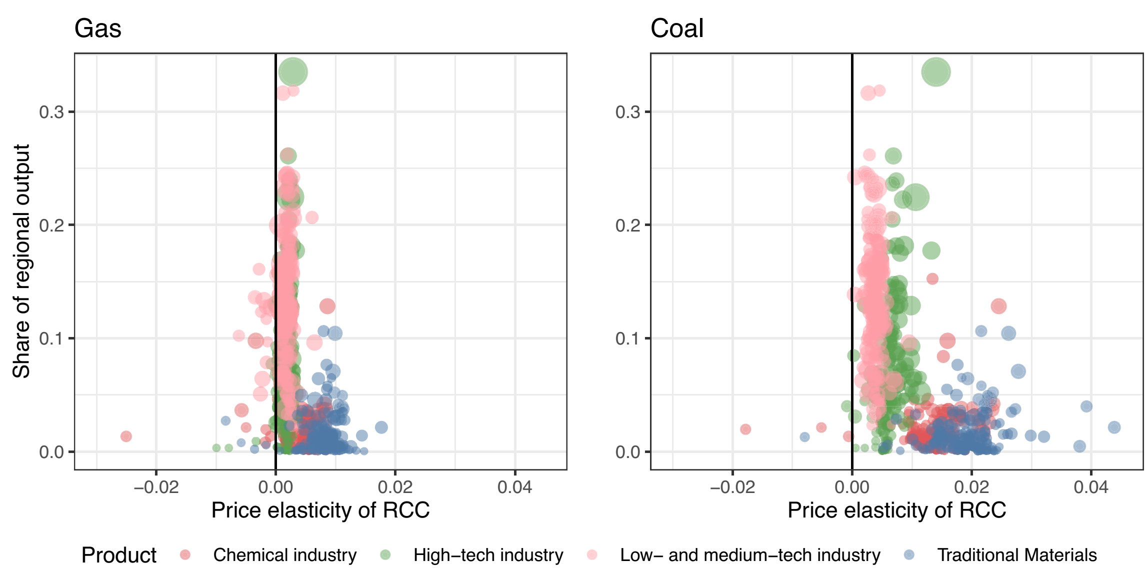

Fig. 3 The elasticity of the global gas (left) or coal (right) price on the competitiveness of the European NUTS 2 regions. Underlying data for this figure are available in Supplementary Information SI5. The elasticity can be interpreted as follows: a 1% increase in the return to global gas results in a η% increase in the RCC. The size of the points reflects the value of production in the region in Euros. The y-axis reflects the share of the production value of the sector of the total production value in the region.

in the region under consideration. For example, for the chemical industry in Hamburg, we observe the largest negative global gas price elasticity. This implies that compared to competitors, the price of chemical products produced in Hamburg rise more after a global gas price shock, resulting in a loss of competitiveness. A positive value implies that the competitive position of the industry-region combination improves: the price increase of competitors is larger as they may be less efficient in their use of gas or coal ('technology effect') or the products produced may be different ('product mix effect').

Products with higher direct energy intensity are more severely affected by the price change in terms of their competitive position, as the size of the price elasticities (either positive or negative) are larger. The global gas price shock shows vulnerabilities and dependencies of certain regions for the use of gas in the production process in all sectors, but mostly in the chemical and low- and medium-technology industry as the price elasticities are negative. In the case of a global coal price shock, almost all regions considered are positively affected and thus competitive opportunities are created. This suggest a low dependency of the European regions on coal compared to competitors.

The traditional materials sector exhibits a notable sensitivity to changes in the coal price in a positive sense, and in most cases also for a global gas price change. This suggests that the European traditional materials sector is relatively efficient in its utilization of fossil fuels compared to its competitors, or that they face lower fossil fuel prices initially.

Figure 4 shows a weighted average of the price elasticities based on the production of the sectors in these regions. This provides the effect of the global price increase on the competitiveness of the industry sector in the region as a whole. In most regions, energy-intensive industries, like chemicals and traditional materials, which have larger price elasticities as shown in Fig. 3, make up a smaller part of the regional output than the other two industrial sectors. Thus, the weighted average for the industrial sector as a whole is smaller for all regions, and mostly for regions that are more diversified in terms of their industrial production.

