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The impact of fossil energy technological progress on sectoral implied energy intensity: Evidence from the U.S. shale gas revolution

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ABSTRACT

This paper investigates how sectoral implied energy intensity responds to energy technology progress, using the U.S. shale gas revolution—the most significant energy breakthrough of the 21st century—as a quasi-natural experiment. Using industry-level input-output and trade data, we implement a difference-in-differences (DID) strategy to identify the effects. We find that the shale revolution, on average, increases sectoral implied energy intensity in countries with higher natural gas import demand. The results are robust to alternative specifications, multiple fixed effects, parallel-trend checks, and placebo tests. Mechanism analysis suggests that the rise in implied energy intensity is driven by increased natural gas imports and intensified competition among gas-exporting countries. Heterogeneity analysis further reveals that skill-intensive sectors, transportation, public services, and environmental industries are more responsive to the shale gas technology shock. These findings underscore the spillover effects of the revolution not only on global trade patterns but also on sectoral energy use, highlighting the need for enhanced coordination in energy technology development and energy security strategies.

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Energy trade has long connected countries all over the world, making breakthroughs in one country's energy sector can generate far-reaching spillover effects across borders. Among such breakthroughs, the U.S. shale gas revolution stands out as one of the most influential of the 21st century. Propelled by advances in hydraulic fracturing and horizontal drilling, it unlocked large-scale production of unconventional gas resources and has transformed the U.S. from a major energy importer to a leading natural gas exporter—reshaping global energy flows and prompting broad industrial adjustments worldwide.

Shale gas, a form of natural gas trapped in low-permeability shale formations, has long been abundant in the United States. However, commercial extraction remained limited for decades due to economic and technical constraints (Wang et al., 2014). In the early 2000s, advances in hydraulic fracturing—a technique that injects high-pressure mixed fluid into shale formations to induce fractures—and horizontal drilling, which allows wells to extend laterally through gas-bearing rock layers, revolutionized shale gas extraction (Wang et al., 2014; Yuan et al., 2015). These technological breakthroughs dramatically reduced production costs and made the development of previously uneconomical reserves viable (Kerr, 2010; Schnoor, 2012). Large-scale commercial production began around 2006, marking the onset of the U.S. shale gas revolution. As shown in Figs. S1 and S2, the share of shale gas in total U.S. natural gas production rose sharply thereafter. This surge represented a key milestone in the United States' pursuit of energy security and independence (Shirazi et al., 2022).

We treat the U.S. shale gas revolution as an exogenous shock to global energy markets and employs a difference-in-differences (DID) framework to estimate the impact on embodied energy intensity at the industry level in other countries. We find that the shale gas revolution significantly increased embodied energy intensity in countries with relatively low proven natural gas reserves. Mechanism analysis reveals two primary trade-based transmission channels. First, the U.S. shale revolution led to an increase in natural gas imports among affected countries. Second, it intensified competition among natural gas-exporting

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economies, thereby altering trade patterns. We further explore heterogeneity insights along three dimensions: industry type, geographical distance from the U.S., and the energy applications. Our analysis combines multiple data sources, including global industry-level input–output tables, country-level proven natural gas reserves, and detailed energy trade statistics.

While a large body of literature has examined the domestic economic impacts of the U.S. shale gas revolution—highlighting its effects on energy prices, manufacturing reshoring, industrial output, and employment (Bonakdarpour et al., 2012; Geng et al., 2016; Krupnick et al., 2013; Wang and Wang, 2015; Kirat, 2021 Bilgili et al., 2016; Arezki et al., 2017; Shakya et al., 2022; Rubaszek and Szafranek, 2025)—limited attention has been paid to its international spillover effects on industrial development. Our study extends this literature by shifting the focus from domestic outcomes to cross-border impacts, particularly the spillovers on embodied energy intensity in countries with higher energy import demand.

