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Does the U.S. Export Global Warming? Coal Trade and the Shale Gas Boom

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Abstract

We examine the effect of the U.S. Shale Gas Boom on global trade and consumption of coal and CO_2 emissions. We estimate a structural model that links the domestic to the international coal market and use it to simulate counterfactual scenarios. Our results show that the total quantity of coal traded around the world in the absence of the Boom is essentially the same as the actual. A compositional change towards dirtier coal could still have significant environmental effects; we show that this is not the case either. Hence, U.S. coal exports simply displaced other coal without affecting global emissions.

Keywords: Coal, Emissions, International Trade, Shale Gas Boom.
JEL codes: F18, L13, Q53.

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1 Introduction

"Even as our nation is pivoting toward a more sustainable energy future, America's oil and coal corporations are racing to position the country as the planet's dirty energy dealer supplying the developing world with cut-rate, high-polluting, climate-damaging fuels. Much like tobacco companies did in the 1990s–when new taxes, regulations and rising consumer awareness undercut domestic demand–Big Carbon is turning to lucrative new markets in booming Asian economies where regulations are looser. Worse, the White House has quietly championed this dirty energy trade."–How the U.S. Exports Global Warming, Tim Dickinson, Rolling Stone, 02/03/2014.

In this paper, we examine the effects of the change in a country's consumption of fossil fuels on the environment worldwide via trade flows. Our work is motivated by the change in the mix of fossil fuels consumed by the U.S. electric power sector. This exogenous change was triggered by the dramatic drop in the price of natural gas in the aftermath of what has become known as the "Shale Gas Boom," (henceforth, Boom) due to new developments in hydraulic fracturing and horizontal drilling (Figure 1). Although the domestic environmental implications of the Boom have been well-studied, to the best of our knowledge, the global environmental implications have not; the paper aims to fill this void.

The downward pressure on the price of U.S. coal due to lower domestic demand by the electric power sector—which has historically accounted for more than 80% of coal consumption—coupled with the inability of the U.S. to export cheap natural gas in large scale made U.S. coal an attractive option for coal-importing countries. In 2009Q1, the U.S. exported 4.2 million metric tons of steam coal for electricity generation while in 2012Q2 it exported almost four times as much. The lower domestic demand for coal by the electric power sector has been attributed, to a large extent, to the dramatic drop in the price of natural gas (gas).[1]

The changing landscape in the U.S. electric power sector due to the Boom, has a two-pronged effect on the trade flows of coal around the world. First, there is a decrease in the domestic demand for coal. Second, there is an increase in export supply of U.S. coal because domestic

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[1] In June of 2008, the average monthly price of gas paid by U.S. power plants was \$12/MMBtu, while that for coal was around \$2/MMBtu. By April of 2012, the coal and natural gas prices were almost at parity with the vast amounts of cheap natural gas that flooded North America being the primary driver of this big change in the relative price of the two fuels. Gas-fired generation was virtually identical to coal-fired generation for the first time since the U.S. Energy Information Administration (EIA) has been collecting data. See `https://www.eia.gov/todayinenergy/detail.php?id=6990`. The widespread coal-to-gas switching throughout the industry, for which we should not also discount contemporaneous environmental policy, and its implications for emissions, are by now well documented. See Linn and Muehlenbachs (2018), Cullen and Mansur (2017), and Knittel et al. (2015), among others. Hausman and Kellogg (2015) provide an in-depth analysis of the economic and environmental impacts of the shale revolution.

producers are looking for alternative markets to sell their product at competitive prices. Translating these domestic comparative statics to global comparative statics of flows of coal around the world is ultimately an empirical question and the answer depends on export supply and import demand elasticities, whose magnitude is determined by several factors. To begin with, the U.S. export supply elasticity is affected by the ability of domestic coal producers to ship coal outside the country.[2] At the same time, the import demand elasticities for U.S. coal in major consuming regions such as Western Europe, China, Japan, and Korea, depend on the availability of, or lack of, close substitutes.

The implications of an increase in exports of U.S. coal for global emissions associated with coal trade are ambiguous. They depend both on the aggregate level and on the composition of world trade flows. For example, an increase in U.S. coal exports may lead to a moderate or no increase in emissions elsewhere if U.S. coal simply displaces domestic coal, or, say, Australian coal, in other countries. Of course, other less or more desirable outcomes, in terms of the Boom's global environmental implications, are possible. This is the case, for example, if low-sulfur (cleaner) coal is displaced by high-sulfur (dirtier) coal.

Our empirical approach to assess the Boom implications on global emissions builds on an econometric model with an international and a domestic component.[3] The first component draws from the literature on international trade. Following Soderbery (2017), we estimate the link between U.S. exports and the global market for coal focusing on the mechanism through which the U.S. gas market affects U.S. coal production and exports. Our trade model allows for upward-sloping export supply curves, which is a notable difference from the standard gravity models that assume perfectly elastic export supply curves, in a partial equilibrium framework. Assuming that export supply curves are subject to shocks (shifts), we treat the Boom as a shock to U.S. coal exports. We then construct counterfactual coal trade flows in the absence of the Boom, which we model as a negative shock to the U.S. export supply of coal.

We allow export supply elasticities to exhibit heterogeneity across importers, goods, and exporters, in contrast to Broda and Weinstein (2006) and Feenstra (1994) (henceforth, FBW). We do so because, although homogeneous import demand elasticities find empirical support

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[2] The ability of U.S. coal producers to ship coal outside the country depends on the current infrastructure of major railroads and ports in the Eastern seaboard that have historically served European markets with metallurgical coal from the Appalachian region. Port infrastructure on the Pacific coast is also very important for U.S. coal producers, especially those in the Western region, for accessing the Asian market. A similar point can be made for the mine, rail, and port utilization in Indonesia, and Australia, which are the world's largest coal producers.

[3] We recognize that both econometric and computable general equilibrium (CGE) models have their advantages and disadvantages.

in the trade data, homogeneous export supply elasticities do not (Soderbery (2015)). In our case, the imported good is one of three types of coal: anthracite, bituminous, and other. Following the standard approach in the literature, a variety is defined by the country of supply for a particular good (Armington (1969)).[4] While the FBW approach is better suited than gravity models for our analysis, their assumption of homogeneous export supply curves across exporters within an importing country is restrictive. Allowing for this heterogeneity is crucial in our case because the shock to the model in our counterfactual scenario starts from one particular (U.S.) export supply curve and then propagates to the rest of the world. Importantly, as we show later in the paper, such heterogeneity in export supply elasticities has material implications for the conclusions of our analysis.

