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INPUT-OUTPUT MODELING AMIDST CRISIS: TRACING NATURAL GAS PATHWAYS IN THE CZECH REPUBLIC DURING THE WAR-INDUCED ENERGY TURMOIL

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Input-Output Modeling Amidst Crisis: Tracing Natural Gas Pathways in the Czech Republic During the War-Induced Energy Turmoil

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Abstract:
The current geopolitical landscape, exemplified by the Russian invasion of Ukraine, has heightened concerns about energy security. This study delves into the nexus of energy security and natural gas utilization in the Czech Republic, offering a thorough analysis amid these turbulent times. Despite the fact that the environment/energy-extended input-output models have been significantly improved, they still fail to fully capture a sector's role in an economic system characterized as a network of sectors as they primarily analyze sectors as both ends of the supply chain, ignoring a significant role of transmission sectors. We overcome this gap by applying a multidimensional approach to scrutinize the energy supply chain in order to assess the repercussions of heightened natural gas prices post-Russian invasion. Specifically, we combine domestic energy input-output demand and price models to assess the economic impacts under constrained alternative energy scenarios, particularly relevant given the challenges of replacing Russian gas. Additionally, leveraging network analysis techniques —node and edge betweenness centrality—and the hypothetical extraction method are used to identify critically important structural elements within the country's natural gas consumption chain. While the former pinpoints vital transmission sectors based on gas flow, the latter gauges sectoral significance by simulating complete disconnections, without being influenced by the number of times the sector appears in the supply chain path. Last, we develop a complete map of the embodied energy flows. Structural Path Analysis traces intermediate product flows, enabling the quantification of embodied energy across the supply chain and its representation as a tree-like structure. Our findings

reveal significant implications of natural gas price fluctuations on key manufacturing industries, notably those engaged in international trade which are vulnerable to energy supply and price disruptions. We emphasize the critical role of sectors providing essential household goods and services, like energy, food, and transportation. Strategic interventions may be necessary to safeguard domestic demand and the competitive edge of vital sectors like automotive. As energy security remains a dynamic and evolving challenge, our research contributes significantly to the ongoing discourse on energy resilience, particularly for countries dependent on energy imports. Despite the fact our study is applied to the energy field, this framework is useful to analyze the footprint of any inputs, including usage of critical materials, environmental inputs, or emissions, which face similar complexities.

JEL: C67, Q43, H56
Keywords: Energy-Extended Input-Output Aanalysis; Energy Supply Chain; Natural Gas Footprint; Embodied Energy; Betwenness Centrality; Hypothetical Extraction; Structural Path Analysis; Input-Output Price Model

1 Introduction

The recent geopolitical developments, notably the ongoing Russian invasion of Ukraine, have redefined the landscape of global energy security, with a particular impact on European economies. The concerns over energy security have resurfaced, underscoring the vulnerabilities associated with the reliance on Russian energy supplies within the European Union. This dynamic is especially pertinent for the Czech Republic, offering a compelling case study due to its historical dependence on Russian gas. Against the backdrop of these geopolitical shifts, the concept of energy security has assumed renewed significance, transcending mere economic considerations. It now encompasses factors crucial for social stability, national defense security, and geopolitical relationships. As the European Union endeavors to diminish its reliance on Russian fossil fuels while concurrently pursuing ambitious emission reduction targets, energy security has become a focal point of policy deliberations.

This research endeavors to navigate the intricate relationship between energy security and the utilization of natural gas within the Czech Republic. Our primary objective is to comprehensively examine the country's energy supply chain, unraveling the complexities of natural gas usage across diverse sectors. Employing an energy input-output model, we establish a connection between the country's natural gas resources and the socioeconomic fabric with economic data from Supply and Use tables, physical accounts of natural gas use by Czech industries from the Czech Statistical Office, average natural gas prices for industries in 2019 from Eurostat, and prices of natural gas in the Title Transfer Facility (TTF) virtual trading port for natural gas in the Netherlands, which is the main reference virtual market for gas trading in Europe, to calculate the increase in natural gas prices following the start of the Russian invasion to assess the potential economic consequences of abrupt changes in natural gas prices when increased gas prices are fully passed through to the consumer with the use of an input-output price model. The substitution of Russian gas is likely to be a challenge in the short-to-medium-run for Czech industries. As such, a sudden shutdown of Russian natural gas imports will have to be compensated through alternative energy sources from other countries, as well as domestic ones. Furthermore, the switch from relatively cheap Russian gas prices to world market spot prices would imply a substantial increase in the gas price. Although the capability for substitution from different industries and households will play a major role in the final effects of a potential embargo on Russian gas, and thus, IO models' zero elasticity of substitution can only be interpreted as energy being an extreme bottleneck in production (Bachmann et al., 2022), their relative simplicity, instinctive nature of capturing inter-industry linkages, total dependence of the Czech Republic on natural gas imports, and slow industrial processes substitution, make the model a powerful tool for analyzing the current situation.

The distinctive value of our approach lies in its multi-dimensional perspective, encompassing analyses of consumption, production, and network interactions. By doing so, we aim to pinpoint critical sectors and transactions, shedding light on the potential sources of ripple effects that may emerge from energy supply disruptions. For these, beyond the traditional production and consumption-based attributions, we employ network analysis techniques (hypothetical extraction and betweenness centrality) to identify structurally important elements in the country's natural gas consumption network. Within IO techniques, node (or vertex) betweenness centrality, first introduced by Liang, Qu, and Xu (2016), is a measure of the *betweenness* of a specific sector that considers the production ties in supply chains. This metric allows for the identification of critical *transmission sectors*, defined as sectors that exist between two ends of a particular supply chain path and that are responsible for the transmission of particularly large amounts of embodied natural gas compared to other sectors. On the other hand, the hypothetical extraction method provides a comprehensive measure of a sector i's importance to the economy, by reflecting the removal of all forward, backward, and internal connections (Miller and Lahr, 2001). As its name suggests, this measure is computed by simulating the "complete extraction" of sector i from its economy. The higher a sector's extraction effect is, the more likely it is for that sector to be critical to the economy that is being studied. We finish by employing Structural Path Analysis (SPA) to map out the intricate energy pathways embedded within the domestic supply chain. Indeed, SPA, in the context of input-output modeling, allows us to trace, through layers of the production system, purchases of intermediate products as they are instigated by final demand purchases of final products (Zhang et al., 2017). By linking SPA with energy data, we can quantify the embodied energy at the end of each supply chain. The embodied energy, detailed in a final consumption attribution, is further remodeled into a tree-like structure of energy consumption occurring in different economic sectors at different stages in the production system. Our analysis reveals the significant impact of natural gas price fluctuations on several key manufacturing industries in the Czech Republic, particularly those producing for international markets such as mineral, chemical, automotive, metalwork, machinery, paper, and rubber and plastic industries. Additionally, we highlight the critical role of sectors providing essential goods and services, including energy, food, and transportation, in household natural gas consumption, underscoring the need for strategic interventions in case of severe disruptions.

2 Methodology and data

Among the large literature evaluating embodied energy in the context of international trade, a few have focused their attention on energy security (Shepard and Pratson, 2020). Within these studies, empirical methods grounded in economics and developed in industrial ecology have emerged as important tools for estimating embodied energy. Environmentally-Extended Input-Output models have routinely been used to calculate sector-specific measures of direct and embodied energy requirements and their related emissions. A significant share of this literature has focused on the identification of key sectors from a production and consumption-based perspective (Weinzettel, Havránek, and Ščasný, 2012). While these measures are important in identifying important sectors relative to particular agents given their budget expenditures (like households or the government), they usually fail to fully capture a sector's role in an economic system characterized as a network of sectors as they only analyze sectors at both ends of the supply chain (Feng et al., 2019). As a result, transmission sectors in the intermediate process of the supply chain that may play a significant role are usually ignored (Liang, Qu, and Xu, 2016). Within IO techniques, the hypothetical extraction method has been widely used to fully capture a sector's relevance by simulating the complete elimination of a sector's external linkages (purchases and sales) to the economy. The resulting reduction in output and energy use is used as a way of measuring the importantness of the sector (Guerra and Sancho, 2010). While the "extraction effect" of a sector captures the combined influence of backward and forward linkages (Miller and Lahr, 2001), it is not influenced by the number of times the sector appears in the supply chain path. As a result, industries with high consumption- or production-based accounts tend to be at the top of the list of the sectors identified by the HP method (Tokito, Nagashima, and Hanaka, 2024). Betweenness-based accounting, on the other hand, is a key sector indicator that weights emissions based on the sector's frequency in supply chain paths. While it does not determine a "real" account of the emissions for intermediate goods industries (as the weighting of emissions leads to an overestimation of the sector's emissions), it allows for the identification of transmission sectors (Tokito, Kagawa, and Hanaka, 2022). To enable an exhaustive depiction of the connections between final production and consumption attributions, and for the classification of sectors based on the location in the supply chain of their overall emissions, we develop a complete map of the flows of embodied energy through the production system building on structural path analysis (Skelton et al., 2011). Lastly, we employ an input-output price model to examine how the experienced rise in natural gas prices may have reverberated throughout the economy in the short-to-medium term.

2.1 Input-Output model

For our study, two main data sets are used: Supply and Use Tables (SUT) in basic prices for the year 2019 from Eurostat, and physical accounts of natural gas use by Czech industries for 2019 from the Czech Statistical Office (CZSO), used to create direct natural gas intensities. The year 2019 is chosen as the basis for our study according to the following criteria: First, the theme of this paper demands that we use the most up-to-date data available while making sure that all the different data sets employed in this study can be combined consistently. Second, we need to consider the possibility that the COVID-19 pandemic, as well as all of the measures adopted by governments, might have significantly affected agents' behavior (Chronopoulos, Lukas, and Wilson, 2020).