We also contribute to the literature on international technology spillovers. While prior studies typically distinguish between technology transfer and product trade as primary spillover channels (Fang et al., 2004; Fu et al., 2010), or examine how technological progress improves energy efficiency at the national level (Wang et al., 2021; Sun et al., 2023), few have explored how trade in energy products reshapes industrial energy intensity across countries. In the case of shale gas, product-based spillovers are particularly salient, as large-scale commercial extraction remains feasible only in the United States due to its unique geological, infrastructural, and technological advantages. In contrast, most other countries either lack comparable reserves or face substantial barriers to development (Yegorov and Boudiaf, 2012; Zhang et al., 2022). By tracing how the shale gas revolution affects embodied energy use in foreign

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3.1. Data

This paper calculates the sectoral embodied energy intensity of other countries based on a multi-regional input-output (MRIO) model. The required data are sourced from the EXIOBASE database (version 3.8.2, Stadler et al., 2021), which is built upon rectangular supply-use tables for 163 sectors, linking national supply and use tables using trade data to create and generate MRIO tables. This paper also uses 2005 oil and gas proven reserves data by country and region, and natural gas trade data between countries and regions, sourced respectively from the Oil & Gas Journal (U.S.) and the United Nations Commodity Trade Statistics Database (UN Comtrade). These datasets are merged with EXIOBASE sectoral input-output data using country and regional abbreviations. Since the EXIOBASE input-output data are expressed in current prices, this paper uses 2005 as the base year and applies a deflation method using price indices to ensure data comparability across years. The descriptive statistics of the main variables in this paper are shown in Table 1.

3.2. Variable definitions

3.2.1. Embodied energy intensity

The embodied energy intensity of an industry refers to the amount of energy consumed per unit of value added that is generated to satisfy the final demand of that industry. It measures the pressure exerted by industrial economic activities on resources. In this study, we select the embodied energy intensity of each sector in various countries as the dependent variable. Following Li and Wang (2021) we calculate it based on a multi-regional input-output (MRIO) model and the derivation process is shown in Supplementary Information Part A.

The implicit energy intensity $AEEI_{is}$ of sector s in country i is expressed as:

$$AEEI_{is} = \frac{EN_{is}}{EVA_{is}} \tag{1}$$

where EN_{is} and EVA_{is} represent the traditional energy intensity and the implicit value-added in the final demand output of sector s in country i.

3.2.2. Potential competition index

This article uses the potential competition index to measure the energy trade competition relationship between countries. Referring to Sun et al. (2022), who constructed the potential competition index to explore the potential crude oil competition relationship between China, Japan, India, and South Korea, this study adopts the same algorithm and constructs the formula as follows:

$$C_{ij}^{\text{in}}(t) = \sum\nolimits_c \left\{ \left(\frac{M_{ci}(t) + M_{cj}(t)}{M_w(t)} \right) \times \left[1 - \frac{\left| \left(M_{ci}(t) \middle/ M_i^{\text{in}}(t) \right) - \left(M_{cj}(t) \middle/ M_j^{\text{in}}(t) \right) \right|}{\left(M_{ci}(t) \middle/ M_i^{\text{in}}(t) \right) + \left(M_{cj}(t) \middle/ M_j^{\text{in}}(t) \right)} \right] \right\} \times 100 \tag{2}$$

$$C_{ij}^{\text{out}}(t) = \sum\nolimits_c \left\{ \left(\frac{M_{ic}(t) + M_{jc}(t)}{M_w(t)} \right) \times \left[1 - \frac{\left| \left(M_{ic}(t) \middle/ M_i^{\text{out}}(t) \right) - \left(M_{jc}(t) \middle/ M_j^{\text{out}}(t) \right) \right|}{\left(M_{ic}(t) \middle/ M_i^{\text{out}}(t) \right) + \left(M_{jc}(t) \middle/ M_j^{\text{out}}(t) \right)} \right] \right\} \times 100 \tag{3}$$

In this formula, $C_{ij}^{\text{in}}(t)$ represents the potential energy import competition index between country i and country j in year t, while $C_{ij}^{\text{out}}(t)$ represents the potential energy export competition index between country i and country j in year t. $M_w(t)$ represents the total energy trade volume in year t, $M_{ci}(t)$ and $M_{cj}(t)$ represent the energy trade volume imported by country i and country j from country c in year t, and $M_{ic}(t)$ and $M_{jc}(t)$ represent the energy trade volume exported by country i and country j from country c in year t. $M_i^{\text{in}}(t)$ represents the total energy import and export volume of country i in year t, respectively. A larger index value indicates a stronger energy trade competition between the two countries.