The second component of our econometric model links U.S. coal production to the domestic price of gas. The trade model allows us to estimate import demand and export supply elasticities while the model for the domestic market—"domestic model"—provides the link between the international market for coal and the U.S. price for gas through the U.S. export supply curve. Having established this link, we calculate counterfactual world coal trade flows eliminating the drop in the U.S. price of gas caused by the Boom. Then, using information on the heat, carbon dioxide (CO_2), and sulfur dioxide (SO_2) content of coal, we translate these trade flows into emissions to estimate the global environmental impact of the Boom.

For our trade model, we use the nonlinear SUR estimator in Soderbery (2017) and UN COMTRADE data between 1990–2014 to estimate import demand and export elasticities, as well as shocks to the export supply curve for U.S. coal. We then utilize the first-order conditions of the domestic model to link these shocks to the domestic price of gas in the U.S.. Estimating the relationship between the price of gas in the U.S. and Europe for 1990–2006, we construct counterfactual U.S. gas prices for 2007–2014. Our assumption is that these counterfactual prices are the ones that would have prevailed in the absence of the Boom. The counterfactual U.S. gas prices allow us to construct counterfactual shocks to the U.S. export supply that translate into counterfactual coal trade flows.

We report detailed results regarding our counterfactual analysis for approximately 40 countries that account for more than 90% of global coal imports and exports during the period of interest. The same group of countries also accounts for more than 90% of imports of U.S. coal. We find that, in the absence of the Boom, the quantity (metric tons) of coal traded is only 0.16% higher than the actual quantity traded. The price (USD/metric ton) and dollar value of coal also increase by less than 0.72%. Moreover, after accounting for heterogeneity in the heat and sulfur content and changes in the equilibrium of the global coal market, we

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[4] For example, U.S. bituminous coal is a different variety from Australian bituminous coal.

find that the CO_2 and SO_2 emissions associated with coal trade flows also remain virtually the same. By accounting for equilibrium global reallocations, and in contrast to commentary around the time of the surge in U.S coal exports, we show that U.S. coal exports simply displaced other coal exports without increasing the total quantity of coal traded and the associated emissions during the Boom.[5] Furthermore, in the absence of the Boom, there is a decrease of 29.7% (27.2%) in the quantity and dollar value of U.S. coal exports with U.S. coal exporters losing $22.3 billion in revenue.

The literature on the global environmental effects of country-level energy shocks is scarce. Our work is most closely related to Wolak (2016). Wolak uses a spatial equilibrium model to assess how the Boom impacted global coal market outcomes accounting for coal-to-gas switching in the electricity sector in the U.S. and Europe, the potential for China to exercise buyer power, and the impact of increasing the coal export capacity of the ports in the Western U.S.. Wolak' paper and ours are quite different in terms of methodology and focus. While his model is mostly calibrated, ours is fully estimated from existing data. On one hand, Wolak's model is better equipped to handle the substitution between coal and gas than our model, which is important for the electric power sector in North America and Western Europe only. Albeit in an informal way, we explore the possibility of substitution between coal and natural gas and its implications for our main results. On the other hand, his model lacks some of the flexibility of our model in terms of trade elasticities. This flexibility is crucial for our counterfactuals because we consider a shock to the export supply curve of a single country. Importantly, we show that a version of our model with limited heterogeneity in export supply elasticities has material implications for our results.

Our paper also contributes to a recent literature on the interplay between environmental economics and international trade studying the effects of the Boom, with the work by Eyer (2014) being the most closely related to our paper. Eyer estimates the effect of domestic natural gas prices on U.S. coal exports and finds that a 1% increase in the domestic price of natural gas leads to a 2.2% decrease in U.S. coal exports.[6] According to his findings,

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[5] According to Afsah and Salcito (2014) had U.S. steam coal exports in each year between 2007 and 2012 been 20.7 million short tons, which is the annual average for 2000–2007, the counterfactual U.S. steam coal exports would have been 82.7 million short tons. Between 2007 and 2012, the actual U.S. exports of steam coal were 207 million short tons. The implied additional CO_2 emissions due to increased exports following the shale gas boom are approximately 149 million tons (see Exhibit 3). In the same paper, the authors show that coal-to-gas switching in the U.S. electric power sector led to a decrease in CO_2 emission of 86 million tons. Hence, there is a net increase in CO_2 emissions of 149-86=63 million tons.

[6] Eyer regresses the log of quarterly coal exports from U.S. ports on the average price of natural gas near each port, the growth rate of world GDP, a time trend, and quarterly fixed effects. He also includes a set of customs region fixed effects. He presents results from an additional specification in which he instruments for the price of natural gas using the number of heating degree days and the number of cooling degree days as instruments.

approximately 75% of the displaced U.S. steam coal was shipped abroad. Although an interesting exercise, Eyer's analysis does not allow for substitutability between U.S coal exports and other coal exports, which are important for the global balance of trade and the associated environmental implications. Arezki et al. (2017) find that U.S. energy-intensive manufacturing sectors benefited from the reduced gas prices due to the Boom. A back-of-the-envelope calculation suggests that energy-intensive manufacturing exports increased by $101 billion in 2012 due to the Boom. Shapiro (2016) finds that the benefits of international trade exceed environmental costs due to CO_2 emissions by two orders of magnitude. While proposed regional carbon taxes on shipping-related CO_2 emissions would increase global welfare and increase the implementing region's GDP, they would also harm poor countries (see also Cristea et al. (2013)).[7]

The remainder of the paper is organized as follows. In Section 2, we provide a background on U.S. coal production and exports, as well as on international coal trade, which the reader familiar with the industry may want to skip. Section 3 first describes the model of international trade and then the model of the U.S. domestic coal market. The empirical findings are reported in Section 4 and the results of the counterfactual trade flows in the absence of the Boom are presented in Section 5. Some additional discussion, extensions, and robustness checks to our main results, follow in Section 6. We finally conclude. All tables and figures are provided after the main text. We relegate some additional material to the on-line Appendix.