Since the main focus of this study is on the sectoral allocation of natural gas in a domestic supply chain, We construct a domestic input-output model in accordance with Eurostat's guidelines for the fixed product sales structure (Model D) transformation(Eurostat, 2008), thereby obtaining a domestic input-output model with 64 industries. Following Eurostat's manual (Eurostat, 2008) and keeping their notation, we define our domestic technical coefficients matrix under the fixed-product sales assumption as follows:

$$A^d = \left(\left(V \cdot \widehat{q-m}^{-1}\right) \cdot U\right) \cdot \hat{g}^{-1}, \tag{1}$$

where $(V \cdot \widehat{q-m}^{-1})$ is the transformation matrix, which under model D reflects the inverse of the product-mix of an industry, V is the industries$\times$products Make matrix from the supply table, $(q-m)$ is the product output vector from domestic production, and g is the industry output vector. As is standard in Input-Output (IO) literature, a hat over a vector refers to the diagonal matrix version of that vector. The derived transformation matrix is also used to convert final demands from the SUT. Throughout the paper, we use "embodied energy in final demand" and "energy use" interchangeably. Whenever "direct energy" use is referred to, it is written explicitly.

2.2 Key sector analysis

Production-based and consumption-based flows accounting for natural gas

As in (Zhang et al., 2017), the basic row balance for the Czech Republic's domestic supply chain is expressed by the following equations:

$$g = Z^d + y^d = Z^d + f^d + f^e = A^d g + f^d + f^e. \tag{2}$$

Rearranging equation (2) leads to the following basic equations:

$$g = (I - A^d)^{-1}(f^d + f^e) = L^d(f^d + f^e). \tag{3}$$

With $Z^d = A^d \cdot \hat{g}$ being the (industries) × (industries) domestic transactions matrix, y^d the vector of final demand excluding imports for final consumption, f^d the vector of final domestic consumption, f^e the vector of domestic exports and L^d the domestic Leontief inverse matrix, composed of l_{ij}^d elements which track the overall direct and indirect input along the domestic supply chain from sector i generating a unit of output of sector j. We link the Leontief inverse to our direct natural gas intensities vector (ε^d) created from the energy consumption accounts, published by the CZSO, and derive the "Type I embodied energy uses" vector as presented in (Skelton et al., 2011):

$$m = \varepsilon^d (I - A^d)^{-1} = \varepsilon^d L^d, \tag{4}$$

composed of m_j elements, which measure used energy from all sectors that has become embodied in one unit of output from sector j. As such, the measure includes direct energy used in the production of a unit output of the j-th sector and the indirect energy consumed due to inter-sector requirements and feedback effects in the supply chain. The contributions of final consumption attributions of natural gas usage by sector can thus be computed as:

$$P^{\text{final}} = m(f^d + f^e). \tag{5}$$

We further define the emissions multiplier matrix M as:

$$M = \hat{\varepsilon}(I - A)^{-1} = \hat{\varepsilon} L, \tag{6}$$

that we employ to characterize the "Type II embodied energy use" as any $1 \times N$ row vector $M_{p:}$ which measures used energy from sector p which will then become embodied in a unit output from each sector. The consumption-based accounting of natural gas use by industry can be determined as:

$$Q^{\text{final}} = M(f^d + f^e). \tag{7}$$

Node betweenness centrality

The *betweenness* of a sector can be defined as the amount of energy consumed by all supply chain paths (which refers to the amount of energy consumed by a starting sector and that is step-by-step driven by the end sector producing final products for final uses) passing through this sector. Formally, we define the vertex betweenness of a sector i as:

$$b_i = \sum_{s=1}^{n}\sum_{t=1}^{n}\sum_{r=1}^{\infty}\sum_{1\le k_1,k_2,\cdots,k_r\le n}(q_r^i \times \varepsilon_s a_{sk_1}a_{k_1k_2}\cdots a_{k_rt}f_t), \tag{8}$$

where s and t are the start and end sectors of a supply chain path, respectively, and passing through r sectors. q_r^i refers to the number of times sector i appears in that particular supply chain path passing through r sectors. $\varepsilon_s a_{sk_1}a_{k_1k_2}...a_{k_rt}f_t$ denotes the embodied energy of the supply chain path. Intuitively, as the number of times sector i appears in a particular supply chain path (and thus its role as a transmission sector) increases, its betweenness value does so as well.

In this study, we employ the modified version of this metric developed in (Tokito, Kagawa, and Hanaka, 2022), which allows for the inclusion of direct energy use from a sector i, as well as the energy use from the first supplier i triggered by the final demand of a sector j. The betweenness centrality of a sector i is thus calculated as follows:

$$\begin{aligned} b_i &= \sum_{l_1=0}^{\infty}\sum_{l_2=0}^{\infty}(\varepsilon A^{l_1}J_{ii}A^{l_2}f) \\ &= \varepsilon J_{ii}f + \varepsilon AJ_{ii}f + \varepsilon AAJ_{ii}f + \cdots + \varepsilon J_{ii}Af + \varepsilon J_{ii}AAf + \cdots \\ &= \varepsilon LJ_{ii}Lf, \end{aligned} \tag{9}$$

where J_{uv} is matrix whose (u,v)-th element is 1 and other elements are zero.

Edge betweenness centrality

In (Hanaka et al., 2017), the authors develop another centrality index than the one originally proposed by Liang, Qu, and Xu (2016): Edge betweenness centrality, which indicates how much *embodied* environmental emissions of product flow through the transaction and to what extent sectors are connecting through a specific edge in terms of supply-chain complexity. Edge betweenness centrality can be a useful indicator to express the importance (or criticality) of a particular transaction in the entire supply-chain network. The IO node betweenness centrality b_{ij} of a specific transaction from sector i to sector j $(i \neq j)$ is defined as:

$$b_{ij} = a_{ij}\varepsilon LJ_{ij}Lf. \tag{10}$$

Hypothetical extraction method

We denote the extraction effect of sector i as:

$$\begin{aligned} h^i &= m - \bar{m}^i \\ &= \varepsilon Lf - \varepsilon\bar{L}^i f - \varepsilon_i f_i. \end{aligned} \tag{11}$$

Although betweenness centrality and hypothetical extraction metrics both belong to the category of accounting methods focusing particularly on *intermediate industries*, the value of betweenness centrality of a sector is always higher than the value of the extraction effect. This is due to the fact that for the betweenness centrality metric of a sector, its value is weighted according to the number of times that sector appears in the supply chain paths. This means that the difference between the hypothetical extraction effect and the betweenness centrality of a sector is explained by the relative importance of that sector in the whole supply chain. As such, we can derive the extraction impact of sector i from its betweenness centrality as proven by Tokito, Kagawa, and Hanaka (2022):

$$\frac{b_i}{(1+t_{ii})} = h^i, \tag{12}$$

where t_{ii} is the i-th diagonal element of the indirect input requirement matrix $T = AL$ and h^i is the hypothetical extraction effect of sector i, which can be interpreted as the total gas use associated with supply chain paths passing through sector i.

Similarly, the hypothetical extraction effect of an inter-industry transaction x_{ij} from sector i to sector j can be computed as:

$$\begin{aligned} h^{ij} &= m - \bar{m}^{ij} \\ &= \varepsilon L f - \varepsilon \bar{L}^{ij} f \\ &= e(L - \bar{L}^{ij}) f, \end{aligned} \tag{13}$$

where $\bar{L}^{ij}$ is the *extracted* Leontief inverse calculated by using the *extracted* input coefficient $\bar{A}^{ij}$. As for its whole sector counterpart, the extraction effect of the transaction from sector i to sector j represents the total emissions associated with the supply chain paths passing through the transaction from sector i to j.

2.3 Mapping of embodied energy flows

For our study, we follow (Skelton et al., 2011), who propose an approach for mapping flows of embodied emissions through the Leontief production system and use it to map not embodied emissions, but embodied energy use. The central difference between their approach and a traditional SPA is that instead of just extracting and ranking individual supply chains according to the consumption of energy occurring at the end of each chain, we consider the energy embodied in the flows of intermediate products linking different economic sectors along supply chains, without ignoring supply chains that would be too small to be included in a traditional SPA, but that when added together represent a considerable share of the total energy use. In order to limit the number of letters, we drop the superscript d denoting domestic accounts for the remainder of the paper, as this study is solely focusing on the Czech domestic supply chain.

Mathematically speaking, the SPA for the embodied energy use paths is performed by expanding the Leontief Inverse by a Taylor series approximation (Zhang et al., 2017) as:

$$Ex = \varepsilon(I-A)^{-1} f = \varepsilon(I + A + A^2 + A^3 + \cdots) f, \tag{14}$$

where each element in the expansion denotes a different Production Layer (PL):

$$\mathrm{PL}^t = (A)^t \quad \text{and} \quad \mathrm{PL}^{t+1} = \mathrm{PL}^t A.$$

As such, each additional production layer (PL^{t+1}) can be interpreted as the production of intermediate products used as inputs in the previous (PL^t) layer. For example, the assembly of a chair, sold to a final consumer occurs at PL^0, while the production of the different elements that form the chair like the plastic handles, the metallic stem, and the cotton seat pad all occur at PL^1, all of which require inputs from PL^2 and so on.