The descriptive statistics of the main variables in this paper are shown in Table 1.

Descriptive statistics of variables.

Variable	Symbols	*N*	Mean	Sd	Min	Max
Implied energy intensity	ln *AEEI*	164304	1.55	1.29	0	46.60
Labor scale	ln *EM*	164304	2.38	2.53	0	12.78
Proven natural gas reserves, 10^3 km^3	$Sg_{i,2005}$	48	3.44	12.46	0	72.64
Proven oil reserves, 100 million tons	$So_{i,2005}$	48	36.11	151.42	0	1017.92
Net natural gas imports, 100 million tons	*Netim_gas*	4809	0.00	0.20	−0.89	11.89
Net oil imports, 100 million tons	*Netim_oil*	4809	−0.02	0.50	−4.18	8.38
Net natural gas imports from the U.S., 100 million tons	*UNim_gas*	4809	0.00	0.19	−0.10	11.89
Import potential competition index	C^{in}	49392	0.30	2.06	0	47.70
Export potential competition index	C^{out}	49392	0.43	2.26	0	80.47

3.3. Empirical model

This study constructs panel data at the country-industry level for the period 2000–2020 through data calculation and organization. Based on the Difference-in-Differences (DID) method, the baseline regression model is specified as follows:

$$\begin{aligned} \ln AEEI_{ist} &= \alpha_0 + \alpha_1 \left(-\ln Sg_{i,2005}\right) \times I_t^{\mathrm{Post}} + \alpha_j \mathrm{Control}_{ist} + \theta_i \\ &\quad + \phi_s + \rho_t + \varepsilon_{ist} \end{aligned} \tag{4}$$

In this model, *i* represents countries, *s* represents industries, and *t* represents years. The dependent variable, $\ln AEEI_{ist}$, is the logarithmic value of the implicit energy intensity of industry *s* in country *i* in year *t*. In the explanatory variables, I_t^{Post} is a dummy variable indicating whether the U.S. shale regression results are presented in columns (3) and (6). Column (4) adds the regression results of $-\ln So_{i,2005} \times I_t^{\text{Post}}$ on top of the results from column (2).

The regression results indicate that after the U.S. shale gas revolution, countries with lower natural gas proven reserves experienced an increase in industry implied energy intensity. On average, a 1% reduction in a country's natural gas reserves leads to a 0.01% increase in the energy consumption per unit of added value in the industry after the U.S. shale gas revolution. Assuming a country's annual industrial GDP reaches one trillion dollars, the country's energy intensity is about 4 tons of standard coal per million dollars, and natural gas prices are about 10 dollars per million BTU, the direct energy cost increase would be approximately 12 million dollars, which would have a minimal impact on the economy. However, for energy-intensive industries, the disparity in energy consumption intensity across industries is amplified, leading to a more significant increase in average industry costs and creating marginal pressures.

Fig. 1 shows the dynamic effects of the U.S. shale gas revolution. The coefficients remain close to zero and statistically insignificant before the revolution, suggesting that differences in industrial implied energy intensity between countries. would have followed parallel trends. After the event, there is a marked and statistically significant increase in industrial implied energy intensity, indicating that the impact of the U.S. shale revolution might be strengthened over time.

4.2. Robustness test

4.2.1. Adjusting the grouping criteria for the experiment group

Generally, countries with larger natural gas reserves tend to be energy exporters, whereas those with smaller reserves are generally importers. To provide an alternative measure of exposure, we replace natural gas reserves with net natural gas imports in 2005. The treatment group is defined as net importers and the control group as net exporters. We use the level of net imports $IMg_{i,2005}$, its logarithm $\ln IMg_{i,2005}$, and its inverse hyperbolic sine transformation $IHS\left(IMg_{i,2005}\right)$ to replace $-\ln Sg_{i,2005}$. The results are columns (1)–(3) of Table S1, indicating that after the shale gas revolution in the U.S., the industry implied energy intensity of net natural gas importing countries increases relative to net exporters, which is consistent with the baseline results.