2 Background

2.1 U.S. Coal

Production: The U.S. has vast amounts of energy in coal fields that spread across its Appalachian, Interior, and Western regions. The Powder River Basin (PRB) alone contains one of the largest sources of energy on the planet with over 200 billion short tons of coal in place, which is equivalent to more than 3,616 quadrillion Btu (quads). According to figures from the World Energy Council for 2011, the U.S. accounts for 28% of global recoverable coal reserves followed by Russia (18%) and China (13%) noting that 10 countries account

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[7] The effect of trade on the environment is theoretically ambiguous. The race-to-the-bottom hypothesis (negative effect) competes against the gains-from-trade hypothesis (positive effect). For example, Frankel and Rose (2005) find that trade tends to reduce three measures of air pollution; in particular, sulfur dioxide and nitrogen dioxide. According to the authors, while results for other environmental measures are not as encouraging, there is little evidence that trade has a detrimental effect on the environment.

for more than 92% of global reserves.[8]

Coal is an organic rock that contains 40%–90% carbon by weight and it is classified into four types (ranks) based on the amount of heat it produces and, for coking or metallurgical coal, its agglomerating ("caking") properties.[9] Lignite is the lowest coal rank. It is a brown coal and it is used almost exclusively as fuel for steam electric power generation with a heat content of 9–17 MMBtu per ton. It is mainly produced in North Dakota and Texas. Sub-bituminous coal, the second type of brown coal, is also used in electric power generation and has a heat content of 17–24 MMBtu. It is produced in vast amounts in the PRB. Bituminous coal, one of the two hard coals, produced in the Appalachian region and the Midwest, has a content of 21–30 MMBtu. It can be used as steam coal in electricity generation, as well as metallurgical coal in steel production. Finally, anthracite, the second of the hard coals, is the highest coal rank with a heat content of 22–28 MMBtu. It is extracted in the U.S. only in northeast Pennsylvania. Between 1994 and 2015, bituminous and sub-bituminous coal have accounted for 93% of annual US production (tons), while anthracite has accounted for less than 1% (EIA, Annual Coal Review).

Exports: Coal consumption by the U.S. electric power sector during 2004–2008 was close to 1 billion short tons, its highest levels since 1992. By 2012, it fell to 824 million short tons because of the drop in gas prices, the slowdown of the economy due to the Great Recession, and a series of regional and federal environmental regulations aiming to curb coal-related emissions. This contraction of the domestic market was accompanied by the surge in exports of U.S. coal exports documented in Figure 1 attracting increased attention in the popular press.[10] As a result, the exports' share in production increased from 5.3% to 12.5% (Figure 2).[11]

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[8] Each of the remaining countries—Australia, India, Germany, Ukraine, Kazakhstan, Indonesia, and Serbia—accounts for less than 10%.

[9] Coking coal refers to bituminous coal suitable for making coke used as a fuel and as a reducing agent in smelting iron ore.

[10] As an example, Andrew Revkin of The New York Times was writing that the "U.S. Push to Export Dirty Fossil Fuels Parallels Past Action on Tobacco," in February, 2014.

[11] Based on data from the EIA and Department of Commerce. Between 2007 and 2012, the share of bituminous coal in U.S. exports increased from 64% to 84%, while the share of other coal decreased from 35% to 15% noting that U.S. coal production dropped from 1,147 million short tons in 2007 to 1,016 million short tons in 2012 (EIA, International Energy Statistics). Section A.1 provides some additional information regarding the split between metallurgical and steam coal of U.S. exports, as well as the customs districts from which U.S. coal is shipped. To give the reader an idea about the magnitude of the increase in coal exports, in 2008, the U.S. exported 5.8 (3.1) million short tons of coal—steam plus metallurgical—to Brazil (France) noting that U.S. coal exports to both countries exhibited an upward trend between 2002 and 2013 and more so in the case of Brazil. In 2012, U.S. coal exports to the two countries were 7.2 and 3.7 million short tons, implying an increase of 24% and 19%, respectively.

2.2 International Trade

According to the EIA international energy statistics, world coal consumption increased from around 5 billion metric tons in 1990 to more than 7.5 billion metric tons by 2012 (Figure A.1, panel (a)).[12] During this time, coal trade increased from 400 million metric tons to more than 1.2 billion (panel (b)) with seaborne trade accounting for about 85% of all trade in the last 25 years.[13] Historically, two regions, Europe (Atlantic Market) and Asia (Pacific Market) have played a key role in coal trade following different trends in recent years as we discuss below. Overall, less than 40 countries account for more than 90% of total exports, total imports, and imports of U.S. coal during this period (Table A.2).

Australia, Indonesia, the U.S., Russia, Colombia, and South Africa are the top exporters, with the first two accounting for more than half of all exports after 2010. Overall, the countries listed in panel (c) of Figure A.1 accounted for more than 80% of all coal exports during 1990–2012. Australia, Indonesia, Russia, and the U.S. account for about 70% of total coal exports (tons) for 1990–2014 (Table A.3). Ten countries accounted for more than 2/3 of annual world coal imports during 1990–2014 (panel (d)). Japan's share of world imports fell from around 50% in 1990 to close to 20% in 2014. Korea's share remained relatively stable around 10%, while China's share was close to 20% for 2010–2014. India's share increased from less than 10% in 2010 to about 20% in 2014, while none of the remaining countries has accounted for more than 5% during the same period (Table A.4). Canada, Japan, Brazil, Italy, and Great Britain, accounted for half of the imports of U.S. coal during 1990–2014 period (Table A.5).

Setting aside the vast energy needs of China and India in recent years, a series of events have also contributed to an increase in the demand for coal worldwide, which in turn also contributed to the increase in U.S. coal exports. The European Union (E.U.) Emissions Trading System essentially collapsed by early 2006 leading to a dramatic drop in the CO_2 permit prices. The Arab Spring began in December 2010 in Tunisia disrupting the E.U. natural gas markets that have historically relied on gas originating in Africa (e.g., Algeria, Egypt, Nigeria). Japanese demand for coal and natural gas increased in March of 2011 due to the Fukushima nuclear accident. The Bowen Basin in Australia, which accounts for close to a third of global metallurgical coal production was hit by floods in December of 2011.[14] More recently, in May 2012, Germany announced that it would retire all its nuclear capacity by 2022 increasing Germany's demand for alternative sources of energy. In early

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[12] We use ISO Alpha 3 country codes to identify countries in various tables and figures. See Table A.1.

[13] Based on annual figures from the IEA Coal Information 2014 (see Table 3.1).

[14] `https://goo.gl/TZ1GMK`.