The vulnerabilities (negative price elasticities) observed for the industry low- and medium-technology products from Fig. 3 mainly occur in the regions within the Netherlands, where the sector is highly dependent on gas. The price competitiveness effect of global coal price increases shows a typical regional pattern where the main internationally oriented manufacturing regions of Europe, such as Ober-Bayern, exhibit stronger positive effects. This is caused by negative efficiency effects in the rest of the world which is competing with these global production centers. We see that these international competition effects are less important for gas prices where efficiency differences between Europe and

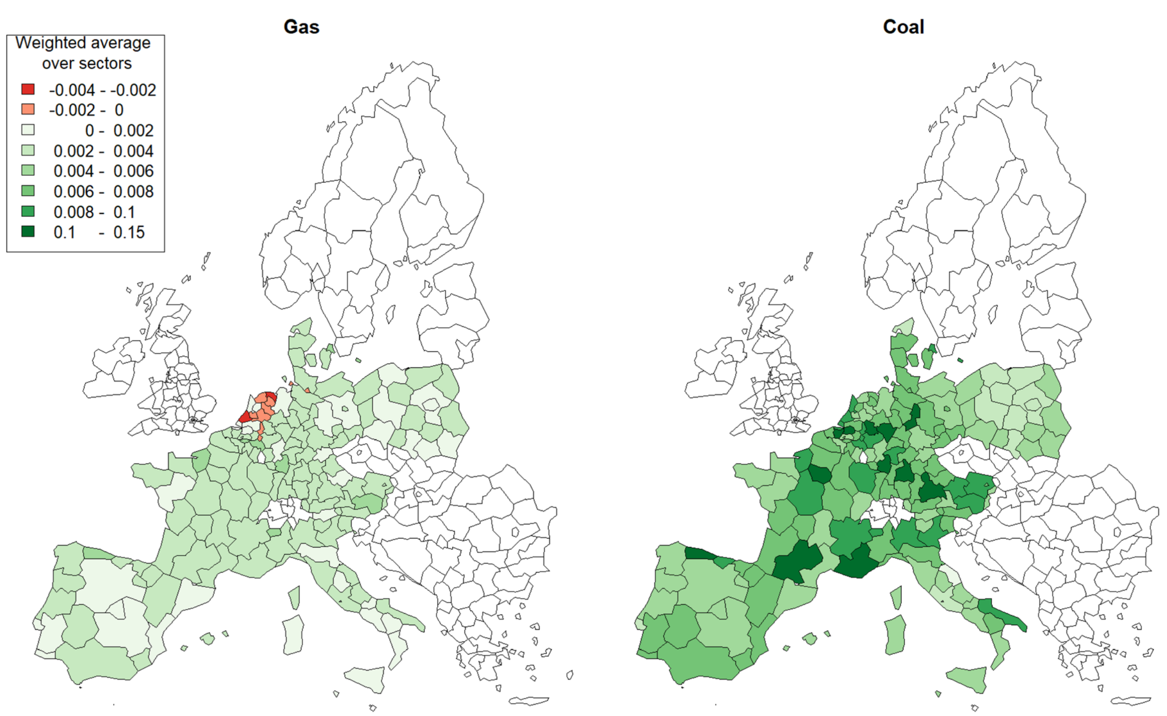

Fig. 4 The elasticity of a global gas (left) or coal (right) price on the competitiveness of the European NUTS 2 regions. Underlying data for this figure are available in Supplementary Information SI5. The weighted average is computed over the production of the sectors traditional materials, low- and medium-technology industry, high-technology industry and chemical industry within the region.