From equations (14) and (6), we can derive all the necessary sets of equations needed to map embodied energy usage throughout the entire domestic production system. An in-depth description of the procedure can be found in (Skelton et al., 2011).

2.4 Input-Output price model

Following (Oosterhaven, 2019), the basic input-output price model can be written as:

$$p' = p'A + p'_v C \tag{15}$$
$$= p'_v C(I - A)^{-1} \tag{16}$$
$$= p'_v CL, \tag{17}$$

with $C = V\hat{x}^{-1}$, and V referring to primary inputs, A the technical-coefficients matrix, x the vector of total output and p'_v the exogenous price increase for natural gas.

As the current price for all products is equal to 1, the outcome of this exercise is relative prices. For example, a result of 1.04 for the new price of good j, would indicate that the new price is 4% higher than the current one. The exogenous price increase for natural gas paid by industrial sectors is calculated by multiplying by the factor of increased price for natural gas in the TTF training point by each sector's monetary value of natural gas inputs required for production derived by multiplying the physical quantities recorded for each sector by the CZSO and prices paid by industry from Eurostat.

3 Results

3.1 Consumption-based and production-based footprint

Natural gas accounted for 17% of total energy supply in 2019, and is expected to remain an important fuel towards 2040 in the context of the country's energy transition. Nevertheless, domestic production accounted only for about 1.5% of domestic demand, meaning that virtually the entirety of this fuel's domestic consumption has been satisfied by imports. Historically, since the beginning of the century, the country has had two main suppliers: Norway, and the Russian Federation, with the former's share accounting for less than 0.5% of total imports from 2015 to 2020 (IEA, 2022).

Figure 1 shows the sectoral natural gas use from a production-based and a consumption-based perspective, with the difference between the two originating from the embodied flows of natural gas along the supply chain. From both, a consumption-based perspective, and a production-based perspective, the top 5 sectors with the highest embodied emissions are the sectors devoted to the production of electricity (S.24), mineral products (S.14), chemicals (S.11), manufactured food products (S.5), metals (S.15), and motor vehicles (S.20). Notably, the difference in embodied emissions from both perspectives between the highest-ranked and the second-highest one is particularly high.

While the final production attribution of natural gas usage by the electricity sector represents around 30% of the total use of natural gas, the production attribution of mineral products is only 12%. Similarly, from a consumption-based perspective, mineral products and electricity generation represent 16.5% and 8% of total embodied gas use in final consumption, respectively.

Figure 2 shows the final consumption attributions of natural gas use broken down by final demand category. A considerable amount of those sectors' embodied energy use is generated by households' final consumption of electricity (S.24) and manufactured food products (S.5). In contrast, embodied gas use in the final demand of mineral, metal, and chemical products originates mostly from exports, with GFCF, Government expenditures, and NGO's final consumption being relatively unimportant in terms of embodied natural gas in their final consumption.

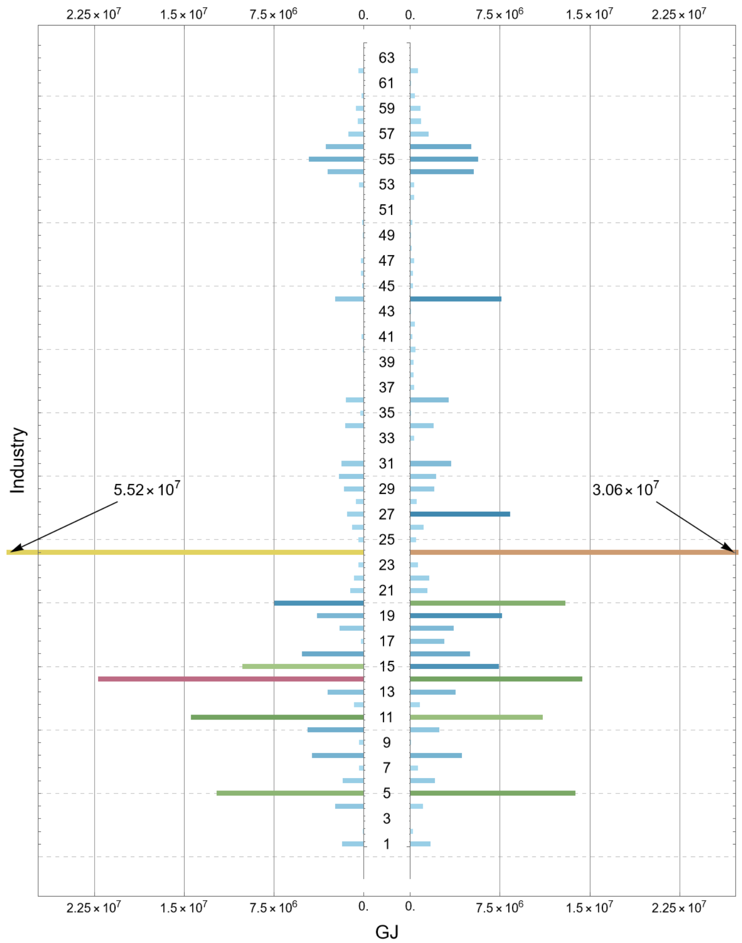

Figure 1: Production-based (left) and consumption-based (right) attributions by sector.

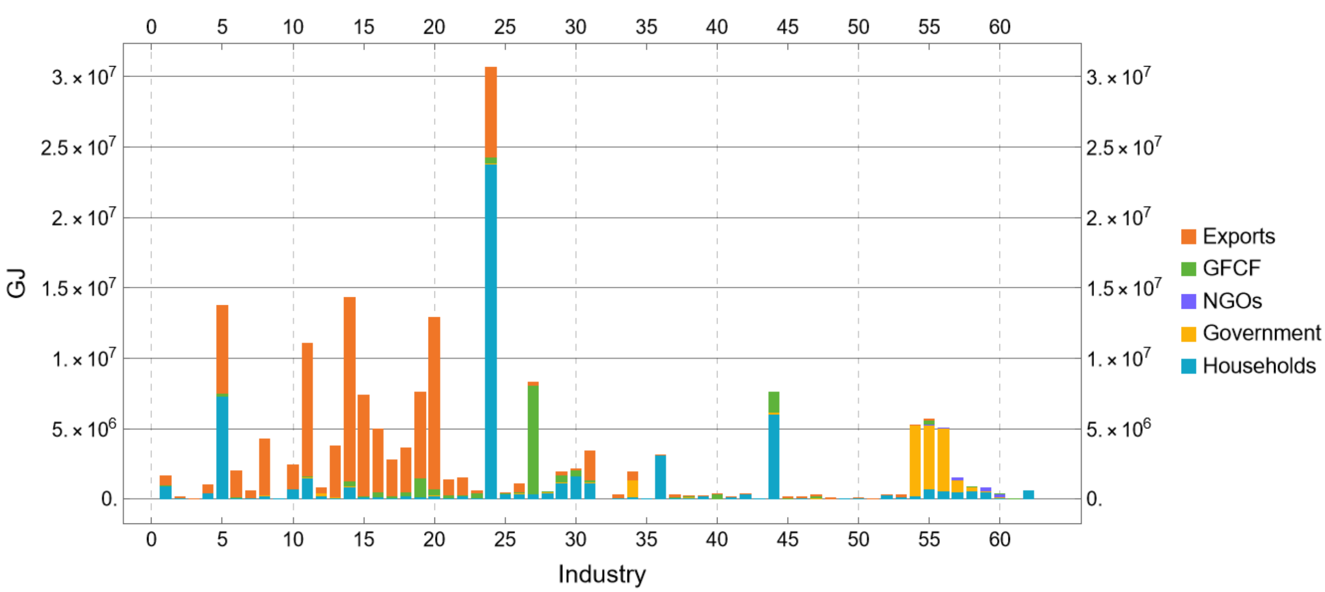

Figure 2: Consumption attributions by final demand category.

From a consumption-based perspective, exports are responsible for half of the total natural gas use in the Czech supply chain. Final consumption by households are responsible for about 30% while both investment and government expenditures are each responsible for about 10%. Embodied natural gas use in NGOs' final consumption remains by far the lowest of them all, representing less than 1% of total gas use (1.85×10^8 GJ). Table 1 reports the top 10 sectors in terms of final consumption attributions of natural gas use for each final demand category.

Top 10 sectors by final consumption attribution for each final demand category

	Households		Government		NGOs		Investment		Exports	
Rank	GJ	Sector	GJ	Sector	GJ	Sector	GJ	Sector	GJ	Sector
1	2.37802×10^7	24	5.01404×10^6	54	262366.	60	7.73551×10^6	27	1.30613×10^7	14
2	7.23362×10^6	5	4.51727×10^6	55	236393.	59	1.43302×10^6	44	1.22098×10^7	20
3	5.99674×10^6	44	4.44973×10^6	56	219411.	57	1.37371×10^6	19	9.43955×10^6	11
4	3.06355×10^6	36	1.18359×10^6	34	112548.	55	500878.	29	7.19958×10^6	15
5	1.58991×10^6	30	861117.	57	18528.1	56	486457.	20	6.37251×10^6	24
6	1.50225×10^6	11	260604.	58	12217.4	58	439694.	24	6.28977×10^6	5
7	1.13687×10^6	29	205695.	12	6663.8	54	416309.	14	6.16886×10^6	19
8	1.09462×10^6	31	152241.	44	5853.41	44	403227.	30	4.50309×10^6	16
9	870766.	1	121791.	31	5591.3	5	387197.	16	4.03649×10^6	8
10	846243.	14	120020.	59	4246.28	24	356464.	23	3.65622×10^6	13

Table 1: Top 10 sectors by final consumption attribution for each final demand category.