2014, Russia, one of the E.U. largest suppliers of energy, invaded Ukraine causing major gas supply disruptions in the E.U. market.[15]

Figure A.2 shows the annual time series of the quantity (million metric tons), value (billion USD), and price (USD/metric ton) of UN COMTRADE import data for the three types of coal used in estimating our international trade model: anthracite, bituminous, and other coal. Consistent with our earlier discussion, there is an upward trend in both quantities and dollars across all three types of coal with the bituminous coal accounting for more than 70% during the entire period. Between 1990 and 2000, coal prices decreased from around $60 per metric ton to almost $40. Between 2000 and 2011, prices for bituminous coal increased by a factor of 3 reaching $160 per ton in 2011 after a brief drop in 2009–2010 due to the most recent recession.[16]

Figure A.3 shows that import prices paid for coal (USD/metric ton) in China, India, Japan, and Korea, are highly comparable and follow the same pattern over time, especially prior to 2005 (panel (a)). The import prices paid in major European markets, such as Germany, Great Britain, the Netherlands, and Spain, also track each other closely and are comparable to those in Asia (panel (b)). In general, the price spread between the European and Asian markets is small. Import prices for coal originating from major producing countries, such as the US, Australia, Indonesia, Russia, Colombia, Canada, and South Africa, track each other closely, which is consistent with spatial arbitrage and competitive supply (panels (c) and (d)). Some signs of divergence in prices, however, seem to have emerged post 2008.[17]

3 Model

Our trade model is designed to quantify competitive equilibrium responses to export supply shocks on a market-by-market basis. In what follows, we link a structural model of the U.S. domestic markets for coal and gas to global markets. To do so, we set the micro-foundations of export supply curves using a flexible model of domestic production of coal. Our model allows us to establish a structural link between the U.S. domestic markets of coal and gas along with how shocks in these domestic markets affect U.S. coal exports around the world.

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[15] This is because Ukraine is the main corridor of Russian natural gas to the E.U.

[16] Section A.2 provides information regarding the primary destinations (sources) of bituminous coal for major exporters (importers).

[17] There is plenty of evidence that the world market for steam coal is integrated, which is in sharp contrast with the world market for natural gas, where three distinct markets have been developed over time: Asian market, European market, and U.S. market.

3.1 International Trade

We maintain common assumptions from new trade theory in a model that is amenable to structural estimation. Once estimated, the model allows us to quantify the welfare implications of CO_2 emissions associated with coal imports due to the effect of U.S. gas prices on the global coal trade. We bring the model to the data following common functional forms and the estimation strategy in Soderbery (2017).

To introduce some notation, we use I to denote the importing country, g to denote the imported good, and v to denote the variety of the imported good. The total number of goods imported by country I is G^I and the total number of varieties is G^I_v. Goods are defined by their COMTRADE HS6 code and their varieties are determined by their country of origin. For our purpose, a good is one of three types of coal: anthracite, bituminous, and other. Following the Armington tradition, U.S. bituminous coal imported in Japan is a different variety from Australian bituminous coal imported in Japan due to physical characteristics, such as heat content (calorific value), sulfur content, ash content, moisture, etc..[18]

We consider a representative consumer in importing country I with constant-elasticity-of-substitution preferences (CES) for variety v of coal type g. The representative consumer aggregates consumption of imported coal varieties via Cobb-Douglas preferences. These underlying assumptions give rise to the following utility function at time t:

$$U^I_t = \prod_{g=1}^{G^I_t} (Q^I_{gt})^{\alpha^I_{gt}} \tag{1}$$

$$Q^I_{gt} \equiv \left(\sum_{v=1}^{G^I_{vt}} (b^I_{gv})^{\frac{1}{\sigma^I_g}} (q^I_{gvt})^{\frac{\sigma^I_g - 1}{\sigma^I_g}} \right)^{\frac{\sigma^I_g}{\sigma^I_g - 1}}, \tag{2}$$

where Q^I_{gt} is the CES aggregate consumption of imported coal varieties assuming G^I_{vt} varieties in total with G^I_t being the total number of goods. Additionally, $\sigma^I_g > 1$ is the elasticity of substitution across coal types and b^I_{gv} are demand shocks that capture variety-specific tastes.

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[18] We use the following the HS6 codes 270111 (anthracite, pulverized or not, not agglomerated), 270112 (bituminous, pulverized or not, not agglomerated), 270119 (other coal, except anthracite or bituminous, pulverized or not, not agglomerated). See `http://comtrade.un.org/db/mr/rfCommoditiesList.aspx?px=H1&cc=2701`. As an example, if Japan imports all three types of coal from the U.S. and Australia only, $G^I = 3$ and $G^I_v = 6$.

For example, b^I_{gv} may capture the fact that coal of type g originating in country v is better suited for the steel industry or the electric power sector due to its coking properties and its sulfur content, respectively. Because of the Cobb-Douglas preferences across coal types, the expenditure for coal type g accounts for α^I_{gt} of the total expenditure associated with purchases of imported coal.

Although we model preferences similar to Shapiro (2016), our approach generally departs from his. Shapiro focuses on emissions due to the transport of a wide range of goods while, we focus on emissions associated with coal trade alone. Hence, we are interested in structurally estimating demand and supply in the world market for coal and the welfare effects from changes in the consumption of imported coal. Notably, assuming utility is log-separable across goods, we can focus on the market for coal in importing countries holding other trade constant, without loss of generality.

We model the international market for coal following Soderbery (2017) and estimate import demand and export supply elasticities allowing for substantial heterogeneity. The import demand for coal of type g implied by (1) is:

$$q^I_{gvt} = \alpha^I_{gt} b^I_{gv} (p^I_{gvt})^{-\sigma^I_g} (\mathcal{P}^I_{gt})^{\sigma^I_g - 1} \tag{3}$$

$$\mathcal{P}^I_{gt} \equiv \left(\sum_{v=1}^{G^I_{vt}} b^I_{gv} \left(p^I_{gvt}\right)^{1-\sigma^I_g} \right)^{\frac{1}{1-\sigma^I_g}}, \tag{4}$$

where p^I_{gvt} is the delivered price and $\mathcal{P}^I_{gt}$ is the CES price index. We combine import demand with a flexible export supply specification to facilitate structural estimation. We assume monopolistic competition among exporters with export supply curves that are variety- and exporter-specific as in Armington (1969) and upward-sloping with a constant inverse export supply elasticity ω^I_{gv}:

$$p^I_{gvt} = exp(\eta^I_{gvt})(q^I_{gvt})^{\omega^I_{gv}}. \tag{5}$$

We also allow for unobservable variety-specific supply shocks η^I_{gvt} for estimation. These shocks serve as the channel through which changes in U.S. gas prices affect the world coal trade flows. The U.S. Shale Gas Boom (Boom) serves as a positive shock to the U.S. coal export supply curve. Given estimates of the import demand, σ^I_g, and inverse export supply, ω^I_{gv}, elasticities, we can calculate the demand and supply shocks using (3) and (5). We then use the firms' profit-maximizing first-order conditions from the domestic model to link U.S.

gas production to world coal trade through these shocks.