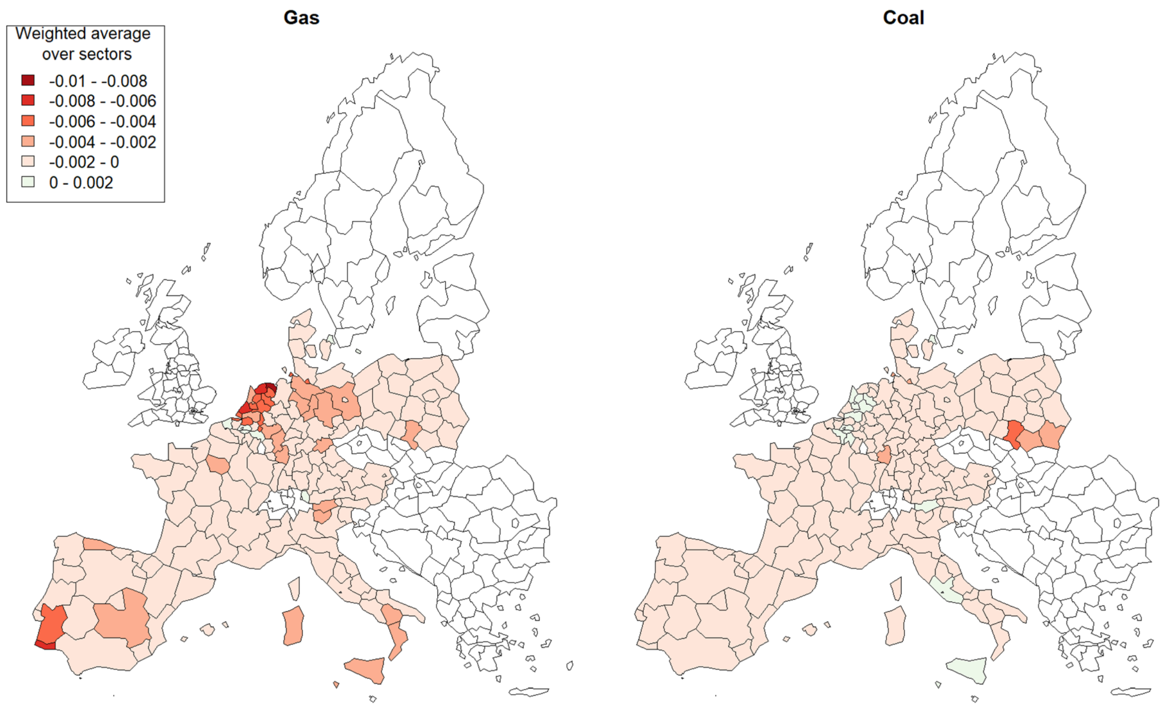

Fig. 5 The elasticity of a European user price of gas (left) or coal (right) on the competitiveness of European NUTS 2 regions. Underlying data for this figure are available in Supplementary Information SI5. The weighted average is computed over the production of the sectors traditional materials, low- and medium-technology industry, high-technology industry and chemical industry within the region.

the rest of the world are probably smaller, although it is noteworthy that within the Netherlands, the more internationally oriented regions of North-Holland and North-Brabant are less affected than the other regions.

5.2 European price shock

Next, we study the short-term effects on the regional cost competitiveness of an increase in European gas and coal user prices,[3] respectively, which could be seen as a European-wide tax on the use of these fossils. This modeling exercise reflects the case of uncertainties surrounding government policies, for example regarding suggested policies like the EU Green Deal or sudden changes in the price of EU ETS certificates, without substitution to suppliers outside of the EU or other adjustments in the use of products. Past fossil price spikes have been heterogeneous across regions resulting in possibly larger effects on competitiveness.

The results in terms of a weighted average per region are shown in Fig. 5, where the regions that lose most in terms of their industrial sector competitiveness are regions with either more heavy industry and less diversification, or that as a whole depend on gas or coal in the industrial production. Reasons for other negative effects of the European price increase could be that regions are less intertwined in GVCs and mostly focused on the European market for the inputs into production. In the Supplementary Information SI1, various maps are included that compare the global with the European price elasticity.

5.3 Increasing resilience by decarbonizing

The effect of decarbonization on regional resilience is studied by a change in the price elasticity, after a reduction of use of fossil energy in production. Specifically, we study a change in the use of gas and to focus on the low- and medium-technology industry sector, due to the large indirect fossil energy use and large share in regional output. However, the methodology can be applied to any proposed change in a product on the resilience of regional competitiveness. Two different scenarios are considered: (1) an efficiency increase (e.g., less gas is required to produce the same product), (2) an increase in electrification, where gas