For the first 5 sectors with the highest levels of embodied gas use on final consumption, households, and exports are the main driving forces. Households are responsible for close to 80% of embodied gas use by the electricity sector (S.24), while exports represent about 20%. Investment, government expenditures, and NGO spending have negligible contributions, each of them contributing around 1% of the entire sector's natural gas footprint. The gas footprint of final demand for the output of sectors 14, 11, and 15 is largely generated by exports, representing at least 85% of the total gas use embodied in those sectors' total aggregated final demand.

3.2 Hypothetical extraction of a sector

We employ the hypothetical extraction method to further identify critical sectors that production and consumption-based accounting methods may overlook. The reason for this is that hypothetical extraction takes into account a sector's role as an intermediate industry, connecting producers and final consumers in the supply chain. Figure 3 charts the calculated extraction effect for each sector in our model. We further report the first 10 sectors with the highest extraction effects in Table 2. The magnitude of each sector's effect encapsulates the linkage between sectors and gas use of supply chain paths passing through that sector. Whereas the hypothetical extraction method identifies the metalworks sector (S.16) as one of the 10 most important sectors in terms of embodied natural gas use, consumption-based accounting fails to do so. The disparity between the two methods stems from the fact that the sector is primarily important from an "emitters" perspective. Indeed, metalworks is the seventh most important sector from a production-based perspective.

Similarly, the sector responsible for the production of machinery and equipment (S.19) is both identified by the hypothetical extraction method and consumption-based accounting as among the 10 most important sectors in terms of embodied gas use due to its relative importance as a

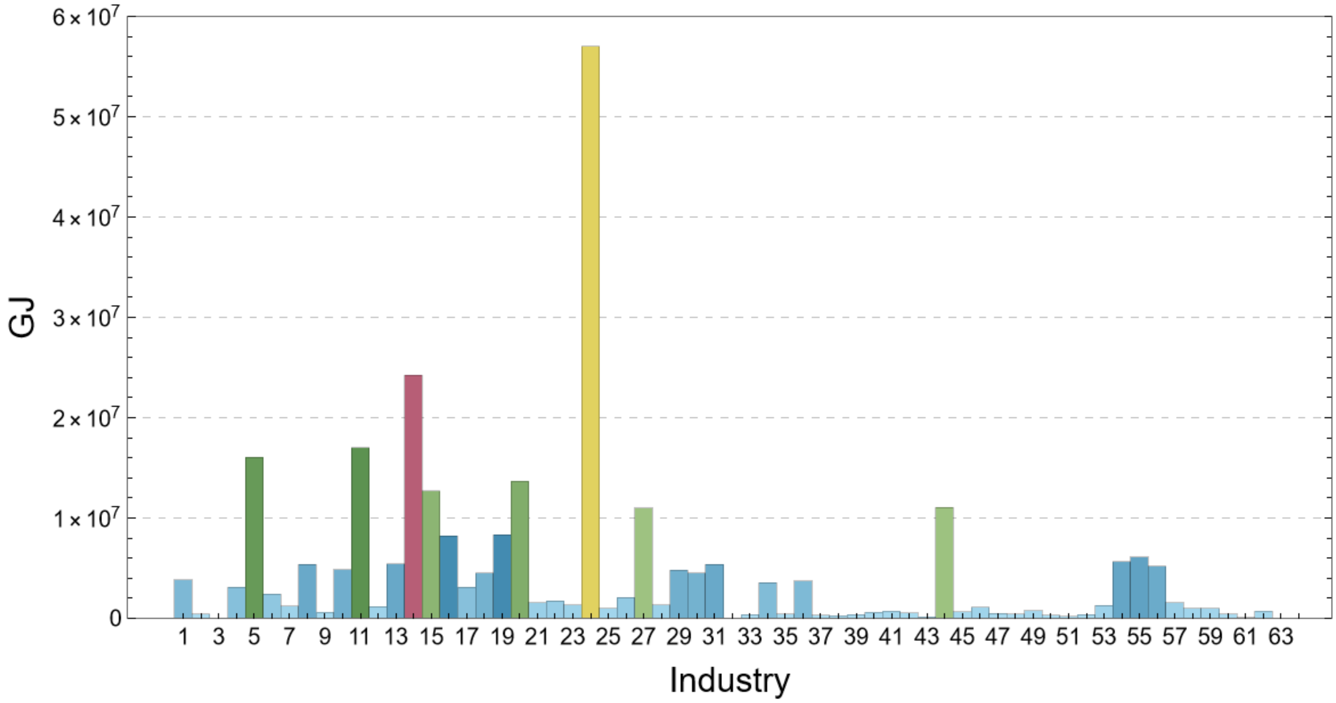

Figure 3: Extraction effect by sector.

"consumer" sector in the domestic supply chain. The extraction method, however, further allows the identification of critical sectors that may go unnoticed by both the consumption-based and the production-based accounting methods. Wholesale trade (S.29) is considered the $18th$ most important sector from an extraction effect perspective but fails to appear in the top 20 of the other two methods. This is due to the relevance of the sector as an intermediate sector, connecting production and consumption-relevant sectors. The amount of gas used associated with the sector's extraction effect is 2.9 and 2.4 times the amount associated with its production and consumption-based metrics, respectively, highlighting the relevance of considering intermediate transactions when determining critical sectors.

Top 10 sectors for higher extraction effects		
Rank	GJ	Sector
1	5.70087×10^7	24. Electricity, gas, steam and air conditioning supply
2	2.42343×10^7	14. Manufacture of other non - metallic mineral products
3	1.70454×10^7	11. Manufacture of chemicals and chemical products
4	1.6053×10^7	5. Manufacture of food products; beverages and tobacco products
5	1.36548×10^7	20. Manufacture of motor vehicles, trailers and semi - trailers
6	1.26796×10^7	15. Manufacture of basic metals
7	1.1042×10^7	44. Real estate activities including imputed rents
8	1.10153×10^7	27. Construction
9	8.32181×10^6	19. Manufacture of machinery and equipment
10	8.19839×10^6	16. Manufacture of fabricated metal products, except machinery and equip.

Table 2: Top 10 sectors for higher extraction effects.

3.3 Node betweenness centrality

Although the hypothetical extraction metric captures embodied natural gas use throughout a sector in supply chains, it fails to inform the analyst of how this natural gas gets captured in terms of the number of times the sector appears in the supply chain, meaning that two different sectors may score the same extraction effect, with one appearing a single time in the supply chain and the other one appearing many times. As such, we employ the node betweenness centrality metric to distinguish critical sectors repeatedly appearing in the domestic Czech supply chain. Figure 4 shows the betweenness centralities calculated for each sector using equation (8).

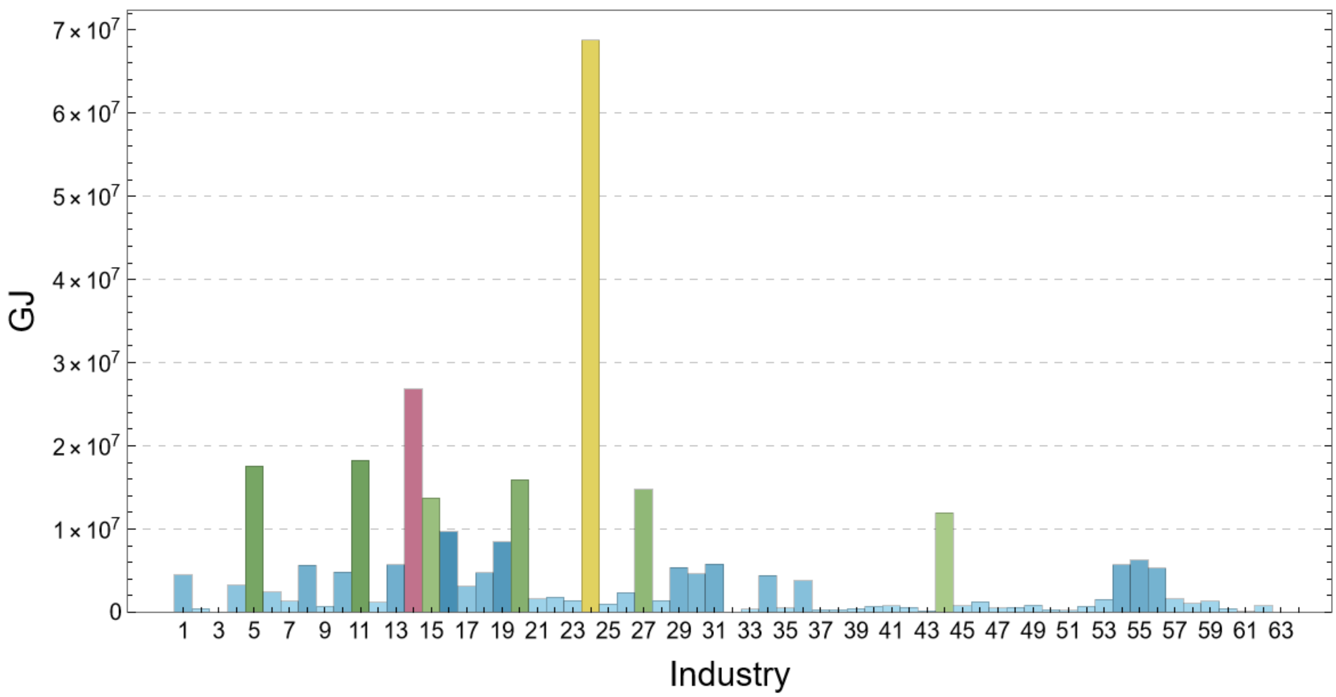

Figure 4: Betweenness centrality by sector.