3.1.1 Brief Digression on Domestic Coal and Natural Gas

For our main results, we assume separability in the utility over the composite domestic (d) and imported goods along the lines of:

$$U_t^I = (Q_{dt}^I)^{\alpha_{dt}^I} \prod_{g=1}^{G_t^I} (Q_{gt}^I)^{\alpha_{gt}^I}. \tag{6}$$

This assumption allows us to focus on prices and the consumption of imported goods for estimation and relax the constraint imposed by the lack of data, primarily on prices, for domestic coal. In a subsequent section, we allow for substitutability between domestic and imported coal and show that the qualitative conclusions of our analysis are robust to including domestic coal in our model.

The setup discussed so far does not allow for substitution between coal and gas, either, which is relevant for electricity generation. Wolak (2016) makes a strong case that such substitution is only possible in North America and Western Europe because of the availability of gas supplied by pipelines and the current gas-fired generation mix in the short and medium term. Hence, by ignoring the substitutability between domestic and imported coal, as well as between gas and imported coal, our elasticity demand estimates may be somewhat biased for countries in Western Europe and North America. Later in the paper, we provide both informal arguments and some empirical facts to show that the substitution between coal and natural gas cannot alter our main results in a material way.

3.2 Domestic Market

We now sketch a stylized model for the U.S. domestic production of coal, which will allow us to establish a link between the U.S. coal export supply shock and the domestic price of gas. We consider a representative firm that extracts coal for sale in the international (f) and domestic (d) markets at time t with (p_{ft}^c, q_{ft}^c) and (p_{dt}^c, q_{dt}^c) being the corresponding prices and quantities.

Consistent with the assumption of monopolistic competition in exports of the trade model, the firm is a price-taker in the foreign market but faces a downward-sloping residual demand curve in the domestic market. The domestic inverse demand for coal is a function of the domestic gas price, p^g_{dt}, and a demand shifter to account for additional factors driving the demand for coal, w_{dt}, such as fossil-fuel generation by electric power plants. Assuming linearity, we write:

$$p^c_d(q^c_{dt}, p^g_{dt}, w^n_{dt}; \theta) = \theta_0 + \theta_1 q^c_{dt} + \theta_2 p^g_{dt} + \theta_3 w_{dt}, \tag{7}$$

where $\theta \equiv (\theta_0, \theta_1, \theta_2, \theta_3)$. The motivation for the domestic inverse demand curve stems from the fact that electric power plants account for the vast majority of coal consumption and natural gas is the closest substitute for coal during the period that is relevant in our analysis.

The hypothetical representative firm first decides how much coal to sell in the domestic market. Subsequently, the firm decides how much to sell in the foreign coal market. Although arbitrage is not possible, the two markets are related through production costs:

$$C(q^c_{dt}, q^c_{ft}; \gamma) = \beta_0 q^c_{dt} + \beta_1 (q^c_{dt})^{\alpha_d} (q^c_{ft})^{\alpha_f}, \tag{8}$$

where $\gamma \equiv (\beta_0, \beta_1, \alpha_d, \alpha_f)'$. The parameters a_f and a_d, associated with the marginal costs, introduce convexity assuming $a_f > 1$ and $a_d > 1$. The interpretation for the functional form in (8) is that extracting coal for the domestic market makes it more costly to extract coal for the foreign market. It captures the salient feature of the mining costs since extracting more coal entails higher marginal costs. In the absence of the foreign market, extraction to serve the domestic market is done at a constant marginal cost β_0. Furthermore, production for the foreign market has a marginal cost, which is increasing in the quantity for the domestic market. Based on the assumptions above, the firm's profit-maximization problem is as follows:

$$\max_{q^c_{dt}, q^c_{ft}} \; p^c_{dt}(q^c_{dt}, p^g_{dt}, w_{dt}; \theta) q^c_{dt} + p^c_{ft} q^c_{ft} - C(q^c_{dt}, q^c_{ft}; \gamma). \tag{9}$$

Given the sequential nature of the problem, we proceed via backward induction starting with the foreign market, where marginal-cost pricing implies:

$$p^c_{ft} = \beta_1 \alpha_f (q^c_{dt})^{\alpha_d} (q^c_{ft})^{\alpha_f - 1}, \tag{10}$$

$$q^c_{ft} = \left(\frac{p^c_{ft}}{\beta_1 \alpha_f (q^c_{dt})^{\alpha_d}} \right)^{\frac{1}{\alpha_f - 1}}. \tag{11}$$

We then move to the profit-maximization problem for the domestic market:

$$\max_{q^c_{dt}} p^c_{dt}(q^c_{dt}, p^g_{dt}, w_{dt}; \theta) q^c_{dt} + p^c_{ft} q^c_{ft}(q^c_{dt}) - C(q^c_{dt}, q^c_{ft}(q^c_{dt}, p^c_{ft}; z); \gamma), \tag{12}$$

where $z \equiv (a_f, a_d, \beta_1)$ and p^c_{ft} is exogenous. The implied first-order condition that provides the optimal amount of domestic coal production is given by:

$$\theta_3 w_{dt} - \beta_0 + \theta_0 + \theta_2 p^g_{dt} + 2\theta_1 q^c_{dt} + \frac{a_d\,(\beta_1 - 1)}{-1 + a_f} \left(\frac{p^c_{ft}}{a_f \beta_1} \right)^{\frac{a_f}{-1+a_f}} (q^c_{dt})^{\frac{1-a_d-a_f}{-1+a_f}} = 0. \tag{13}$$

In the special case of $\beta_1 = 1$, which does not compromise the most important feature of the assumed cost function—extracting coal for the domestic market makes it more costly to extract coal for the international market—we have the following linear equation to solve for q^c_{dt}:

$$\theta_3 w_{dt} - \beta_0 + \theta_0 + \theta_2 p^g_{dt} + 2\theta_1 q^c_{dt} = 0, \tag{14}$$

which implies

$$q^c_{dt} = H(p^g_{dt}, w_{dt}; \theta, \gamma) \equiv \frac{\beta_0 - \theta_0 - \theta_2 p^g_{dt} - \theta_3 w_{dt}}{2\theta_1}. \tag{15}$$

Given the nature of the profit-maximization problem, knowing the optimal level of domestic production allows us to infer production for the foreign market:

$$q^c_{ft} = G(p^g_{dt}, w_{dt}, p^c_{ft}; \theta, \gamma). \tag{16}$$

Recall that the export supply curve is given by

$$p^I_{gvt} = exp(\eta^I_{gvt})(q^I_{gvt})^{\omega^I_{gvt}}. \tag{17}$$

Using (10), we establish a link between the domestic and foreign markets using the following

$$q^I_{gvt} = q^c_{ft} \tag{18}$$

$$\omega^I_{gv} = \alpha_f - 1 \tag{19}$$

$$exp(\eta^I_{gvt}) = \beta_1 \alpha_f (H(p^g_{dt}, w_{dt}; \theta, \gamma))^{\alpha_d}. \tag{20}$$

4 Empirical Analysis

4.1 International Trade

Data and Estimation: We estimate import demand and inverse export supply elasticities leveraging time variation in prices and quantities within import and across export markets. We obtain consistent estimates of the supply and demand elasticities for every exported variety of coal in every importing country via nonlinear Seemingly Unrelated Regressions (NLSUR) as in Soderbery (2017). Similar to Feenstra (1994) and Broda and Weinstein (2006), the key identifying assumption in Soderbery is that once we control for good and time effects by first- and reference-country differencing the data, the variety-level errors entering the system of demand and supply equations are uncorrelated.

