


Article

The Coal, Petroleum, and Gas Embedded in the Sectoral Demand-and-Supply Chain: Evidence from China

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Abstract: The United Nations' Sustainable Development Goal (SDG) number seven expressly calls for universal access to affordable and sustainable energy. Energy sustainability will require a reduction in energy consumption, including embedded energy consumption in sectoral demand and supply chains. However, few studies have estimated the amount of coal, petroleum, and gas (fossil fuel) embedded in demand-and-supply chains (FFEDS). Furthermore, the inter-and intra-sectoral energy linkages are understudied. This study quantifies China's FFEDS, the world's largest energy consumer. According to the findings, the highest levels of coal, natural gas, and petroleum consumption (CNGPC) are embedded in the construction sector's input demand. "Electricity and steam production and supply" total intermediate exports (internal plus inter-sectoral) stimulated the highest coal consumption. "Crude petroleum products and natural gas products" and "railway freight transport" aggregate supplies induced the highest volume of natural gas and petroleum consumption. Compared to intra-sectoral demand, inter-sectoral demand stimulated significantly larger CNGPCs. In contrast, CNGPC's inter- and inter-sectoral supplies were nearly identical. Modifying current carbon taxation and credit mechanisms to include energy embedded in demand and supply can help to achieve SDG 7.

Keywords: fossil fuel; Ghosh supply (price) model; industrial linkage; input-output model; Leontief demand (inverse) model; sustainability; United Nations sustainable development goals



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1. Introduction

Coal, petroleum, and natural gas (fossil fuels) have fueled economies for nearly 150 years and now provide more than 80% of the world's energy [1]. Petroleum accounted for approximately 39% of global energy consumption in 2014; coal accounted for 28%; natural gas accounted for 22% [2]. After five years, the share of fossil fuels remained stable in 2019, with petroleum accounting for nearly 33.1%, coal accounting for 27%, and gas accounting for 24.3%, accounting for almost 84.4% of total global energy consumption [3]. COVID-19 compelled a large number of countries to cut their energy consumption. China, the world's largest energy consumer (24% in 2020), was the only country that recovered quickly from the crisis [4]. In 2020, the country's energy consumption had increased by 2.2% over the previous five years [4]. Global energy consumption will increase by 50% by 2050 [5]. It is critical to consider how, in addition to renewable energy, the fossil fuel virtual demand-and-supply side trade can aid to target and distribute energy consumption reduction responsibility among various sectoral stakeholders. Understanding the inter- and intra-sectoral suppliers and demanders of large energy consumers, such as China, can help to improve the efficiency of energy supply chains that is critical to achieve the United Nations' Sustainable Development Goal (SDG) 7 of ensuring "universal access to affordable, reliable, sustainable, and modern energy" [6].

The related literature primarily addresses four major issues: (1) the impact of various drivers on energy consumption; (2) the impact of energy consumption on various socio-economic development indicators; (3) the dual role of energy consumption as a response (dependent) and an explanatory (independent) factor; and (4) energy consumption forecasting. The following Table 1 summarizes some of the pertinent research on energy consumption.

Table 1. Pertinent literature on energy consumption.

Major Category	Study	Main Topic	Key Findings
Drivers of energy consumption	Lange et al. [7]	Information and communication technologies (ICT)	In general, energy consumption increases as a result of ICT.
	Sedlmeir et al. [8]	Blockchain Technology	This study established that the energy usage of blockchain technology varies considerably depending on the design decision.
	Alvarado et al. [9]	Economic development and human capital	Economic growth does not reduce fossil fuel consumption. Contrarily, human capital cuts down on non-renewable consumption.
	Rode et al. [10]	The social cost of carbon	One ton of CO ₂ released today is expected to reduce total future energy expenditures (consumption).
	Shi et al. [11]	Household	Due to the current household convergence dynamics, most Chinese households' energy usage will likely decrease.
	Jian et al. [12]	Non-economic factors	The findings indicate that education, the rule of law, and societal globalization have a long-term detrimental influence on energy use.
Energy consumption as a driver	Aruga et al. [13]	COVID-19	The study established a long-term correlation between COVID-19 cases and energy use.
	Adebayo and Rjoub [14]	Environmental degradation	In the short and long term, fossil fuels (non-renewable energy) contribute to environmental damage.
	Topcu et al. [15]	Economic growth	In high-income countries, energy use boosted economic growth.
	Rehman et al. [16]	Economic growth	Energy usage has a positive and negative effects on Pakistan's economic growth.
	Wu et al. [17]	Carbon emissions	Energy usage is a significant contributor to rising carbon emissions.
	Khan et al. [18]	CO ₂ emissions	Energy use contributes to Pakistan's CO ₂ emissions in the short and long terms.
Ivanovski et al. [19]	Economic growth	Consumption of non-renewable energy has a favorable and significant influence on economic growth in OECD countries.	

Table 1. Cont.

Major Category	Study	Main Topic	Key Findings
Energy consumption as response and explanatory variable	Khan et al. [20]	Capital formation and economic growth	Pakistan's energy sector (consumption) and long-run GDP production are interdependent.
	Odugbesan and Rjoub [21]	Economic growth and CO ₂ emission	The study discovered that Nigeria and Indonesia had a one-way relationship between energy consumption and growth, and Mexico and Turkey had a bilateral relationship.
	Baz et al. [22]	Ecological footprint	In Pakistan, positive shocks to environmental quality caused energy consumption and vice versa.
	Aslan et al. [23]	Economic growth	Energy consumption contributes to economic growth at low and moderate levels of growth. According to the short-run causality test, economic development and all explanatory variables are bidirectionally causal.
Forecasting	Shao et al. [24]	Hotel buildings	Forecasting can help to visualize the hotel's actual energy usage and recommend operational changes to reduce energy consumption.
	Peng et al. [25]	Energy consumption forecasting with many variables	The producer price index or crude petroleum imports play a crucial role in energy consumption.
	Pham et al. [26]	Multiple buildings	Forecasting the building energy usage trends can help to increase energy efficiency.
	Liu et al. [27]	Grinding mechanism for cement raw materials	The study's suggested a framework for predicting real-time energy consumption in raw material grinding.
	Bianco et al. [28]	Italian hotel sector	The paper shows that making energy-saving changes that are financially viable could save the country 1.6 TWh (13% of primary energy) by 2030.
	Ahmad and Zhang [29]	Different business sectors	The review's findings showed a significant potential worldwide energy demand until 2040.

Simultaneously, significant research has been conducted on the material and environmental linkages. Direct and indirect inter-sectoral imports and exports are sectoral (industrial) interconnections [30]. Forward linkage is a term that refers to a sector's connectivity with its intermediary importers upstream [31,32]. Backward linkage refers to the relationship between exporters and a supply chain intermediary [31,32]. Specialists disagree on how to compute forward and backward links. Some have argued that the Leontief inverse model [33] should be used to calculate both backward and forward connections [34,35]. Others believe that the Leontief inverse [33] model should be used exclusively for backward

linkage measurements [30,32]. The Ghosh supply [36] model should be used for forward linkage measurements [30,32]. Nonetheless, both the Leontief and Ghosh models are widely used to investigate various types and dimensions of sectoral and industrial linkages.