The values derived from this technique should be carefully interpreted. Given the fact that the betweenness-based method purposefully allocates the energy consumption of a supply chain path to every sector the path passes through, the energy consumption is calculated multiple times, equal to the number of sectors between the beginning and end of the supply chain path. As a result, the total energy consumption calculated using betweenness centrality for all sectors is usually larger than the overall energy consumption of the economy. Table 4 lists the 10 most important sectors according to their betweenness value. When comparing tables 2 and 3, we note that the ranking of sectors changes slightly, with the sector devotevoted to construction activities (S.27) having a higher betweenness rank due to its more frequent appearance in supply chain paths than metal production (S.15) and real estate activities (S.41) which scored higher in terms of extraction effect. However, the same sectors are identified as critical by both measures. As shown in equation (12), the difference between a sector's betweenness and extraction effect originates from the element of the indirect input requirement matrix associated with that sector (t_{ii}), which represents the total supply chain paths from start sector i to end sector i.

The value of each sector's betweenness centrality and extraction effect is plotted in Figure 5, where each point represents a specific sector, linked to its identifying number by a curved line. The closer a sector is to the dashed line, the closer that sector's betweenness and extraction values are. The closer a sector's dot is to the top-right corner, the higher that sector's betweenness and extraction effect are.

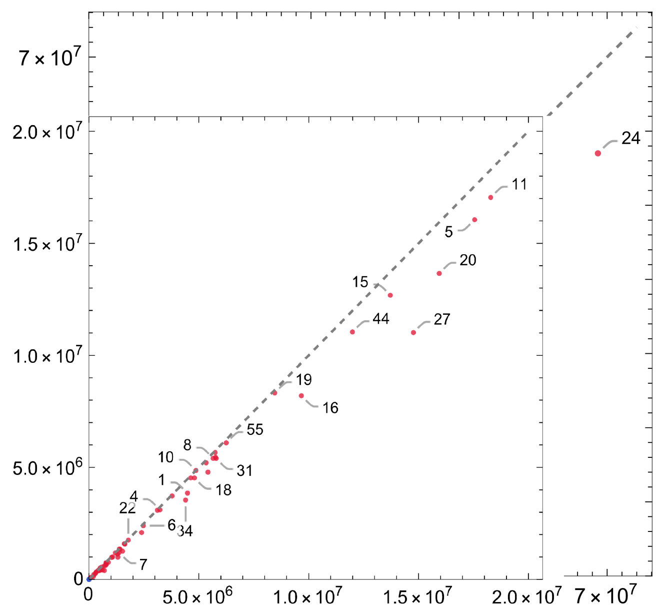

Figure 5: node betweenness centrality (x-axis) versus Extraction effect (y-axis).

Top 10 sectors for betweenness centrality		
Rank	GJ	Sector
1	6.87537×10^7	24
2	2.68202×10^7	14
3	1.82868×10^7	11
4	1.75516×10^7	5
5	1.59437×10^7	20
6	1.47683×10^7	27
7	1.37185×10^7	15
8	1.19923×10^7	44
9	9.66799×10^6	16
10	8.45693×10^6	19

Table 3: Top 10 sectors for betweenness centrality.

Figure 6 summarizes our results from Section 3.1 and Section 3.3 by plotting the rankings of each sector in terms of production-based, consumption-based accounting, and betweenness centrality, each represented by an individual axis. Rankings go from 1 to 64, with 1 being the highest and 64 being the lowest. The higher a sector's ranking is for a specific metric, the closer the color of that sector's dot will be to the colors of the axis.

3.4 Edge betweenness centrality and hypothetical extraction of inter-industry transactions

We extend our analysis by not only identifying critical sectors existing in the middle of supply chains but specific transactions as well by using the inter-industry transaction hypothetical extraction and edge betweenness centrality methods. By doing so, we are able to highlight close relationships between two different but critical sectors. The top 10 transactions with the highest betweenness are presented in Table 4.

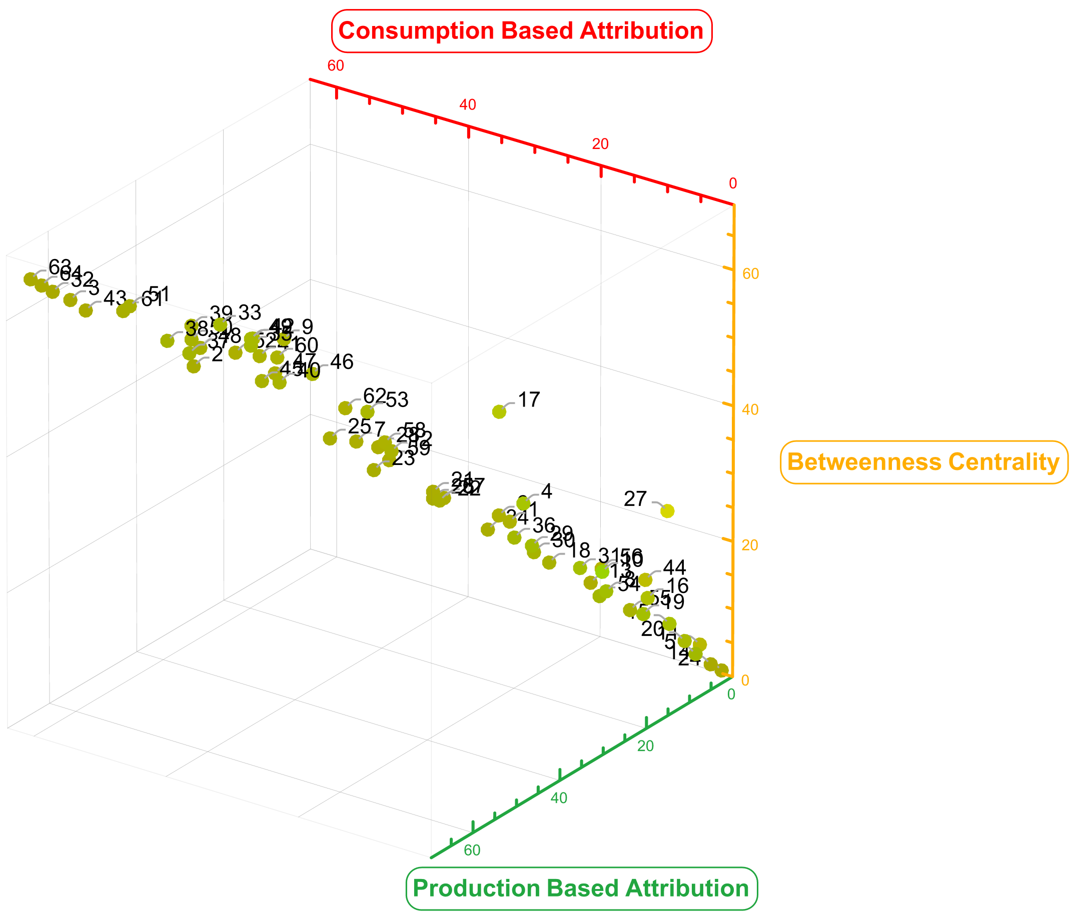

Figure 6: Ranking of sectors by production-based, consumption-based, and betweenness-based natural gas footprints.

Top 10 transactions for edge betweenness centrality

Rank	Source Sector	Receiving Sector	GJ
1	14	27	4.99497×10^6
2	24	44	3.63966×10^6
3	14	44	2.23014×10^6
4	1	5	1.64368×10^6
5	24	11	1.58458×10^6
6	24	54	1.41983×10^6
7	15	19	1.30543×10^6
8	24	14	1.29475×10^6
9	24	5	1.19254×10^6
10	24	17	1.18709×10^6

Table 4: Top 10 transaction for edge betweenness centrality.

The results show strong proximity between the identified sectors by the vertex betweenness and those from the edge betweenness. For all top transactions, at least one of the two sectors linked belongs to the critical sector list presented in Table 3. Importantly, more than half of the identified transactions from Table 4 have the sector devoted to electricity (S.24) as the source sector, while it never appears as a receiving sector. This result helps us to understand the significant difference between that sector's production-based and consumption-based attributions.

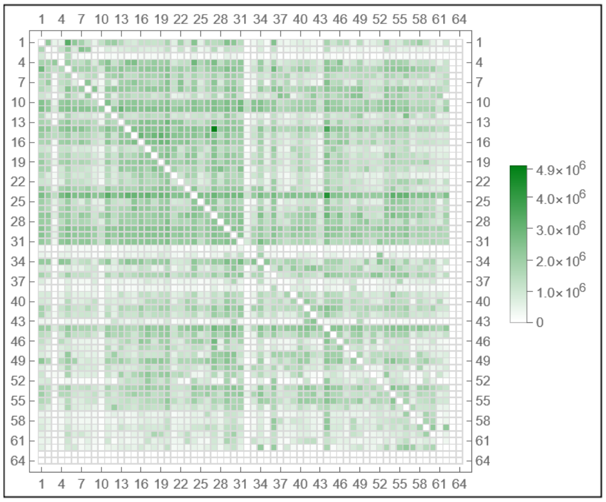

Figure 7: Matrix plot of inter-transaction extraction effects.