Feenstra's estimator, which entails 2SLS estimation using variety (country of origin) fixed effects as instruments assuming panel data for different varieties in a given market (importing country), cannot accommodate heterogeneity in export supply elasticities. Soderbery's estimator can. It does so by combining the standard system of demand and supply equations for importing countries from Feenstra's estimator with a system of demand and supply equations for exporters ("exporter system"). The estimator requires that the variety-level errors entering the exporter system are also uncorrelated and it invokes a destination-country differencing.[19]

The only data required for our NLSUR estimation are bilateral trade flows associated with country pairs for the three types of coal, which are readily available from the UN COMTRADE data for 1990–2014. The raw data at the HS6 level pertain to 194 exporting and 143 importing countries. Although not all countries trade coal with each other, there are 5,647 inverse export supply elasticities and 413 import demand elasticities to be estimated. Recall that the former exhibit variation by origin (exporting country) and coal type for each importing country (ω^I_{gv}) while the latter exhibit variation by importing country and coal type (σ^I_g) only.[20] Following the elimination of observations associated with some clear price

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[19] For a succinct illustration of Feenstra's estimator see Section 2.3 in Soderbery (2015). The issue with Feenstra's estimator in the case of heterogeneity in export supply elasticities is shown in equations (5) and (6) of Soderbery (2017). Equations (8) and (9) in Soderbery (2017) provide the additional system of demand and supply equations for exporters. Equations (10) and (11) are the NLSUR equations. Note that we apply the Broda and Weinstein (2006) weighting scheme in the NLSUR estimation as in Soderbery (2017) to address measurement error in prices since trade data record unit values.

[20] For example, although we estimate a different inverse export supply elasticity for U.S. and Australian bituminous coal for Japan, we estimate a single import demand elasticity for bituminous coal. During 1990–2014, there were 5 varieties of bituminous coal, from different exporting countries that were shipped to an importing country, on average, each year. The average number of varieties of anthracite and other coal are

outliers, the data used for estimation pertain to 192 exporting and 141 importing countries for a total of 5,258 export supply and 402 import demand elasticities.[21]

To alleviate the computational burden due to the high-dimension of the parameter space and the highly nonlinear nature of the NLSUR optimization problem in hand, we assume countries in the same region have identical supply technologies with some adjustments. In particular, major exporting countries are excluded from the regional aggregation.[22] Although this is a restrictive assumption, it still allows for heterogeneity in our estimates. Importantly, due to the weighting scheme of the NLSUR estimator, the export supply elasticity for a particular region is influenced the most by the data for the region's largest exporter. Applying the estimator requires imports from at least two countries that both export to at least one other destination for a minimum of three periods.

Estimates: Before discussing our elasticity estimates in detail, the reader should note that ω is a measure of importer buyer power. Given that ω governs the degree of pass through of a shock to delivered prices, a large ω implies a high degree of importer buyer power because there is low pass through of any price changes for more inelastic export supply curves.

Table 1 provides basic summary statistics for the inverse export supply (ω^I_{gv}) and import demand (σ^I_g) elasticities for the three types of coal.[23] According to panel B, across all three types of coal—anthracite, bituminous, and other—the median ω is 0.28 while the median σ is 3.3. The standard deviation for the two elasticities is 0.20 and 0.61, respectively. For bituminous coal, which accounts for more than 70% of all coal trade during the period we analyze, the median ω is 0.22 while the median σ is 3.40. The standard deviation of the two elasticities is 0.17 and 0.57.

Table 2 provides summary statistics for ω and σ by major importer in the case of bituminous coal. It also provides information about the size of the importing country in terms of GDP and its imports of bituminous coal in USD and tons. The standard deviation of ω highlights the degree of heterogeneity in the curvature of the supply curves of the exporters serving a particular importer. Table 3 provides summary statistics for ω for major exporters along

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very similar.

[21] The removal of these outliers has no material implications for the total quantity of coal which drops from 15,355.21 to 15,355.15 million metric tons.

[22] Table A.6 and the associated note provides information regarding the aggregation discussed here. An implication of our aggregation is that, for example, Mongolia and Vietnam, which are the 11th and 12th largest exporters accounting for a combined 2.45% of total exports during the period we analyze (see Table A.3), have the same export supply elasticities for bituminous coal because they all belong to the region we define as Asia (ASA).

[23] To economize on notation, we use ω and σ to refer to the inverse export supply and import demand elasticities in the remainder of our discussion.

with information on the size of the exporter similar to Table 2.

For the largest importer in our sample, Japan, the median ω is 0.26 implying a median export elasticity, $1/\omega$, equal to 3.84, such that a 1% increase in the price of bituminous coal leads to a 3.84% increase in bituminous coal exports to Japan. Among Japan's major exporters, the U.S. and Russia are the ones with the smallest and largest ω values of 0.10 and 0.91, respectively. For Australia and Indonesia, which account for 3 out of 4 tons of bituminous coal exported to Japan, the ω values are 0.26 and 0.30, respectively.

For China, the median ω is 0.05. Among countries exporting bituminous coal to China, the smallest ω values are those for Australia, Indonesia, Kazakhstan, and Mongolia, while the largest one is for South Africa. Because Australia, Indonesia, and Mongolia, collectively account for 71% of China's bituminous coal imports, a plausible explanation for the magnitude of our estimates is China's reliance on imports from them. The ω values for other major producers exporting to China are as follows: 0.10 (Russia), 0.27 (Colombia), and 0.51 (U.S.). Although Russia accounts for the rather notable 8% of China's bituminous coal imports that makes China rather reliant on Russian coal, Colombia and the U.S. account for 3% and 0.9%, respectively.

For the big European importers of bituminous coal, the median ω values are between 0.10 for Great Britain and Spain and 0.25 for Italy. In the case of Brazil, the median ω is 0.45. However, there is a substantial heterogeneity in the values of ω for the Latin American country with its standard deviation being 1.58. Substantial heterogeneity is also a feature of the ω values for Russia. India, which is the smallest importer of bituminous coal, has a median ω value of 0.45.