Chen et al. [37] quantified the embodied carbon emissions associated with the inter-sectoral connections that connect Australia's two largest cities, Melbourne and Sydney. Sajid and Rahman [38] estimated Pakistan's agriculture sector's land, water, CO₂, and nitrogen linkages. Blanco and Thaler [39] calculated the inter-sectoral water connections in Spain's Castile and León regions. Sajid [40] figured the CO₂ embedded in inter-sectoral linkages and final demand in Pakistan, taking the country's high climate risk into account. Sajid et al. [41] estimated the supply side impact of labor and capital in China, the United States of America, and India on promoting sectoral carbon linkages. Wang et al. [42] estimated the air pollutant connections in several major Chinese cities. Sajid et al. [43] established sectoral backward links between CO₂ emissions and final demand in China. Sajid et al. [44] quantified the carbon links between India's energy and non-energy sectors. Deng et al. [45] examined the linkages between China's water, energy, and food supply chains. Fang and Chen [46] investigated the water and carbon exchanges between China's various provinces. Sajid and Gonzalez [47] estimated the effects of COVID-19 demand shocks on major Asia-Pacific countries' sectoral carbon linkages. He et al. [48] examined China's sectoral pollution connections. Sajid et al. [49] examined the CO₂ emissions from the mining sector in the world's ten largest economies. Sajid [50] identified the drivers of intermediate sectoral consumption (backward) linkages embedded in the Chinese household demand. Sajid et al. [51] quantified the CO₂ linkages between the land, air, and water transport sectors in the EU's seven largest emitters. Several studies have also examined various countries' sectoral/industrial energy connections. For example, Guerra and Sancho [52] calculated the sectoral energy links in the Spanish economy. Faridzad et al. [53] quantified Iran's fossil energy sectoral linkages. Tsirimokos [54] estimated and compared China's and the United States' energy ties. Wang and Yang [55] estimated the petroleum embedded in Germany's intermediate inter-sectoral and final trade. This study's relevance is in the intermediate trade embed petroleum consumption. As per their findings, the "heavy manufacturing" sector had the most considerable petroleum consumption quantity embedded in the intermediate sectoral import and export.

Despite extensive research on energy consumption and material/environmental connections across sectors, the following research gaps persist in the related literature. Few study energy consumption in general, particularly sectoral energy linkages, separately estimate coal, petroleum, and natural gas links. Second, little is known about the world's largest energy consumer, China's, demand-and-supply chain embedded in various fossil fuel sectoral linkages. Rather than that, the majority of related studies have estimated sectoral energy linkages (chains) by aggregating the different types of fossil fuel (energy) linkages [52–54]. Furthermore, the energy linkage studies did not further decompose the backward and forward linkages in inter- and intra-sectoral links. This study uses the Leontief inverse model to estimate the Chinese intra- and inter-sectoral demand-chain embedded fossil linkages of various significant types, including coal, natural gas, and petroleum. The study uses the Ghosh supply model to calculate China's sectoral supply chain's induced fossil links. Additionally, the study dissects the inter-sectoral demand-and-supply chains for fossil fuels into their sectoral origins and destinations.

Quantifying the under-investigated intermediate inter-sectoral demand-and-supply-chain embedded primary fossil energy consumption, such as coal, petroleum, and natural gas, has several methodological and policy implications for domestic and international researchers and policymakers. The estimation and decomposition of the rarely estimated key fossil fuel demand-and-supply-side sectoral linkages can assist in revealing differences in embedded energy usage patterns across different fossil fuel types. Furthermore, the calculation can identify the leading sectoral suppliers (pushers) and demanders (pullers) of embedded energy consumption. That can assist Chinese, and more broadly, other countries and UN climate-related policymakers (such as those responsible for the SDG 7 achievement)

in simply reallocating energy consumption responsibility from traditional direct consumers to diverse stakeholders.

In addition to policymakers, our research also holds notable methodological significance for related future works. There are several ways to estimate the intermediate linkages under the classical multiplier approaches. Miller and Lahr [30] and Miller and Blair [32] represent a detailed historical perspective for estimating sectoral linkages under the traditional multiplier approaches. Furthermore, some recent works, such as those by Ali [56], Chen et al. [37], and Sun et al. [57], estimated carbon linkages using the conventional multiplier approach. Meanwhile, Lenzen [31] estimated pollutant, energy, water, land, and carbon linkages under the classical approach. However, due to scattered definition and estimations procures of linkages, there is still a need to present a comprehensive but straightforward approach for estimating sectoral ecological linkages. This paper shows that the intermediate energy flows matrix (IEFM) can be obtained by diagonalizing the final demand and the environmental intensity multipliers. After obtaining the IEFM, the estimations of the total, forward, backward, and net energy linkages are straightforward. The remainder of the article is structured as follows. Section 2 explains the methods and data sources; Section 3 presents the findings; Section 4 discusses our results compared to previous research; and Section 5 concludes our study and presents future implications. Table 2 contains the full forms of the abbreviations used in our article.

Table 2. Nomenclature.

Full Form	Abbreviation
National input-output table	NIOT
Exajoule	EJ
“Electricity and steam production and supply”	ESPS
“Railway freight transport”	RFT
“Railway passenger transport”	RPT
“Petroleum refining”	PR
“Crude petroleum products and Natural gas products”	CPNGP
“Other special industrial equipment”	OSIE
“Public administration and other sectors”	PDO
“Health services”	HS
“Coal mining and processing”	CMP
“Wholesale and retail trade”	WRT
“Steel-processing”	SP
“Water freight and passengers transport”	WFPT
“Cement and cement asbestos products”	CCAP
“Non-metal minerals and other mining”	NMOM
“Air passenger transport”	APT

2. Methods and Data Sources

2.1. Methods

2.1.1. Fossil Fuels Embedded in the Sectoral Demand

The basic Leontief demand model is generally presented using the following equation [58]:

$$\mathbf{x} = \mathbf{L}\mathbf{f} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \quad (1)$$

where \mathbf{x} represents the vector of sectoral output and \mathbf{L} shows the matrix of the Leontief inverse. Additionally, \mathbf{f} gives the vector of final demand and \mathbf{A} denotes the direct input coefficient matrix, where $a_{lm} = \frac{x_{lm}}{x_m}$ depicts the per unit input demand of sector m from l . By diagonalizing the vector \mathbf{f} , we can have a matrix of intermediate sectoral demand.