[3] Included in Europe trade block group assumed here are the countries: Cyprus, Switzerland, Malta, Luxembourg, Latvia, Croatia, Lithuania, Norway, Slovakia, Slovenia, Sweden, Romania, Portugal, Poland, Italy, Ireland, Hungary, France, Finland, Spain, Greece, Estonia, Denmark, Czech Republic, Bulgaria, The Netherlands, Austria, The United Kingdom and Belgium.

is substituted for electricity. In what follows, we do not consider the technological feasibility of the efficiency or electr

ification in production, but take this as given, and we do not take into account the costs of realizing this change in the production process. We compute the relative percentage change of the global price elasticity such that the negative or positive value of the price elasticity is maintained and the value indicates the extent to which resilience has increased or decreased due to the decarbonization efforts.

5.3.1 Own production process

First, we consider an efficiency increase in the production process, such that the direct use of gas in the production of the sector which competitiveness we study decreases. Figure 6 shows the changes in the global price elasticity for gas in case the production process of the low- and medium-technology industry is made more efficient. The cost increase of the sector that is becoming more efficient is now reduced, which results in enhanced resilience. The size of the effects varies over the regions, which points to region and industry specific opportunities to reduce the vulnerability to gas price shocks, as seen in Fig. 4. Regions can turn the negative dependency into a positive opportunity to gain competitiveness if efficiency improvements are sufficiently large. For example, energy-intensive chemical industries could invest in the best available new technologies which competitors may not have yet, which can result in large gains in energy efficiency of the sector (Cefic, 2025; Crijns-Graus et al., 2020). This supports the discussion by Esty and Porter (1998), which states that adopting industrial ecology concepts within firms can increase their competitiveness. Additionally, our analysis shows that increased regional resilience can be an additional benefit of increasing resource productivity.

Electrification of the production process has much smaller effects on the resilience. However, as we do not take into account the associated costs, comparisons between the two scenarios should be interpreted with caution. Figure 6 shows the change in the global price elasticity for gas in case of electrification in the low- and medium-technology industry sector. Replacing raw natural gas for electricity, where the electricity generation makes use of natural gas as well, can result in only a small reduction in dependency on natural gas in the supply chain as a whole. The reason for this is that the price increase of gas is passed on in the electricity price and hence still affects the cost price of the industry under consideration. When electricity generation becomes less dependent on gas and more on renewables, this strategy may become more useful to enhance resilience.