Among the largest exporters, the U.S., Kazakhstan, and Poland are the least exposed to importer buyer power with median ω values in the tight range 0.12–0.13 (Table 3).[24] For Australia, Indonesia, Colombia, and South Africa, the median ω values are 0.19–0.27. The biggest importers of Australian bituminous coal are Japan (57%), Korea (18%), and China (10%), with the remaining importers accounting for no more than 2% each. The same three countries are also the biggest importers of Indonesian bituminous coal accounting for 35% (Japan), 25% (Korea), and 15% (China) of Indonesia's total exports. Both Colombian and South African bituminous coal have multiple European destinations (e.g., the Netherlands, France, Germany) whose individual imports account up to 17% of the two counties' exports.[25]

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[24] In the case of the U.S., no major importing country accounts for more than 12% of its bituminous coal exports. For Kazakhstan, Russia (55%) and Ukraine (26%) together account for 81% of its exports. Germany (41%) and France (16%) account for about a half of Poland's exports with several other European countries accounting for 2%–5% each.

[25] In the case of Canada and Russia, the median ω values are 0.35 and 0.91, respectively. About 70% of

Moving to the import demand elasticities reported in the rightmost column of Table 2, we see σ values between 2.26 for Russia, and 5.98 for Brazil. On one hand, almost the entirety (94%) of Russia' imports of bituminous coal are from Kazakhstan (69%) and the U.S. (25%), which means that there are few substitutes available to Russia. This limited substitutability offers a plausible explanation for the low elasticity we estimate for Russia. On the other hand, Brazil imports bituminous coal from multiple countries: U.S. (42%), Australia (23%), Colombia (14%), Canada (9%). Hence, there is plethora of alternatives for Brazil, which is also a plausible explanation for the high elasticity we estimate. The values of σ for Korea and Japan are very similar, at 4.21 and 4.36. For both countries, there is also plethora of exporters—Australia, Indonesia, China, Canada, Russia, and the U.S—that gives rise to the high elasticities we estimate. For the big European importers, we see σ values between 2.82 for Spain and 4.68 for Germany. For India, which is the smallest importer, we see a demand elasticity of 2.70. The rather small demand elasticity we estimate for India is consistent with the fact that domestic coal is not a good substitute for particular applications despite the fact that domestic production accounts for about 90% of all coal consumption in India during 2003–2013.[26]

4.2 Domestic Market

The domestic production model generates an equation that relates the estimated export supply shock, $exp(\widehat{\eta}^I_{gvt})$, to the U.S. price of gas in (20). In a fully structural model, the functional form for $H(\cdot)$ in (15) depends on the functional form of the inverse domestic demand, the production costs, as well as the assumption regarding the model of competition of U.S. coal producers as we discussed in Section 3.2. For the purpose of our counterfactuals, and aiming to allow some flexibility in this important relationship, we estimate via OLS the following model:

$$\widehat{\eta}^I_{gvt} = h(\cdot) + u_{gvt} = \mu_{Ig} + \sum_{g=1}^{G} \mu_g p^g_{dt} + u_{gvt} \tag{21}$$

$$\widehat{\eta}^I_{gvt} \equiv ln(p^I_{gvt}) - \widehat{\omega}^I_{gv} ln(q_{gvt}), \tag{22}$$

Canada's bituminous coal exports are to Japan (45%) and Korea (24%). Common destinations of Russian bituminous coal exports are Japan (17%), Great Britain (13%), Ukraine (13%), Korea (11%), and Turkey (10%). Canada and Russia face significant competition from other major exporters, such as Australia and Indonesia, in both Japan and Korea, which gives the two Asian countries significant leverage against them and explains the ω values we estimate.

[26] As we discuss in Section A.4, our inverse export and import demand elasticity estimates are comparable to others in the literature.

where $\widehat{\eta}_{gvt}^{I}$ is the variety-specific shock to the inverse export supply estimated using our trade model and $h(\cdot)$ is the logarithmic transformation of $H(\cdot)$. Furthermore, μ_{Ig} is an importer-by-coal-type fixed effect, p_{dt}^{g} is the U.S. price of gas for which we use an annual average of the Henry Hub benchmark, and μ_g allows for a slope coefficient that is coal-type specific noting that the annual frequency is due to the COMTRADE data used to obtain $\widehat{\eta}_{gvt}^{I}$. Furthermore, we expect positive slope coefficients, such that an increase in the U.S. price of gas shifts the U.S. export supply curve leftward.[27]

According to Table 4, the regression in (21) has an R^2 of 0.81, which is not surprising given the importer-by-coal-type fixed effects, and the slope coefficients have the proper signs. The interactions of the gas price with the coal-type fixed effects are all significant at 1%. The slope coefficient for other coal is roughly 3 times as large as the other two slope coefficients, which are of similar magnitude.[28]

5 Counterfactual Analysis

5.1 Overview

The counterfactual analysis is based on calculating worldwide trade flows for coal in the absence the decrease in the U.S. price of gas due to the Shale Gas Boom (Boom). We assess the implications of the decrease in the price of gas by comparing actual and counterfactual values of economic variables of interest, such as prices, quantities, dollar sales, and consumer welfare. In addition, we compare the actual and counterfactual carbon dioxide (CO_2) and sulfur dioxide (SO_2) content of trade flows based on the physical characteristics of coal traded around the world. All counterfactual analyses are performed excluding outcomes associated with inverse export supply and import demand elasticities in the top and bottom 10% of

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[27] A potential concern about the model in (21) is that we don't control for U.S. environmental policy in the electric power sector, which is correlated with the U.S. price of gas, and is part of w_{dt} in (20). The correlation should be fairly strong because the electric power sector has accounted for 25% of the annual U.S. gas consumption, on average, between 1990 and 2014 (EIA, Monthly Energy Review). A point can also be made that there is a negative relationship between the U.S. price of gas and U.S environmental policy because lower gas prices allow more aggressive policies, such as stricter emission standards for coal-fired plants. The dependent variable in (21) is the intercept of a constant elasticity inverse export supply curve, which is expected to be negatively correlated with the U.S. environmental policy because, all else equal, a more aggressive environmental policy implies a shift to the right of the inverse export supply curve. However, this relationship is expected to be weak given the long list of factors affecting the international market for coal. Therefore, there is a possibility for an upward, but small bias, in our estimates for the effect of the gas price.

[28] As for the flexibility of the specification in (21), we experimented with higher-degree polynomials, but nonlinear transformations of the gas price did not seem to matter.

their distributions to mitigate the effects of outliers. We also assume that the counterfactual import demand shocks b^I_{gv} are the same as their actual counterparts.