$$\mathbf{X} = \hat{\mathbf{L}}\mathbf{f} = (\mathbf{I} - \hat{\mathbf{A}})^{-1}\hat{\mathbf{f}} \quad (2)$$

where \mathbf{X} represents a $n \times n$ matrix of intermediate demand. Equation (2) can be extended to derive the energy demand matrix by adding the vectors of energy consumption intensities.

$$\mathbf{CD} = \hat{\mathbf{c}}\mathbf{L}\mathbf{f} = \hat{\mathbf{c}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \quad (3)$$

$$\mathbf{OD} = \hat{\mathbf{o}}\mathbf{L}\mathbf{f} = \hat{\mathbf{o}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \quad (4)$$

$$\mathbf{GD} = \hat{\mathbf{g}}\mathbf{L}\mathbf{f} = \hat{\mathbf{g}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \quad (5)$$

where \mathbf{CD} , \mathbf{OD} , and \mathbf{GD} depict the coal, petroleum, and gas $n \times n$ intermediate demand matrices, respectively. Additionally, $\hat{\mathbf{c}}$, $\hat{\mathbf{o}}$, and $\hat{\mathbf{g}}$ represent the diagonalized energy intensity vectors of coal, petroleum, and gas, respectively. The fuel intensity vectors are estimated by dividing the total sectoral direct fuel consumption by the total sectoral output. The total volume of fossil fuels embedded in the demand chain (including inter and intra-sectoral) for a target sector r can be estimated by aggregating the $n \times 1$ column vector presenting the inter and intra-sectoral demand from the intermediate energy demand matrix.

$$cd_r = \text{sum} \begin{bmatrix} cd_{r,r} \\ cd_{2,r} \\ \vdots \\ cd_{n,r} \end{bmatrix} \quad (6)$$

$$od_r = \text{sum} \begin{bmatrix} od_{r,r} \\ od_{2,r} \\ \vdots \\ od_{n,r} \end{bmatrix} \quad (7)$$

$$gd_r = \text{sum} \begin{bmatrix} gd_{r,r} \\ gd_{2,r} \\ \vdots \\ gd_{n,r} \end{bmatrix} \quad (8)$$

where cd_r , od_r , and gd_r present the target sector r 's total intermedia demand embedded energy consumption, i.e., total backward fossil fuel linkage. Based on Equations (6)–(8), the target sector demand embedded in the upstream inter-sectoral and intra-sectoral requirement induced by fossil fuel linkages can be estimated below.

$$cd_{-r,r} = \sum_{-r=1}^{n-1} \mathbf{cd}_{-r,r} \quad (9)$$

$$od_{-r,r} = \sum_{-r=1}^{n-1} \mathbf{od}_{-r,r} \quad (10)$$

$$gd_{-r,r} = \sum_{-r=1}^{n-1} \mathbf{gd}_{-r,r} \quad (11)$$

where $cd_{-r,r}$, $od_{-r,r}$, and $gd_{-r,r}$ represent scalar values of target sector demand embedded backward fossil fuel linkages. $-r$ ($r = 1, 2, 3 \dots, n$) symbolizes all other remaining sectors of a country. $\mathbf{cd}_{-r,r}$, $\mathbf{od}_{-r,r}$, and $\mathbf{gd}_{-r,r}$ depict the vectors of target sectors demand embedded fossil fuel consumption at upstream sectors. Similarly, $cd_{r,r}$, $od_{r,r}$, and $gd_{r,r}$ represent the scalar values of the target sector's internal demand embedded fossil fuel consumption.

2.1.2. Fossil Fuels Embedded in the Sectoral Supply

The basic Ghosh supply model is usually presented using the following equation [35,41]:

$$\mathbf{x} = \mathbf{vG} = \mathbf{v}(\mathbf{I} - \mathbf{B})^{-1} \quad (12)$$

where \mathbf{x} depicts the total output vector. $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$ denotes the Ghosh inverse matrix. \mathbf{B} symbolizes the direct output coefficient matrix, where $b_{lm} = \frac{x_{lm}}{x_l}$ show the fraction of sector l output sold to sector m . \mathbf{v} represents $1 \times n$ row vector of value-added (labor compensation + production taxes + net operating surplus + net mixed income + fixed capital compensation – subsidies). By diagonalizing the \mathbf{v} vector, the matrix intermediate sectoral supplies can be obtained as follows:

$$\mathbf{X} = \hat{\mathbf{v}}\mathbf{G} = \hat{\mathbf{v}}(\mathbf{I} - \mathbf{B})^{-1} \quad (13)$$

where \mathbf{X} represents the matrix of intermediate sectoral supplies. By adding the vectors of sectoral fossil fuel consumption intensities to Equation (13), the sectoral fossil fuel supply matrix can be obtained in the following manner:

$$\mathbf{CS} = \hat{\mathbf{v}}\mathbf{G}\hat{\mathbf{c}} = \hat{\mathbf{v}}(\mathbf{I} - \mathbf{B})^{-1}\hat{\mathbf{c}} \quad (14)$$

$$\mathbf{OS} = \hat{\mathbf{o}}\mathbf{L}\hat{\mathbf{f}} = \hat{\mathbf{o}}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{f}} \quad (15)$$

$$\mathbf{GS} = \hat{\mathbf{g}}\mathbf{L}\hat{\mathbf{f}} = \hat{\mathbf{g}}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{f}} \quad (16)$$

where \mathbf{CS} , \mathbf{OS} , and \mathbf{GS} represent the $n \times n$ intermediate supply matrices of the coal, petroleum, and gas, respectively. The total volume of fossil fuels embedded in the supply chain (including inter and intra-sectoral) for a target sector can be quantified by accumulating the $1 \times n$ row vector of inter and intra-sectoral supply from the intermediate energy supply matrix.

$$cs_r = \text{sum} [cs_{r,r} \quad cs_{r,1} \quad \cdots \quad cs_{r,n}] \quad (17)$$

$$os_r = \text{sum} [os_{r,r} \quad os_{r,1} \quad \cdots \quad os_{r,n}] \quad (18)$$

$$gs_r = \text{sum} [gs_{r,r} \quad gs_{r,1} \quad \cdots \quad gs_{r,n}] \quad (19)$$

where cd_r , od_r , and gd_r denote the target sector r 's total intermediate supply embedded energy consumption, i.e., total forward fossil fuel linkage. The following formulas derived from Equations (17) and (18) were employed to quantify the fossil fuel consumption embedded in the inter-sectoral forward supply chain of the target sector.

$$cs_{r,-r} = \sum_{-r=1}^{n-1} \mathbf{cs}_{r,-r} \quad (20)$$

$$os_{r,-r} = \sum_{-r=1}^{n-1} \mathbf{os}_{r,-r} \quad (21)$$

$$gs_{r,-r} = \sum_{-r=1}^{n-1} \mathbf{gs}_{r,-r} \quad (22)$$

where $cs_{r,-r}$, $os_{r,-r}$, and $gs_{r,-r}$ represent scalar values of target sector supply embedded inter-sectoral forward fossil fuel linkages. $\mathbf{cs}_{r,-r}$, $\mathbf{os}_{r,-r}$, and $\mathbf{gs}_{r,-r}$ denote the vectors of target sectors supply embedded fossil fuel consumption at downstream sectors. Correspondingly, $cs_{r,r}$, $os_{r,r}$, and $gs_{r,r}$ depict the scalar values of the target sector's intra-sectoral supply embedded fossil fuel consumption.