Considering that countries with large natural gas reserves may still import natural gas, we further replace the proven natural gas reserves with the per capita natural gas reserves in 2005. First, a dummy variable for the per capita natural gas reserves in 2005, $Pg_{i,2005}$, is constructed. If the per capita natural gas reserves are below the median, the value of the dummy variable is set to 1, otherwise it is set to 0. Next, the per capita natural gas reserves, $PSg_{i,2005}$ (unit: 100 million tons), is constructed to replace the log of natural gas proven reserves, $\ln Sg_{i,2005}$, in the regression model. The results are presented in columns (1)–(2) of Table S2, which indicate that countries with lower per capita reserves exhibit a relatively greater increase in implied energy intensity after the shale revolution, again aligning with the benchmark results.

4.2.2. Changing fixed effects

To address potential heterogeneity in sectoral responses across countries and over time, we further include country-by-industry and year-by-industry fixed effects to address omitted variable bias. The results, reported in Table S3, show that the coefficient of the core variable remains consistent, confirming the robustness of our findings.

4.2.3. Placebo test

We also conduct a placebo test by randomly reassigning the timing of the shale gas revolution and then repeat the estimation 1000 times. As shown in Fig. S3, the estimated coefficients are almost insignificant at the 10% level, whereas the actual interaction coefficient remains significantly negative. This confirms that the results are not driven by random shocks or unrelated policy interventions.

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5.1. Mechanism analysis

5.1.1. The US shale gas revolution and the international trade of natural gas

As U.S. import demand declined and its export increasingly expanded, natural gas supplies originally directed to the U.S. were reallocated to other energy-importing countries. This redistribution increased natural gas inflows to these countries and, in turn, raised their sectoral implied energy intensity. To test this mechanism, we replace the dependent variable with national natural gas trade volume and apply the IHS transformation for estimation. Given that the U.S. became a net exporter after 2017 under Trump's pro-fossil fuel policies, we further introduce time dummies for 2006 and 2017 to distinguish short-run and long-term effects.

Table 3 reports the estimation results. Column (1) uses net natural gas imports as the dependent variable, while columns (2) and (3) replace it with the logarithmic values of natural gas imports and exports, respectively. Column (4) takes net natural gas imports from the U.S. as the dependent variable, and columns (5) and (6) use the logarithmic values of imports from and exports to the U.S. The key independent variables are interaction terms

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The impact of the U.S. shale gas revolution on international natural gas trade.

Dependent variables	*Netim*	ln *im*	ln *ex*	*UNetim*	ln *Uim*	ln *Uex*
	(1)	(2)	(3)	(4)	(5)	(6)
$-\ln Sg_{i,2005} \times I_{t,2006-2016}^{\text{Post}}$	0.003***	0.001**	−0.001*	0.000	−0.000	0.000**
	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
$-\ln Sg_{i,2005} \times I_{t,\geq 2017}^{\text{Post}}$	0.003**	0.002**	−0.001	−0.001	0.000	0.000*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)
Constant	0.025***	0.019***	0.002	0.003***	0.001	0.000***
	(0.007)	(0.004)	(0.003)	(0.001)	(0.001)	(0.000)
Year FE	Y	Y	Y	Y	Y	Y
Country FE	Y	Y	Y	Y	Y	Y
N	4809	4809	4809	4809	4809	4809
R^2	0.165	0.478	0.257	0.087	0.099	0.015

Notes: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$; Standard errors are clustered at the country-industry level and are presented in parentheses.

between two time dummy variables and the inverse of the logarithm of proven natural gas reserves, with time and country fixed effects controlled. The results show that the U.S. shale gas revolution has a significant short-term effect on increasing natural gas imports in countries with lower reserves. However, this increase mainly reflects imports from other suppliers rather than directly from the U.S. (columns 2 and 5). Furthermore, such countries also reduced natural gas exports (column 3). In the long term, the shale evolution leads to a rise in U.S. natural gas exports and reshapes global trade patterns, although the magnitude of this effect is relatively modest.