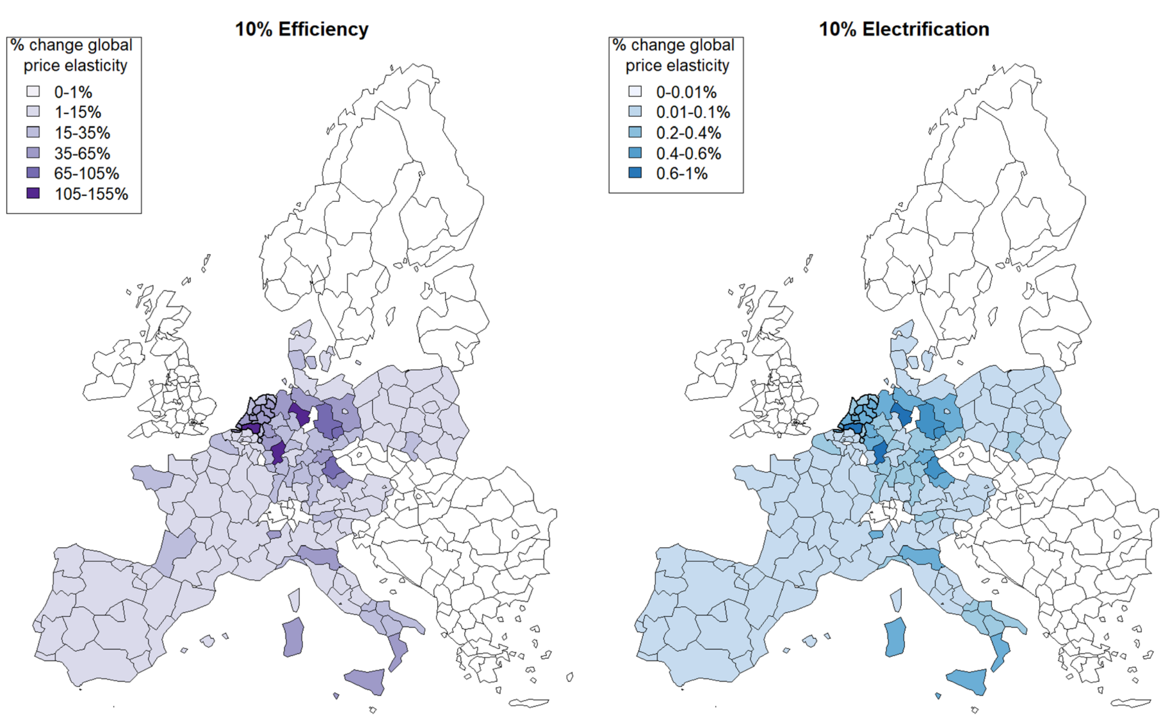

Fig. 6 The effects on resilience of efficiency (left) and of increased electrification of 10% in low- and medium-technology industry in the region. Underlying data for this figure are available in Supplementary Information SI5. The 10% reduction is 10% of the current use of gas for producing 1 euro of the product. Regions with a bold border have negative global price elasticities (e.g., are vulnerable in terms of the competitive position to global price shocks).

5.3.2 Upstream production process

Finally, we look at how efficiency improvements or electrification upstream in the production process can affect the resilience to gas price shocks in low- and medium-technology industries. Figure 7 shows the cases where efficiency increases in upstream sectors have a large effect on the resilience of the low- and medium-technology sector. The full results are included in Supplementary Information SI4.

Electricity is an important input into production, and thus an improvement in efficiency in electricity generation can reduce the cost increase of downstream industries significantly. However, we observe that the direction of the effect on resilience depends whether the European electricity generation becomes less gas-intensive, or whether this happens outside of Europe. In the first case, this benefits most European regions, as the change in the global price elasticity is on average positive. This presents competitive opportunities when efficiency increases take place. However, simultaneously, there is a threat of the electricity generation outside of Europe getting less gas-intensive: relatively, the European regions are then relying more on gas in electricity and therefore the vulnerability increases. A similar story holds for oil refinery and cokes production. Interestingly, for traditional materials, the European regions do also make use of inputs from outside of Europe, creating heterogeneous effects from a gas efficiency increase (see Fig. S8 in the Supplementary Information SI1). The results show that the positive effects on resilience for the low- and medium-technology industry sector occurs in regions that have large industrial sectors and that are possibly competing internationally, and thus using more inputs from outside of Europe. The smaller regions, with smaller industrial sectors, source more of their inputs within Europe and thus only experience negative effects from increased competition on the resilience.

Figure 7 also shows a specific regional effect in that, for both transport and private services, the own-region effect is often smaller than the own-country effect. This is due to the fact that both types of services are commonly not obtained from one's own region, but from specialized regions. Targeted policies on these sectors will therefore often have effects on downstream sectors in other regions of the same country.

Results of the electrification scenario for upstream production processes are plotted in Fig. 8, where the full results are included in the Supplementary Information SI4. Here, in terms of size, the resilience effect is a lot smaller than the case of efficiency. For most sectors within the country or in the same region the patterns and relative sizes are comparable to the efficiency scenario. However, the location-specific electrification effects on resilience in several upstream sectors is more proclaimed. Electrification in the production of private services, transport and traditional materials outside of the own country considered, results in larger negative effects on resilience than in the efficiency case. Competitors may be better able to reduce the dependency of gas by electrification, due to the gas dependency in electricity generation in most European regions. We refer to the Supplementary Information SI4 for a careful case by case analysis that is needed for determining region and industry specific effects, as not only efficiency but also competitors vary over the regions.