2.2. Data Sources

The study used the EORA MRIO's NIOT and associated energy consumption data for 2016 [59–61]. Eora's global supply chain database is built on a multi-region input-output table (MRIO) paradigm that generates time series of high-resolution input-output tables with environmental and social satellite reports for 190 nations [62].

Eora has been used to analyze financial data at "Deloitte, KPMG, Ernst & Young, McKinsey Global Institute, Amazon.com, the European Commission, the IMF, the World Bank, and the United Nations" [63]. Over 800 colleges and institutions have already downloaded the information. Over 1200 citations have been made to the primary publications and research using Eora in "Nature, Nature Climate Change, and PNAS." "Science and the New York Times" have also highlighted Eora-based studies, as have "Scientific American, TIME, the Washington Post, BBC, Le Monde, FAZ, and National Geographic" [63].

For easy understanding, Chinese national income tax and energy consumption data were classified into 123 commodities (for straightforward interpretation, we refer to commodities as sectors). Due to a lack of data on energy consumption, our study excluded the "Re-export and Re-import" sector. The Supplementary Materials contain the demand and supply matrices for fossil fuels, along with their original classifications.

3. Results

3.1. Direct Fossil Fuel Use by Sectors

Figure 1 illustrates the direct use of fossil fuels by various sectors in 2016. With nearly 37 EJ, ESPS was China's largest direct coal consumer by far. ESPS was followed by direct coal consumption in steel processing (5 EJ) and coking (6 EJ). With approximately 4 EJ, the RFT sector consumed the most petroleum fuel in China in 2016. Meanwhile, with nearly 2.4 EJ and 1.7 EJ, respectively, the RPT and PR sectors were the second and third largest direct consumers of petrol. Finally, ESPS (0.35 EJ) consumed the most natural gas in China. The CPNGP and RFT, which consumed 0.34 EJ and 0.26 EJ of natural gas, respectively, closely tracked the ESPS.

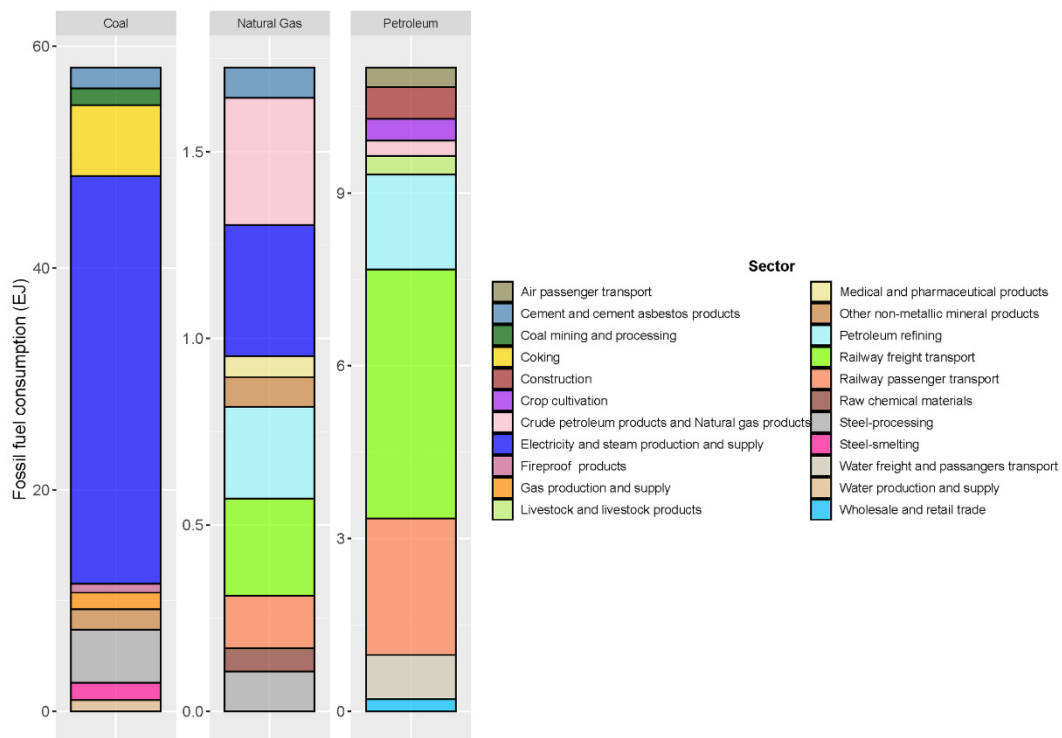


Figure 1. Direct fossil fuel use by different sectors during 2016. The estimates are based on EORA MRIO's NIOT.

3.2. Fossil Fuel Embedded in the Sectoral Total Demand-and-Supply Chain

Figure 2 shows China's fossil fuel consumption embedded in the total demand-and-supply chains (internal and inter-sectoral consumption). The construction sector's demand, at nearly 18.1 EJ, accounted for the highest volume of coal consumption, including internal consumption and usage in upstream sectors. ESPS (4.1 EJ) and OSIE (2.8 EJ) demands accounted for the second and third highest coal consumption, respectively. The construction sector consumed the most natural gas (0.71 EJ) internally and externally (i.e., total demand chain). PDO and HS induced the second and third highest volumes of natural gas consumption, respectively, with 0.1 EJ and 0.09 EJ. Finally, the construction sector's demand influenced the highest level of petroleum consumption (3.3 EJ), both internally and externally. The need for petrol by RPT (0.87 EJ) and PDO (0.83 EJ) was the second and third largest simulators of petrol consumption in the total demand chain, respectively.