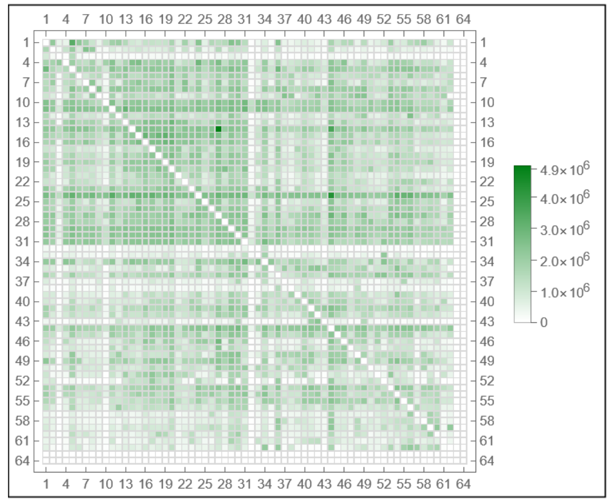

Figure 8: Matrix plot of edge betweenness centrality.

The same situation is found in the minerals production sector (S.14), the second most represented sector as a source. Of all sectors represented in Table 4, crops and animal production (S.1) is the only sector missing from the top 10 critical sectors list from a betweenness perspective. Turning to figures 7 and 8, which summarize our results from edge betweenness and transaction extraction effects, we can see that the transaction from crop and animal production to the manufacture of food products ($1 \rightarrow 5$) is highlighted as relatively important not only by the betweenness metric (1.64×10^6 GJ) but also by the extraction method (1.61×10^6 GJ).

Figures 7, 8 and 9 show the levels derived by calculating the betweeness, extraction effect, and their difference, respectively, for all $i \rightarrow j$ transactions with $i \neq j$ in a matrix plot format, with the row of the matrix corresponding to the source, or "sending", sector and the column corresponding to the receiving sector. The intensity of an element's color reflects the magnitude in GJ of the value associated with that particular transaction for the given metric. To the naked eye, it is difficult to distinguish the differences between the two metrics, so we compute the difference between them and present these results in Figure 9. This difference ought to be interpreted by the reader as the weighted importance of the transaction in the supply chain network.

For improved readability of the most important results, we further report the values of the 10 most important transactions from this list in Table 5. Complementary to the discussion regarding the results from Table 4, transaction $1 \rightarrow 5$ is identified as being the transaction with the largest difference between the two metrics. As for their sector-level counterparts, the gap between the two is explained by the weights given to a sector according to the frequency ($a_{ij}l_{ji}$ from equation (10)) at which they appear in the supply chain.

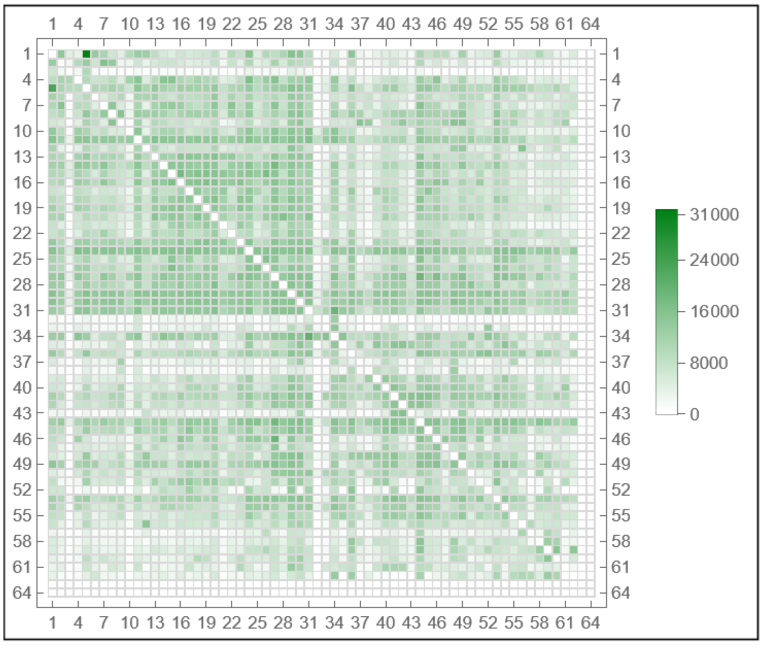

Figure 9: Matrix plot of the difference between edge betweenness and inter-industry transaction extraction.

Top 10 transactions by difference between betweenness and extraction effects for transactions			
Rank	Source Sector	Receiving Sector	GJ
1	1	5	31856.
2	5	1	14342.1
3	34	31	8408.17
4	31	34	6535.5
5	46	27	6467.74
6	27	44	5716.
7	44	27	4246.16
8	15	16	3596.6
9	14	27	2877.43
10	24	44	2566.

Table 5: Top 10 transactions in terms of the difference between betweenness and extraction effects.

3.5 Mapping of embodied energy flows

In order to provide a detailed but also practical visual representation of a map linking final production and consumption attribution of natural gas use in the domestic Czech supply chain, we aggregate our 64 original sectors into 8 clusters by following an aggregation scheme inspired by Zhang, Caron, and Winchester (2019) that relies on the clustering of sectors according to their gas use intensity and total output. Table 6 shows the aggregation results after clustering.

		sectors
clusters	cl1	1, 24, 25, 33, 47, 58
	cl2	5, 8, 16, 20, 27, 31
	cl3	34, 36, 55, 56, 57
	cl4	2, 9, 10, 11, 18, 21, 22, 23, 37, 39, 41, 44, 46, 48, 62
	cl5	13, 26, 32, 45, 49, 63
	cl6	19, 28, 29, 30, 35, 38, 40, 54, 59, 60
	cl7	7, 42, 43, 50
	cl8	3, 4, 6, 12, 14, 15, 17, 51, 52, 53, 61, 64

Table 6: Clustering of IO sectors.

The mapping developed in this section allows for a detailed investigation of the natural gas use in the entire domestic supply chain of the Czech Republic. It provides a visual and quantitative description of how the natural gas use from our sectorial clusters has gone and where the natural gas used embodied in final demand products originates from. The results of the mapping approach are summarized in the Sankey diagram from Figure 10. Sankey diagrams follow the requirement of energy conservation from a physical point of view of production systems and illustrate the energy flows using flow charts (Yang and Song, 2019).

The interpretation of the Sankey plot shown in 10 is as follows: From left to right, the widths of indicated flows represent the magnitude of embodied energy use. The left-hand side of the map shows the total final production attribution (production-based account) of energy use ($P_p^{\text{final}} = M_{p;}f$ for cluster p), a measure of the amount of gas used from a given cluster p that has become embodied in a "basket of final demand" f. The right-hand side of the map shows each cluster's final consumption attribution (consumption-based account), defined as the amount of natural gas from all clusters that has become embodied in a cluster q's elemental final demand ($E_q^0 = m_q f_q$).

The central part of the diagram reveals the intermediate consumption attribution for each cluster (represented by knots) at PL^3, PL^2, and PL^1. Flows from PL^t to PL^{t-1} measure the embodied energy from all clusters in the output of cluster i at PL^t purchased by cluster j at PL^{t-1}. The last flows on the right-hand side of the diagram indicate the embodied energy use attributed to final consumption by final demand category. Due to the map's conservation of energy requirement, the sum of embodied primary energy in final production equals the sum of those in final consumption.

Depending on the cluster, direct natural gas use at PL^0 can represent as low as 19% of that cluster's final consumption attribution (cl7) up to about 80% (cl2). On average, direct natural gas use at PL^0 represents about 52% of a cluster's final consumption attribution. When aggregated, direct gas use at PL^0 represents close to 59% of the country's total natural gas consumption (185.2M GJ), meaning that the remaining 41% is contributed by intermediate inputs at PL^1. Although in some instances, the individual flow of embodied gas from one cluster p to another cluster q from PL^{t-1} to PL^t represents a significant portion of cluster q's consumption attribution at PL^t, as for the flow going from cl1 to cl2, between PL^1 to PL^0, which represents about 16% of cluster cl2's final consumption attribution, generally speaking, these flows tend to be relatively small when considered individually. However, when aggregated and considered as a group, they can represent a considerable share of embodied natural gas use, as shown at the beginning of this paragraph.