5.1.2. The shale gas revolution in the U.S. and potential competition with natural gas

We further test whether the U.S. shale gas revolution reshaped potential competition in global natural gas trade. The potential competition index is used as the dependent variable to examine changes in competition between the U.S. and other countries, as well as among non-U.S. countries.

The results in Table 4 indicate that the shale revolution increased potential export competition between the U.S. and countries with higher natural gas reserves in both the short and long term, suggesting intensified supplier-side competition. Among non-U.S. countries, potential competition in natural gas imports remains unchanged, while export competition increases significantly. This implies that the shale gas revolution enhanced the market power of importing countries.

Second, in terms of mechanisms, the paper finds that the U.S. shale gas revolution influenced the implied energy intensity of other countries' industries through international natural gas trade. In the short term, the shale gas revolution led countries with lower gas reserves to increase natural gas imports from other exporting countries to fill domestic supply gaps. In the long term, the revolution increased U.S. exports to other countries while reducing its own natural gas imports, suggesting that the surge in U.S. shale gas production structurally changed global supply and demand in the natural gas market.

Third, the heterogeneity analysis reveals that the impact of the U.S. shale gas revolution on implied energy intensity varies across industries and geographical distances. Specifically, it had significant effects on the implied energy intensity of public utilities, agriculture, services, sanitation, and capital-intensive industries. The analysis by geographic distance shows that the revolution had a more pronounced effect on countries located at short and medium distances from the U.S., highlighting the importance of geographic proximity in the spillover of energy technology. Moreover, an analysis of the heterogeneity of energy use in the power generation sector shows that the revolution increased both fossil fuel and renewable energy use in countries with lower natural gas reserves.

Based on these findings, the following policy implications emerge:

First, in terms of energy security and dependence, we find that the U.S. shale gas revolution has enhanced U.S. influence in global fossil energy markets. Countries with high energy import dependence—especially in Asia and Europe—should recognize the risks associated with external supply shocks and respond by increasing investment in the research and development of both unconventional fossil energy and renewable energy technologies. By diversifying energy sources and strengthening energy independence, these countries can enhance their energy security and mitigate risks arising from external energy market fluctuations.

Second, the shale gas revolution has significantly altered global trade patterns by reshaping natural gas flows. Our results suggest that trade-induced spillovers affect energy use across countries and industries in asymmetric ways. Policymakers should proactively monitor shifts in global energy trade networks and develop adaptive trade strategies—particularly for gas-exporting nations facing intensified competition. For energy-importing countries, enhancing infrastructure to accommodate diversified suppliers can reduce reliance on dominant exporters. In this context, regional cooperation becomes critical for reducing uncertainty and ensuring stable supply chains.

Third, in terms of technological innovation and industrial transformation, the shale gas revolution demonstrates that energy technology progress generates spillover effects across regions and industries. While the shale gas revolution may have led to increased fossil fuel use in some countries in the short term, long-term environmental policies are needed to encourage clean energy adoption. To promote industrial upgrading and sustainable energy development, countries should consider their energy endowments, market dynamics, and technology trends when formulating energy policies, increase support for emerging energy technologies, and advance cross-industry and cross-regional collaborative innovation through energy sector innovation.

In conclusion, the U.S. shale gas revolution has not only reshaped the global energy market landscape but also had far-reaching effects on energy consumption patterns and industrial structures in other countries through multiple mechanisms. This study provides important empirical evidence on the international spillover effects of energy technological progress and offers valuable insights for policymakers in formulating responses to energy security and environmental challenges. Looking ahead, as energy technologies continue to evolve and the global energy market undergoes further transformation, countries must strengthen cooperation to collectively address energy and environmental issues and promote sustainable global development.

C t t tt t

- **:** Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **:** Supervision, Resources, Funding acquisition, Conceptualization. **-** **:** Writing – review & editing, Validation, Formal analysis.

C t t t

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