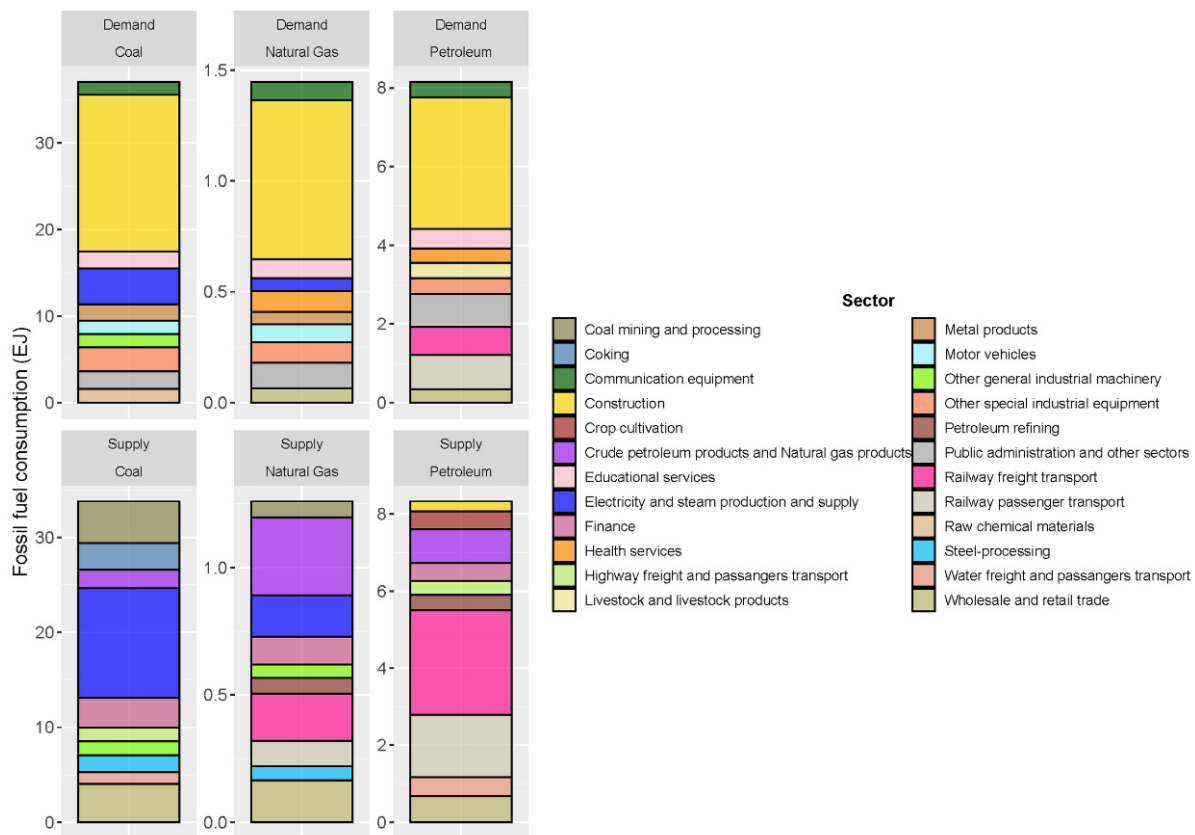


Figure 2. Total demand and supply chain (internal and external chains) embedded fossil fuel consumption.

The ESPS total supply chain consumed the most coal (11.6 EJ) (including internal and inter-sectoral supply). Internal and inter-sectoral sales of CMP (4.4 EJ) and WRT (4.02 EJ) coal accounted for the second and third largest coal consumption. In comparison, CPNGP's internal and external supplies (0.31 EJ) accounted for the lion's share of natural gas consumption. It was followed by the natural gas embedded supplies RFT (0.18 EJ) and WRT (0.16 EJ). RFT (2.7 EJ) possessed the highest proportion of petroleum in its total supplies. At the same time, the aggregate supplies of RPT (1.62 EJ) and CPNGP (0.88 EJ) included the second and third largest quantities of petroleum usage, respectively.

3.3. Fossil Fuel Embedded in the Sectoral Net Demand-and-Supply Chain

Figure 3 presents a comparison of fossil energy embedded in China's internal and external (inter-sectoral) demand and supply chains. In general, when compared to the interior, the downstream sectors' demand for fossil fuels resulted in the most significant

volume of fossil fuel usage in the upstream sectors. Sectoral requirements accounted for nearly 74%, 84%, and 68% of total coal, natural gas, and petroleum consumption in the upstream sectors. However, the consumption of fossil fuels associated with internal and inter-sectoral supplies was relatively evenly distributed. Nearly 64%, 53%, and 44% of coal, natural gas, and petroleum, respectively, were embedded in inter-sectoral downstream supply chains.

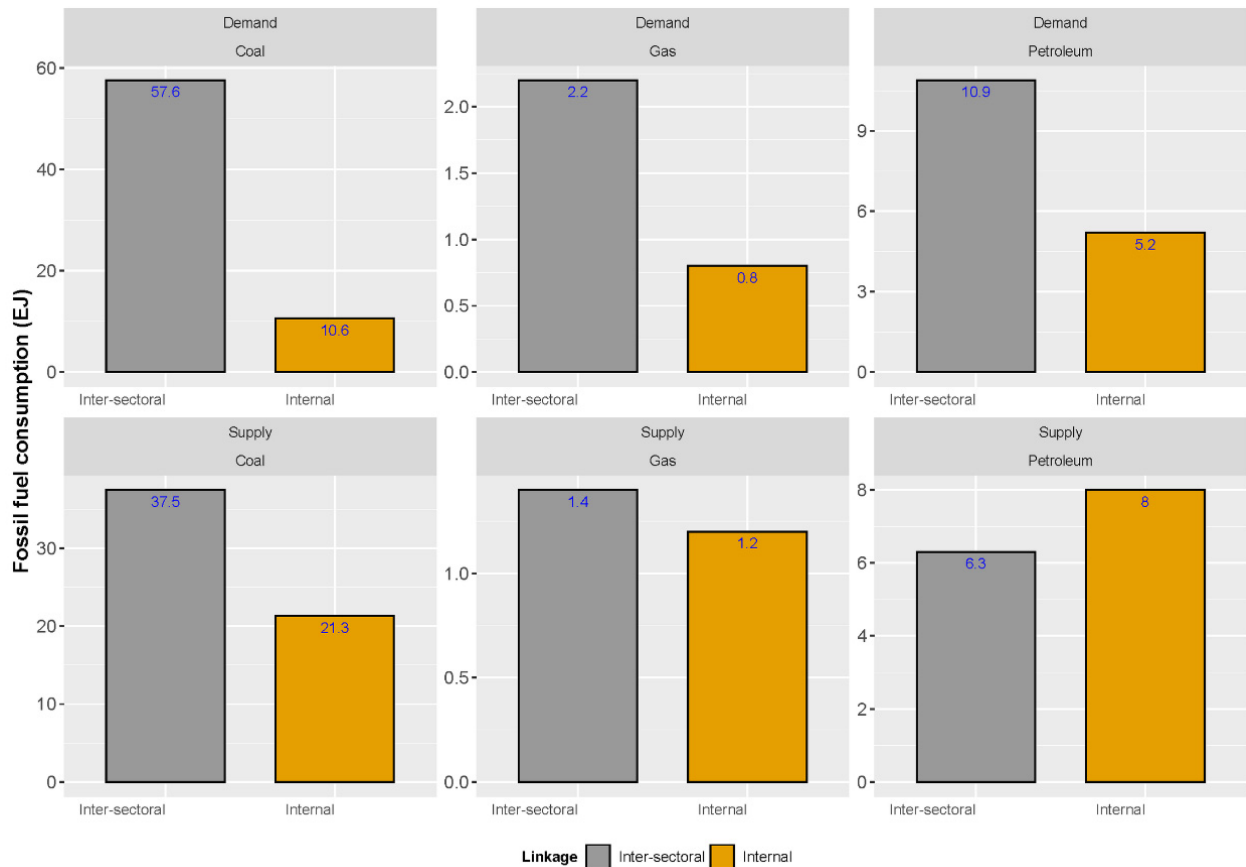


Figure 3. A comparison of fossil fuel consumption induced in inter and intra-sectoral demand-and-supply chains.