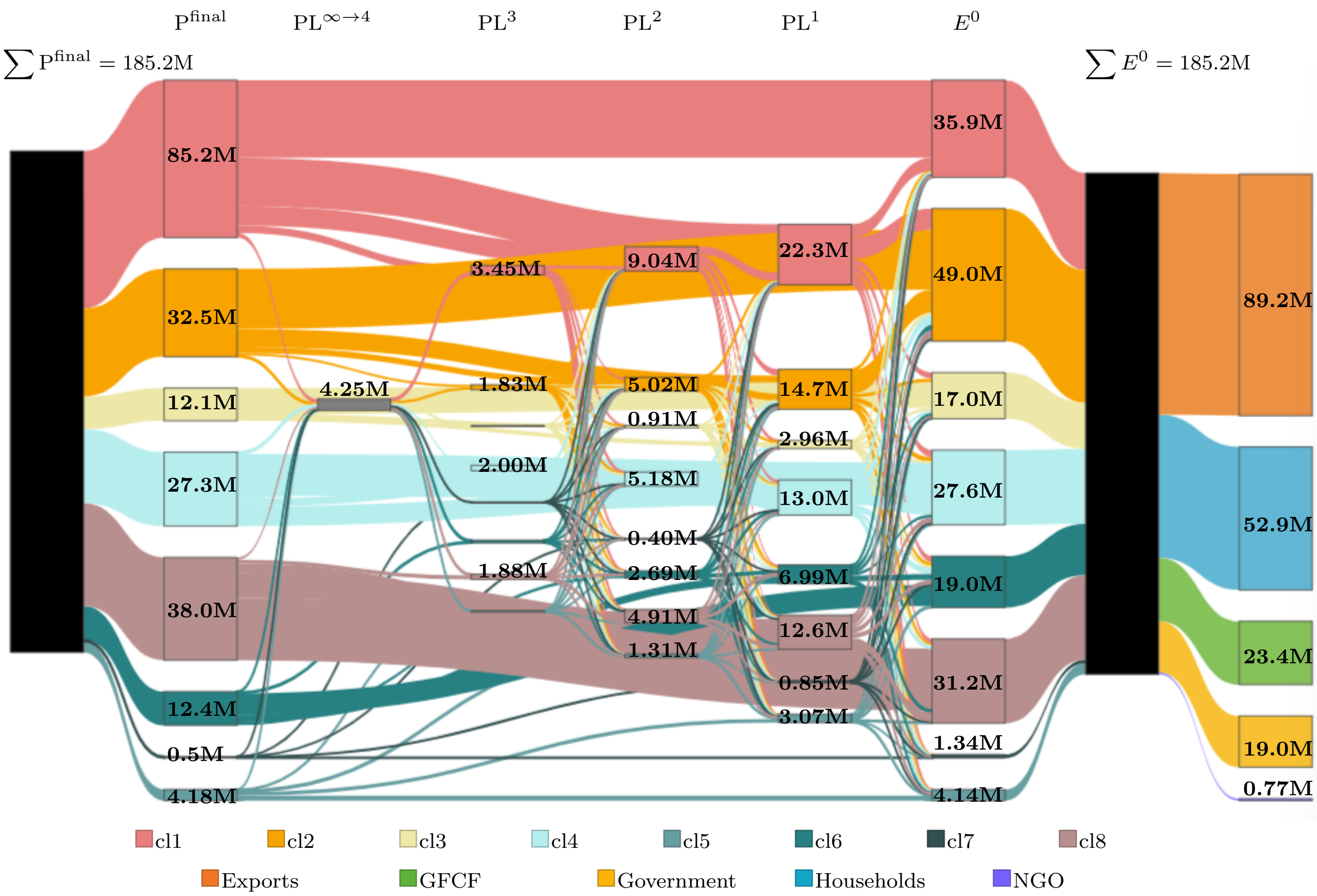

Figure 10: Map of embodied natural gas for the domestic Czech supply network.

Normalized evolution of consumption and production attributions

Following (Skelton et al., 2011), we calculate the "total consumption attribution" of a cluster s of natural gas as the sum of that cluster's "Emissions Pure Backward Linkage" (EPBL)(Sonis et al., 1995) ($EPBL_s = \varepsilon^*(I - A^*)^{-1}A_{:s}x_s$, with x_s being the total output of cluster s, $A_{:s}$ the column vector of all intermediate purchases made by s, A^* the intermediate purchases matrix, with purchases by and from s set to zero, and ε^* the intensity vector of direct gas use per unit of output, with the emissions intensity for cluster s set to zero) and its final production attribution. This allows us to present each cluster's final and intermediate production and consumption attributions as a percentage of its total consumption attribution in order to identify where in the supply chain that cluster's overall natural gas use is concentrated. Figure 11 shows the normalized consumption and production attributions from PL^3 to PL^0. "Starred" markers refer to intermediate attributions, while dotted markers represent final attributions. The solid lines connecting the markers are meant to ease the reader's visualization of a cluster's attributions from $\mathrm{PL}^3 \to \mathrm{PL}^2 \to \mathrm{PL}^1 \to \mathrm{PL}^0$. They are not meant to be interpreted as a continuous series.

Figure 11's visual representation allows the characterization of the evolution of a cluster's production and consumption attribution of natural gas use at different stages in the supply chain. For example, cluster 7 is characterized by having a relatively high final consumption attribution (about 60%) and a low final production attribution (roughly 25%) of its total consumption attribution. The relative importance of this cluster's normalized consumption attribution with respect to its

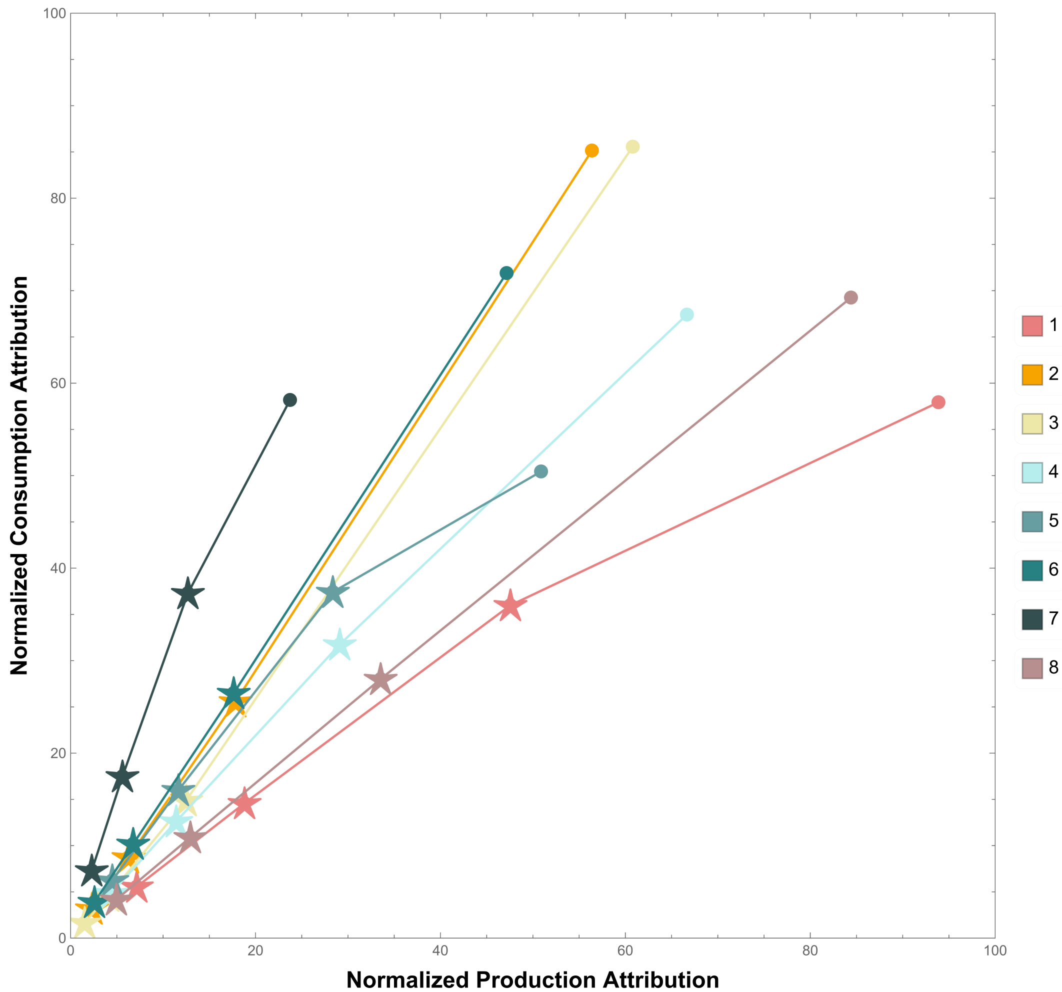

Figure 11: Evolution of cluster production and consumption attributions of natural gas use from PL^3 to PL^0 normalized as a percentage of cluster total consumption attribution.

normalized production attribution remains true for each production layer explicitly represented in Figure 11. For example, at PL^1, cluster 7's intermediate consumption attribution represents just under 40% of its total consumption attribution, while its production counterpart only represents about 15%. This cluster could thus be characterized as being "consumer-facing", meaning that this cluster's product supply requires the use of energy-intensive (in terms of natural gas) inputs. Clusters with steadily increasing production and consumption attributions across all layers, such as clusters 4 or 8, may be referred to as "comprehensive producers". For a detailed description of the different cases, the reader is referred to the methodological paper by Skelton et al. (2011).

3.6 Price effects following a natural gas price increase

The Sankey Diagram from Figure 12, generated with Eurostat's material flows visualization tool (Nuss et al., 2017) shows how natural gas imports in the Czech Republic represent the totality of natural gas used in its supply network. This means that in a domestic IO model of the Czech Republic, natural gas can be considered as a primary input. As such, we compute the potential effect a hike in natural gas prices could have. It is important to note that these results are highly unlikely to capture well reality. Substitution will definitely be one of the decisive factors determining the overall impact of Russian natural gas disruptions (Bachmann et al., 2022). As such, a simple input-output price model, in this context, can only provide hints as to what the potential effect on the economy in terms of prices might be. Nonetheless, The fact that the Czech Republic is fully dependent on Russian gas, and receives it almost entirely from Germany, makes the input-output price model useful to the extent in which in the short-run, industries will have very low capability to switch from one fuel to another.