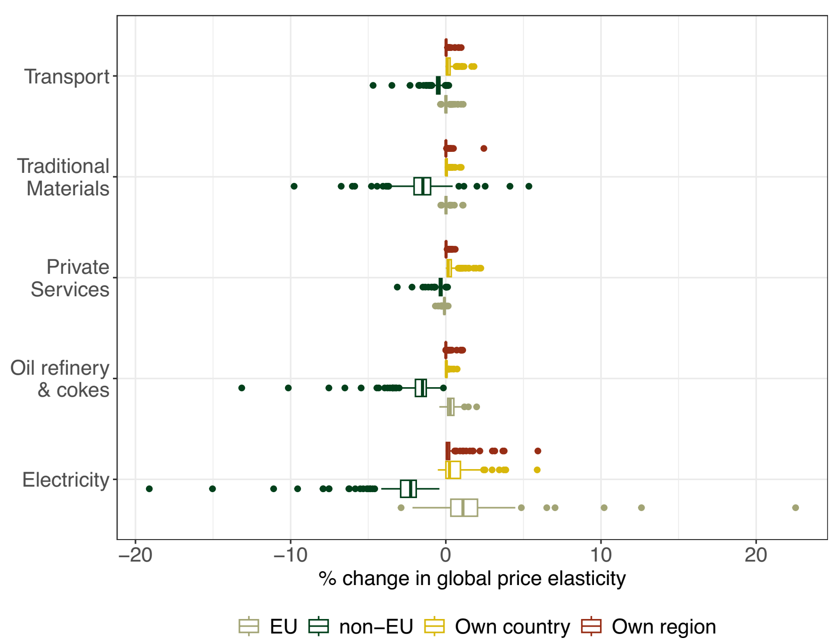

Fig. 7 The percentage change in the global price elasticity of competitiveness for the low- and medium technology industry from a 10% efficiency increase of gas in the upstream sectors presented on the y-axis and the source of the sector in the regions denoted by various colors. Underlying data for this figure are available in Supplementary Information SI5. The 10% reduction is 10% of the current use of gas for producing 1 Euro of the product in the production of the upstream sector in the indicated region (in Europe, outside of Europe, or within the country the respective region is in).

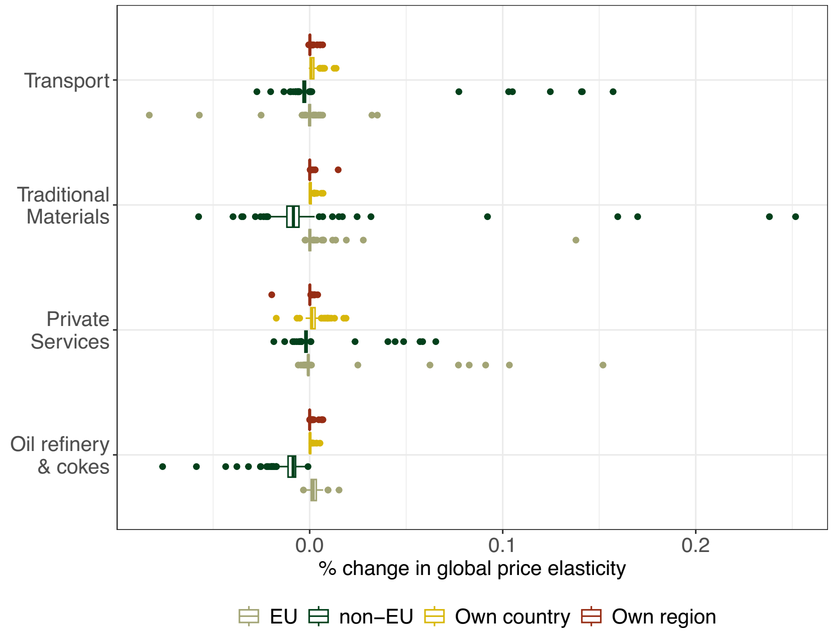

Fig. 8 The percentage change in the global price elasticity of competitiveness for the low- and medium technology industry from a 10% substitution of gas for electricity in the sectors presented on the y-axis. Underlying data for this figure are available in Supplementary Information SI5. The 10% electrification is 10% of the current use of gas for producing 1 euro of the produc t in the production of the upstream sector that is replaced with electricity, in the indicated region (in Europe, outside of Europe, or within the country the respective region is in).

6 Conclusion

Recent fluctuations in gas prices have made the dependency of economies on gas a reason for concern, where future price spikes may be unavoidable. Due to historical path-dependency, regional economies are to a varying degree specialized in energy-intensive industries. This implies large variation in dependency on fossil fuels depending on the structure of the region. Enhancing regional resilience to shocks is becoming an important policy objective to limit the potential damages from future shocks, whereas a shift towards a green economy and the consequent transformation of the energy system can help in increasing this resilience. In this paper, we analyzed the sensitivity of regional competitiveness to changes in fossil fuel costs and explored how decarbonization initiatives can enhance resilience.