Figure 4 depicts the sector-specific consumption of fossil fuels embedded in internal and external demand-and-supply chains. The construction sector's demand resulted in the highest upstream consumption of coal (17.86 EJ), natural gas (0.67 EJ), and petroleum (2.81 EJ). WRT's downstream supplies included the greatest coal consumption (3.95 EJ) and natural gas consumption (0.13 EJ). However, with a value of 0.73 EJ, CPNGP inter-sectoral supplies contained the biggest volume of inter-sectoral petroleum usage. The highest level of internal coal consumption was stimulated by ESPS demand at 3.94 EJ. However, RPT's demand for natural gas and petroleum was the most significant contributor to intra-sectoral consumption, accounting for 0.05 EJ and 0.86 EJ, respectively. ESPS' internal supplies (10.57 EJ) accounted for the lion's share of intra-sectoral coal consumption. The CPNGP's (0.19 EJ) and RFT's (2.65 EJ) supplies drove the most internal natural gas and petroleum consumption, respectively.

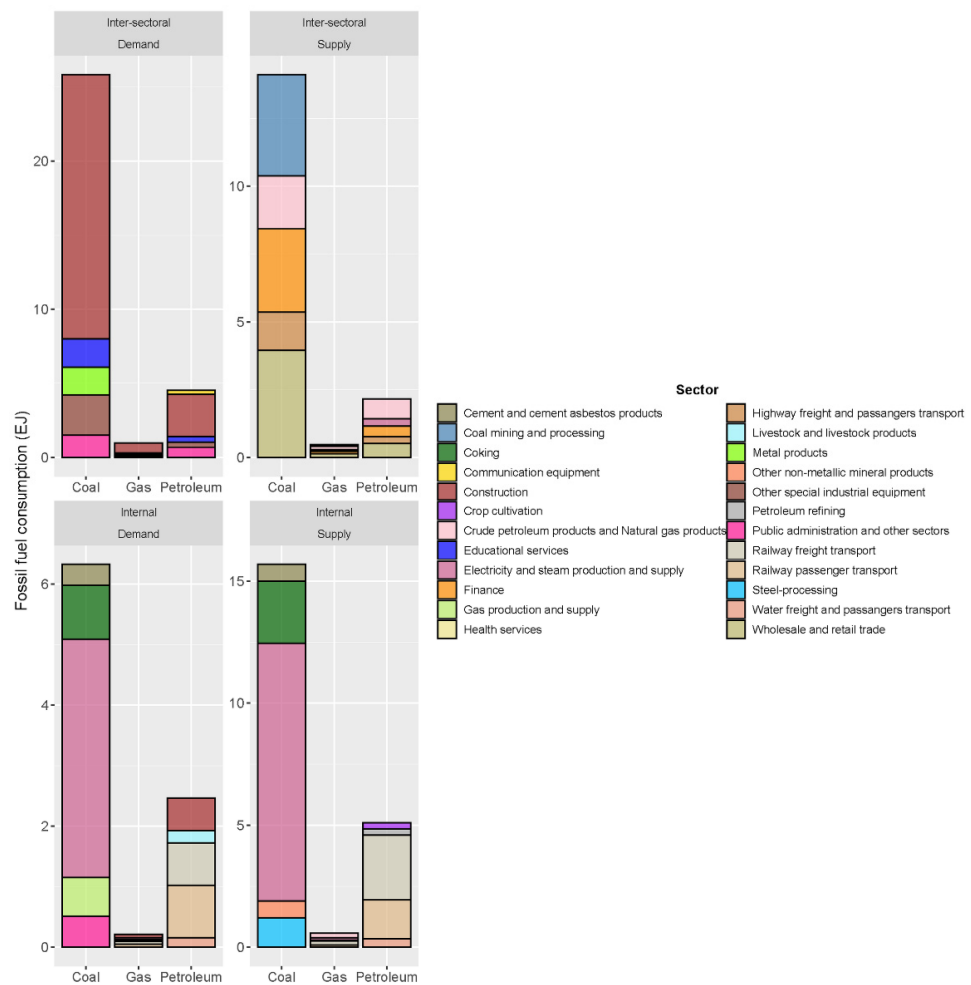


Figure 4. The sector-wise internal and external fossil fuel demand-and-supply chains.

3.4. Decomposed Demand-and-Supply Embedded Fossil Fuel Linkages

Figure 5 presents the agriculture sector's demand-driven fossil fuel linkages. Our analysis of the construction sector's (the largest demand-embedded fossil fuel importer) backward energy links revealed that the ESPS (8.26 EJ), SP (2.18 EJ), and coking (1.95 EJ) were the primary upstream sources of coal usage. In comparison, CPNGP (0.09 EJ), ESPS (0.08 EJ), and PR (0.07 EJ) were the primary sources of backward natural-gas-embedded imports for the construction sector, while RFT (1.02 EJ), PR (0.48 EJ), and WFPT (0.19 EJ) accounted for the majority of the Construction sector's inter-sectoral petroleum consumption.

Figure 6 depicts the sectors' decomposed fossil fuel supply chains with the most significant impact. WRT's exports to other industries embedded the most coal and natural gas use. While the CPNGP sector's sales to the downstream sector accounted for the majority of petroleum consumption, WRT's coal and natural gas embedded supplies primarily went to ESPS (2.26 EJ), coking (0.41 EJ), and SP (0.26 EJ). Meanwhile, the CPNGP's most considerable petroleum-embedded supplies (0.45 EJ) were exported to PR.