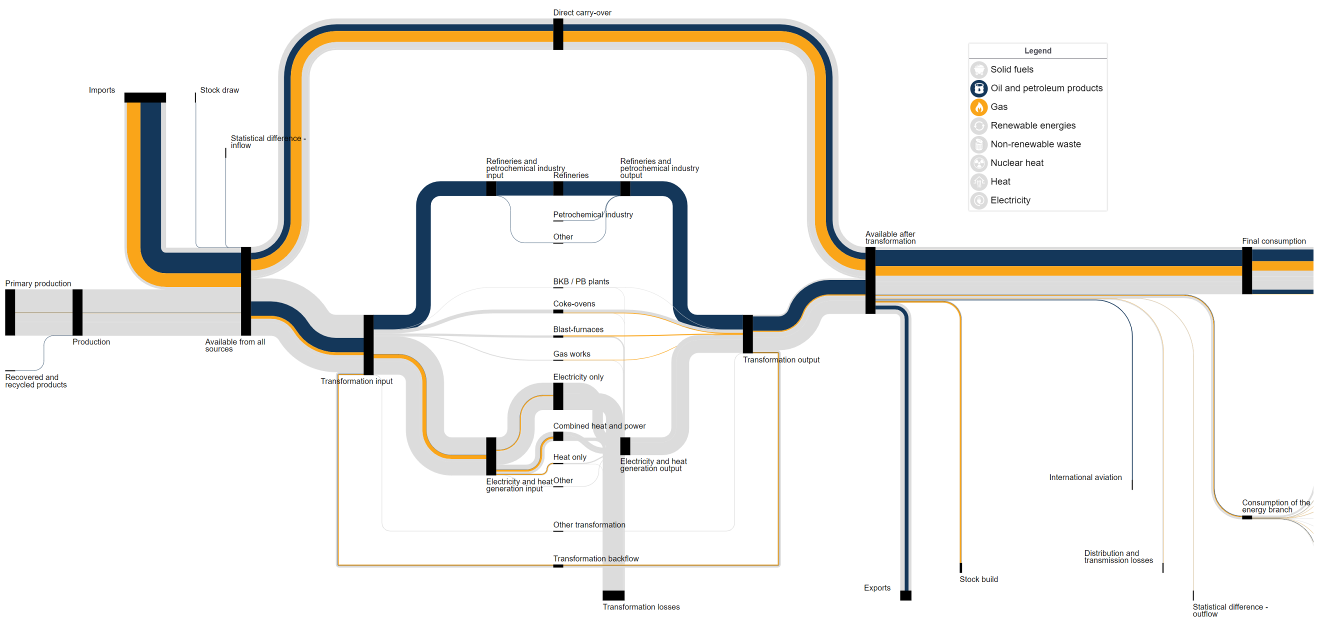

Figure 12: Sankey Diagram of energy flows for the Czech Republic in 2019.

To assess the effect of a price increase, we first convert our physical accounts of natural gas into monetary ones. For this, we collect natural gas prices for industries from Eurostat. They are in euros per GJ and are dependent upon the amounts of natural gas employed by that given industry. Bounds). Natural gas prices in the TTF have risen from around 78 €/MWh to 191 €/MWh. Since the TTF Neutral Gas Price Index is the volume-weighted average price of all trades executed in all the spot contracts, we use the IO price model assuming an increase in natural gas prices of 240%. The Figure below shows price effects by industry.

Sectors affected the most are naturally those with the highest gas total requirements. Sectors 10, 24, and 14 are the ones experiencing the highest increase in prices. Sector 10's output price increases by 12.7%, while the price of sectors 24 and 14 increase by 5.4% and 3.4%, respectively. Most other prices rise by a number between 0% and 2%, while on average, prices rise by 7.5%. A sector-by-sector plot of the results can be found in Figure 13.

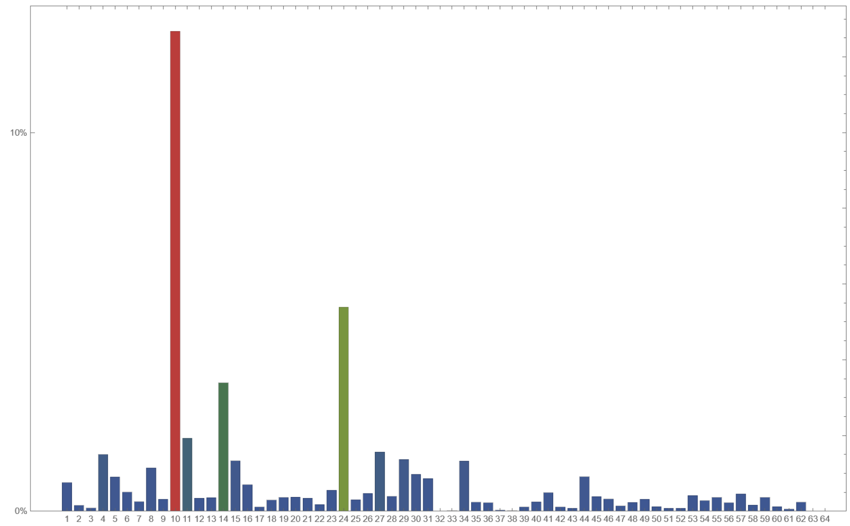

Figure 13: Price effects after an increase of natural gas prices.

4 Conclusion

In this paper, our comprehensive analysis delves into the intricate web of natural gas utilization within the domestic supply chain of the Czech Republic. As geopolitical dynamics continue to shape the energy landscape, recent events such as the invasion of Ukraine by Russia have cast a spotlight on the vulnerability of energy supply chains worldwide. European nations, including the Czech Republic, have experienced market disruptions and price fluctuations due to these geopolitical shifts, underlining the significance of energy security in sustaining economic stability and development.

To better understand the multifaceted role of natural gas within the Czech economy, we employ a holistic approach to identify critical sectors and their reliance on natural gas inputs. Through various analytical frameworks, we illuminate the interconnectedness of energy sources and socioeconomic systems. Additionally, our examination of potential price impacts on industrial output offers insights into the short-term economic implications of natural gas price fluctuations.

While our analysis sheds light on the energy landscape of the Czech Republic, it is important to note that energy security remains a complex and evolving concern. As the energy transition continues and global events reshape energy markets, a comprehensive assessment of potential risks and vulnerabilities is crucial for informed decision-making. The application of more advanced economic models, akin to studies like (Bachmann et al., 2022) and (Di Bella et al., 2022), can further enhance our understanding of the broader economic consequences of energy disruptions. Nevertheless, industrial processes in the Czech Republic are unlikely to dramatically change in the foreseeable future, thus rendering our analysis vital for the future development of policies seeking to limit the disrupting effects of the energy crisis on economic activity. Our results indicate a clear importance in terms of gas consumption of several manufacturing industries whose output is for the most part consumed outside of the country like in the case of mineral, chemical, automotive, metalwork, machinery, paper, and rubber and plastic industries. On the other hand, households' most important sectors in terms of their attributable natural gas consumption are sectors supplying essential goods and services, like electricity and other energy products or services like electricity and heating, food products, housing, transport or agricultural goods. In case of a severe disruption, government intervention may be required to protect domestic demand and at-risk households, and/or the country's competitive advantage in pivotal national sectors like the automotive industry. The results from this paper are expected to help the country's government bodies understand the potential implications of their interventions at different levels of the country's supply chain.

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5 Annex

Table 1: 64-Industry Classification.

1	Crop and animal production, hunting, and related service activities
2	Forestry and logging
3	Fishing and aquaculture
4	Mining and quarrying
5	Manufacture of food products; beverages and tobacco products
6	Manufacture of textiles, wearing apparel, leather and related products
7	Manufacture of wood and of products of wood and cork, straw and plaiting materials
8	Manufacture of paper and paper products
9	Printing and reproduction of recorded media
10	Manufacture of coke and refined petroleum products
11	Manufacture of chemicals and chemical products
12	Manufacture of basic pharmaceutical products
13	Manufacture of rubber and plastic products
14	Manufacture of other non-metallic mineral products
15	Manufacture of basic metals
16	Manufacture of fabricated metal products, except machinery and equipment
17	Manufacture of computer, electronic and optical products
18	Manufacture of electrical equipment
19	Manufacture of machinery and equipment n.e.c.
20	Manufacture of motor vehicles, trailers and semi-trailers
21	Manufacture of other transport equipment
22	Manufacture of furniture; other manufacturing
23	Repair and installation of machinery and equipment
24	Electricity, gas, steam and air conditioning supply
25	Water collection, treatment and supply
26	Sewerage, waste management, remediation activities
27	Construction
28	Wholesale and retail trade and repair of motor vehicles and motorcycles
29	Wholesale trade, except of motor vehicles and motorcycles
30	Retail trade, except of motor vehicles and motorcycles
31	Land transport and transport via pipelines
32	Water transport
33	Air transport
34	Warehousing and support activities for transportation
35	Postal and courier activities
36	Accommodation and food service activities
37	Publishing activities
38	Motion picture, video, programming and broadcasting activities

39	Telecommunications
40	Computer programming, consultancy, and information service activities
41	Financial service activities, except insurance and pension funding
42	Insurance, reinsurance and pension funding, except compulsory social security
43	Activities auxiliary to financial services and insurance activities
44	Real estate activities including imputed rents
45	Legal and accounting activities; activities of head offices; management consultancy activities
46	Architectural and engineering activities; technical testing and analysis
47	Scientific research and development
48	Advertising and market research
49	Other professional, scientific and technical activities; veterinary activities
50	Rental and leasing activities
51	Employment activities
52	Travel agency, tour operator reservation service and related activities
53	Security and investigation, service and landscape, office administrative and support activities
54	Public administration and defense; compulsory social security
55	Education
56	Human health activities
57	Residential care activities and social work activities without accommodation
58	Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities
59	Sports activities and amusement and recreation activities
60	Activities of membership organizations
61	Repair of computers and personal and household goods
62	Other personal service activities
63	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
64	Activities of extraterritorial organizations and bodies

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