We use a novel model for regional cost competition (RCC), combining an input–output price model and the revealed competition measure developed in Thissen et al. (2013). The model uniquely demonstrates the first-order impact of cost changes on industry competitiveness across locations, which serves as an indicator for potential effects on industry-specific regional development. Analyzing an industry's cost changes relative to its spatially differentiated competitors is preferable to examining isolated regional cost changes. This approach also avoids dependence on firms' adjustment mechanisms (i.e., regional and industry-specific substitution elasticities), which are necessary but generally unknown when simulating actual impacts using models like CGE models. It also offers the advantage of pinpointing actual reasons for structural effects, unlike reduced-form econometric estimations that only show final impacts.

The results show that regions in Europe are resilient to global coal price increases, suggesting a low dependency on coal, whereas they are more vulnerable to natural gas price shocks in terms of their competitive position. The size of the total effect on the regional industrial competitiveness in the case of a global gas price shock is negative in a few regions. Vulnerable regions either have a large dependency on gas in electricity generation and a historical pattern of gas intensity in production or specialized in energy-intensive industries. The traditional materials sector in the European regions is positively affected in terms of the competitive position by global fossil fuel price shocks. Thus, the sector is efficient in its use of fossil fuels compared to competitors, suggesting it is operating at the technological frontier.

In the case of a user end-price shock for gas and coal in Europe, competitiveness of the European regions decreases. The extent to which a region is affected depends on the location of the competitors and which inputs it is using in production. However, as the global price results show, many regions are operating at the technological frontier and are efficient in their use of fossil fuels. A loss in competitiveness of these regions and a reallocation of production to locations where the technology is less efficient, could thus result in less efficient use of fossils. Improvements in efficiency in the use of gas and electrification in the production process can increase resilience of the region, as cost increases are suppressed by using less gas. Thus, an additional benefit from increased energy efficiency is that this also increases resilience to future shocks. Electrification, however, has much smaller effects on the resilience. At the same time, the results show that if competitors become more efficient in the use of gas, this decreases resilience. It is therefore important to not stay behind in such improvements to limit the effects of future gas price shocks.

Analyzing efficiency and electrification in upstream sectors provides insights in the dependencies of regions on the value chain. Increasing the efficiency of the use of gas in electricity generation and oil refinery and cokes production within the same region, country or in Europe, can increase resilience for the low- and medium-tech industry in most European regions. Thus, international cooperation may be warranted to reduce the reliance on natural gas which may affect the resilience of downstream sectors positively. However, if such improvements occur outside of Europe, where these inputs are mostly used by competitors of the European regions, resilience decreases. For electrification, the size of the effect on resilience is smaller, but patterns remain the same. However, electrification can result in larger benefits for competitors, due to the gas intensity in European electricity generation.

Thus, the contribution of this paper is twofold. First, we provided a new model and methodology to study price shocks and changes in the inputs used in production in an input–output framework which can be applied to a range of other research questions. Second, we provided insight into the intricate relationships between energy price fluctuations and competitive dynamics at the regional and industry levels. This analysis allowed us to identify the specific threats and opportunities that arise from these changes, taking into account the interplay of technological advancements, dependency and shifts in energy types.

Some limitations remain and are left for future research to improve upon. For example, we do not take into account the dynamics of the transformation of the production process towards a more decarbonized process and only provide a comparative static analysis. There are limitations and constraints as to in which sectors these adjustments can be done. In a dynamic approach, a first-mover advantage which provides a comparative advantage in the long-run can be better captured. In addition, when time series data would be available, an extended analysis could provide insights in how this resilience changes over time. More consistent time series, regional-level data on energy use by type and interregional trade flows could therefore considerably improve the analysis and its reliability.

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Data availability As classified national supply and use tables from Eurostat are used for the creation of the regional Supply and Use tables, the data used for this study are available from the corresponding author upon reasonable request for research purposes.

Declarations

Conflict of interest The authors declare no conflict of interest.

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