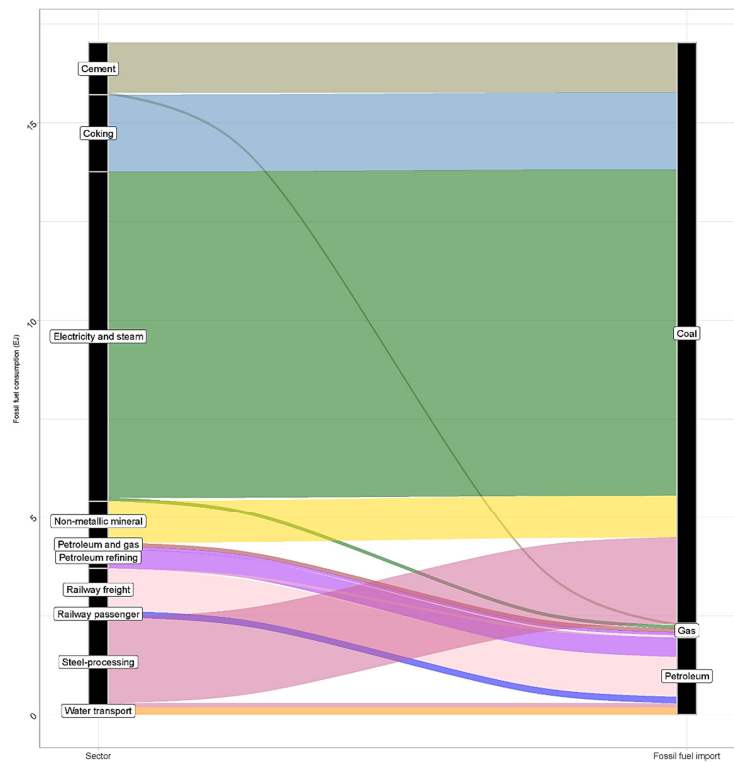


Figure 5. Decomposed inter-sectoral demand chain of the construction sector. The following names are shortened to better present the graphics: Cement = CCAP, Electricity and steam = ESPS, Non-metallic mineral = NMOM, Petroleum and gas = CPNGP, Railway freight = RFT, Railway passenger = RPT, Water transport = WRT.

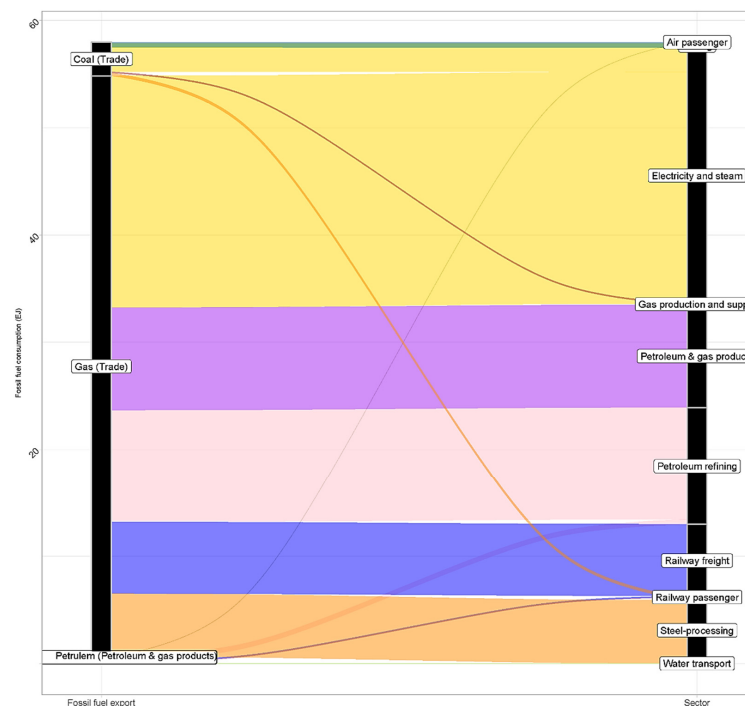


Figure 6. The decomposed fossil fuel supply chains of the topmost impact sectors. The following names are shortened to better present the graphics: Trade = WRT, Petroleum and gas products = CPNGP, Air passenger = APT, Electricity and steam = ESPS.

4. Discussion

Energy consumption has a significant long-term positive impact on air pollution [64]. Fossil fuels account for most of the world's energy consumption [2,3]. COVID-19 decreased many nations' energy consumption [4]. However, China's energy consumption increased by 2.2% in 2020, the COVID-19-affected year [4]. Sectoral connections can provide insight into the origins and destinations of environmental impacts associated with intermediate sectoral trade [35,44]. Cross-sectoral energy policies can aid in the adoption of more environmentally friendly manufacturing processes [53]. However, the energy consumption literature has traditionally concentrated on the drivers of energy consumption [7–9]; energy consumption as a driver [14,15,19]; and energy consumption's dual role as a response and an explanatory variable [21–23], and forecasting [26,28,29]. Numerous studies have also examined the energy connections between various regions, such as Spain [52], Iran [53], and India and China [54]. These studies, however, have estimated the combined energy connections of various nations. Furthermore, the energy-linkage studies did not further decompose the backward and forward linkages in inter- and intra-sectoral links. We addressed this research gap in this study by quantifying the primary energy consumption sources in China, namely coal, natural gas, and petroleum. The study estimated total, net (internal and inter-sectoral), and decomposed (disaggregation of inter-sectoral connections) embedded fossil fuel demand-and-supply chain linkages using Leontief's inverse [33] and Ghosh supply models [36].

Furthermore, besides the general scarcity of literature on estimating different types of fossil fuel inter and intra-sectoral linkages, the estimation procedure, especially the traditional multiplier approaches, is diversified (see [30,32]). This article included a simple methodology for estimating demand and supply side linkages for various fossil fuel types and related empirical results. The Chinese coal, natural gas, and petroleum linkages were chosen as a case study because the various fossil fuel linkages are generally understudied. In addition, China is the world's leading consumer of fossil fuels, although, in order to keep things simple and focus on the estimation procedure, only one regional case example was considered. As the readers' needs dictate, the same linkage estimation rules presented in the methodology section can be extended to a multi-regional scenario. The following sections discuss our study's significant findings.

4.1. Discussion of Results

ESPS was China's largest direct coal and natural gas user in 2016 with 37 EJ and 0.35 EJ, respectively. With nearly 4 EJ, China's largest petroleum consumer was the RFT sector. With 18.15 EJ, 0.71 EJ, and 3.3 EJ of total demand embedded coal, natural gas, and petroleum usage, the construction sector had the highest total demand for embedded coal, natural gas, and petroleum consumption. Inter-sectoral imports from the construction sector also stimulated the highest levels of coal (17.86 EJ), natural gas (0.67 EJ), and petroleum (2.81 EJ) consumption in the upstream sectors. Other studies have discovered that the construction sector's demand has the greatest influence on inter-sectoral and inter-regional environmental impacts, including the consumption of upstream suppliers' inter-sectoral carbon [44] and inter-regional air pollutants [42]. The construction sector, in particular, has the highest absolute total backward energy linkage in China [54]. The ESPS demand accounted for most intra-sectoral coal consumption, accounting for 3.94 EJ. RPT demand influenced the largest intra-sectoral consumption of natural gas and petroleum by 0.05 EJ and 0.86 EJ, respectively. However, prior research in general, and specifically energy-linkage-related research, has not quantified the sectoral demand impacts of various fossil fuels, such as coal, natural gas, and petroleum. Furthermore, the energy-linkage literature has not separated inter- and inter-sectoral demand-and-supply chains [52–54]. Estimating demand-related fossil fuel linkages for various fuel types enhances the significance of our findings compared to the seldom presented combined energy linkages in other works. Additionally, the presentation of cross- and intra-sectoral connections enhances the importance of our study. In addition to direct energy consumers, policymakers should also focus on the

critical downstream consumers of different types of fossil fuels. Policymakers (particularly Chinese policymakers), depending upon the carbon content of different fossil fuels (coal, petroleum, and natural gas), can introduce sectoral energy consumer carbon taxes. This carbon-content-based carbon tax estimation of Chinese sectoral consumption embedded coal, petroleum, and natural gas is not possible under the above-discussed literature that generally presented the combined energy linkages of China and other countries.

According to our findings, sectoral impacts vary according to the type of fossil energy consumed. ESPS' total supply (internal plus inter-sectoral) of 11.56 EJ accounted for the bulk of China's coal consumption in 2016. CPNGP and RFT complete supplies, estimated at 0.31 EJ and 2.71 EJ, respectively, accounted for most of China's natural gas and petroleum consumption. With 3.95 EJ and 0.13 EJ of inter-sectoral supply embedded coal and natural gas usage, the WRT sector had the highest volume of inter-sectoral supply embedded coal and natural gas usage. In contrast, inter-sectoral CPNGP supplies accounted for the lion's share of petroleum consumption. Recent evidence from Wang and Yang [55] showed that the heavy manufacturing sector, including CPNGP, was the largest supplier (exporter) of Germany's international inter-sectoral embedded petroleum exports. However, unlike our work, they employed the conventional Leontief demand model to estimate the petroleum embedded in inter-sectoral supplies. Internal supplies of ESPS (10.57 EJ), CPNGP (0.19 EJ), and RFT (2.65 EJ) consumed the most energy. Tsirimokos [54] discovered that China's "Mining and quarrying" sector had the most significant forward energy linkage in 2014. Additional Ghosh supply-model-based CO₂ linkage estimations have identified the electricity and utility sectors as the primary drivers of embedded sectoral emissions [35,41]. As the sectoral consumers of embedded fossil fuels, embedded coal, petroleum, and natural gas suppliers can be carbon taxed. Therefore, a diversified and just approach can be adopted by introducing a 50%:50% reallocation of fossil fuel usage responsibility between consumers and suppliers of embedded fossil fuel consumption.

The dismantling of cross-sectoral environmental ties enables us to ascertain the primary sources and destinations of a country's environmental (carbon) impacts [40,44]. The construction sector's demand was the primary source of fossil fuel consumption at other upstream sectors. Demand from the construction sector resulted in the highest 8.26 EJ coal consumption at ESPS. The most significant volume of gas consumption (0.09 EJ) was stimulated by demand for CPNGP's products in the construction sector. Finally, the sector's requirement for RFT resulted in the chief upstream coal consumption of 1.02 EJ. On the other hand, WRT possessed the most valuable embedded coal and natural gas inter-sectoral supplies. ESPS was the primary destination of WRT's virtual coal and natural gas consumption, accounting for 2.26 EJ and 21.60 EJ, respectively. However, the CPNP's primary source of petroleum consumption, 0.45 EJ, was embedded in its supplies to PR. The dissection of the demand and supply chains of embedded fossil fuel consumption can guide industrial managers in deciding which sectors are primarily responsible for embedded energy consumption. This identification can help logistics and supply chain managers to reduce the imports from and exports to the high-embedded energy consumer sectors to minimize the financial burden from the taxes mentioned above.

4.2. Limitations and Suggestions for Future Research

It is beyond the scope of this research to estimate the fossil fuel embedded in international or inter-regional inter-sectoral trade. Therefore, future works can quantify the fossil fuel consumption in global or regional inter-sectoral demand-and-supply chains and extend the estimation procedure presented in our study trade using the multi-regional input-output model.

In addition to the above discussed results-based policy implications, technological innovation [65,66], transition to renewable and better energy options [67,68], reallocation of industries based on regional carbon efficiencies [69], and targeting of final demand's socio-economic drivers [70,71] may help in economic progress and reduction of the overall

fossil fuel consumption. Therefore, these dimensions can also be researched in sectoral demand-and-supply chain embedded fossil fuel consumption works.

5. Conclusions

As a result of the preceding discussion, it can be concluded that, compared to conventional energy-embedded linkages, the estimation of various energy linkages, such as coal, natural gas, and petroleum, revealed significantly different volumes and patterns across fuel types. Additionally, our findings shed new light on previously overlooked demand–supply embedded inter- and intra-sectoral linkages. The inter-sectoral backward links contained the greatest demand-embedded fossil fuel linkages compared to internal links. However, supply chain embedded fossil fuel connections revealed similar contributions (in terms of total volume) from intra- and inter-sectoral relations. Inter-sectoral imports from the construction sector stimulated the upstream sectors' highest levels of coal (17.86 EJ), natural gas (0.67 EJ), and petroleum (2.81 EJ) consumption. The ESPS demand, at 3.94 EJ, accounted for the majority of intra-sectoral coal consumption. By 0.05 EJ and 0.86 EJ, respectively, RPT demand had the most significant influence on the intra-sectoral consumption of natural gas and petroleum. The WRT sector had the highest volume of inter-sectoral supply embedded coal and natural gas consumption, at 3.95 EJ and 0.13 EJ, respectively. In comparison, inter-sectoral CPNGP supplies accounted for most petroleum consumption. The most energy was consumed by the internal supplies of ESPS (10.57 EJ), CPNGP (0.19 EJ), and RFT (2.65 EJ).

Apart from the conventional energy efficiency improvements, it is recommended based on our findings that the inputs available to the significant embedded energy importers, such as construction, be rationed. Simultaneously, the embedded energy outputs of the major inter- and inter-sectoral suppliers, such as ESPS and CPNGP, RFT, and WRT, should be curbed. To accomplish this, policymakers can incorporate the effects of energy-embedded intermediate sectoral imports and exports into established carbon taxation and trading markets. That can contribute to achieve the UN's Sustainable Development Goals, particularly SDG 7. This inclusion can aid in just mitigation by diversifying the climate protection burden between the major demanders and suppliers.

Additionally, the involvement of diverse stakeholders can assist businesses in meeting their social and moral responsibilities to society. That is necessary for contemporary societies to increase the acceptability of products and services among environmentally conscious consumers. Future studies can use the multi-regional input-output tables to understand better the inter-regional fossil fuel linkages of different regions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su14031888/s1>. Supplementary data file. This file contains both the fossil fuel demand and supply matrices. These matrices are used as a basis for estimating total, net and decomposed demand and supply induced sectoral fossil fuel linkages of China. The file also provides accounts of internal, inter-sectoral, and decomposed inter-sectoral linkages in Petajoule (PJ).

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