The underlying reasoning of the counterfactual exercise is straightforward. First, in the absence of the Boom, the gas price in the U.S. is higher. Second, the counterfactual demand for gas (coal) in the U.S. electric power sector is lower (higher) than the actual demand. This is the case because coal and gas are closer substitutes for electric power plants when gas prices are lower even accounting for the fact that it takes a larger amount of heat (MMBtu) generated by using coal than by using gas to generate the same amount of electricity.[29] Finally, the increased U.S. domestic demand for coal is served by the domestic supply and plays the role of a negative shock to the U.S. coal export supply curve.

Our counterfactual analysis essentially shows how the positive shock to the U.S. domestic supply of gas due to the Boom affected the international coal trade. Additionally, our trade model allows for U.S exports to displace–or be displaced by–exports from other countries in each destination. Having estimated the relationship between the export supply shocks (η^I_{gvt}) and the U.S. price of gas (p^g_{dt}) in Section 4.2, we can compute counterfactual export supply shocks and simulate the counterfactual trade flows using (20) and the counterfactual U.S. price of gas, $p^g_{dt,CF}$.

In particular, using p^g_{dt} and p^g_{et} to denote the U.S Henry Hub and the Europe import border gas prices from the World Bank Pink Sheets for 1990–2006, we calculate counterfactual prices using the following equation:

$$p^g_{dt,CF} = \begin{cases} p^g_{dt}, & t = 1990, ...2006 \\ \widehat{\lambda}_0 + \widehat{\lambda}_1 p^g_{et}, & t = 2007, ...2014. \end{cases} \tag{23}$$

where $\widehat{\lambda}_0$ and $\widehat{\lambda}_1$ are the OLS estimates from the following regression:

$$p^g_{dt,CF} = \lambda_0 + \lambda_1 p^g_{et} + u_t, \quad t = 1990, ...2006. \tag{24}$$

Figure 3 shows that the difference between the actual and counterfactual U.S. gas prices is most notable in 2011 and 2012 with the counterfactual prices being almost three times as high as the actual prices. More specifically, in the absence of the Boom, the average annual price increase is 136% during 2007–2014. As a side note, assuming that European gas prices would have been higher in the absence of the Boom due to less intense competition from U.S. coal exports, then our estimated counterfactual gas prices are biased downward and we

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[29] Coal-fired electric generating units have higher heat rates (consumption-over-generation) ratios that can be as high as 1.5 times the heat rates of gas-fired units.

underestimate the difference between actual and counterfactual prices.[30]

To calculate the counterfactual global coal trade equilibrium, we first need to calculate the changes in U.S. exports to every importing country and then calculate how competing exporters respond to changes in the prices and quantities of U.S. coal exports. The trade model from Section 3.1, provides estimates of the import demand (σ^I_g) and inverse export supply (ω^I_{gv}) elasticities. Given our estimates, prices and quantities of coal are driven by the export supply and import demand shocks η^I_{gvt} and b^I_{gv}, respectively, along with the structure of the import market, which is captured by the price index ($\mathcal{P}^I_{gt}$).

Table A.8 provides summary statistics for the exponentiated actual and counterfactual supply shocks by major importer of U.S. coal aggregating across the three types of coal. Consistent with the comparative statics discussed earlier, the counterfactual supply shocks are generally higher than the actual ones, such that the counterfactual U.S. exports are smaller than the actual U.S. exports at all price levels.

Moving to variables of interest, the first economic variable is the change in the price index for coal imports implied by the change in the U.S. inverse export supply curve, which is derived from the trade model:

$$\Delta ln(\mathcal{P}^I_{gt}) = \tfrac{1}{1+\overline{\omega}^I_{gt}}\Delta\overline{\eta}^I_{gt} \tag{25}$$

$$\Delta\overline{\eta}^I_{gt} \equiv \overline{\eta}^I_{gt,CF} - \overline{\eta}^I_{gt}, \tag{26}$$

where $\overline{\omega}^I_{gt}$ and $\overline{\eta}^I_{gt}$ are quantity-weighted harmonic means of the inverse export supply elasticities and shocks using the actual quantities. We see immediately that the magnitude of the change in the price index depends on the importance of the change in the U.S. export supply shock in the market overall. With the counterfactual price index in hand, we calculate counterfactual prices and quantities for every exporter and importer using the following differences:

$$\Delta ln(p^I_{gvt}) = \frac{1}{1+\sigma^I_g\omega^I_{gv}}\Delta\eta^I_{gvt} + \frac{\omega^I_{gv}(\sigma^I_g - 1)}{1+\sigma^I_g\omega^I_{gv}}\Delta ln(\mathcal{P}^I_{gt}) \tag{27}$$

$$\Delta ln(q^I_{gvt}) = \frac{-\sigma^I_g}{1+\sigma^I_g\omega^I_{gv}}\Delta\eta^I_{gvt} + \frac{(\sigma^I_g - 1)}{1+\sigma^I_g\omega^I_{gv}}\Delta ln(\mathcal{P}^I_{gt}) \tag{28}$$

$$\Delta\eta^I_{gvt} \equiv \eta^I_{gvt,CF} - \eta^I_{gvt}. \tag{29}$$

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[30] We also experimented with a specification that included an Asian gas benchmark price, the price of liquefied natural gas in Japan from the World Bank Pink Sheets. Given the substantially higher Asian prices during this period, the counterfactual prices are much higher (up to 9-fold increase) than the ones reported here.

Non-U.S. exports are only affected by changes in the price index in each importing country because $\Delta\eta^I_{gvt} = 0$ for non-U.S. coal exports. U.S. exports are affected by both the shifts in the export supply curve and the resulting impact on the price index.

The changes in prices and quantities in each importing country allow us to calculate the compensating and equivalent variation using standard expressions for the Cobb-Douglas family of utility functions given the functional form in (1). The equivalent variation (EV) is equal to the amount of money the consumers in importing countries would have to receive after the change in the price of coal in the absence of the Boom to be just as well off as they were before the price change. The compensating variation (CV) measures the amount of money the consumers would have to receive if they were to be compensated exactly for the price change. Therefore, positive CV and EV values imply consumers in importing countries are worse off in the absence of the Boom.

5.2 Economic Outcomes

Table 5 shows detailed actual and counterfactual dollars, quantities, and prices, as well as the implied percentage change in the absence of the Boom, by exporter. Table 7 provides a similar breakdown by importer. The comparison of actual and counterfactual outcomes is limited to the period 2007–2014 and the difference is due to the increase in the U.S. domestic price of gas in the absence of the Boom. Moreover, we aggregate across the three types of coal and we calculate differences as counterfactual minus actual values.

Overall, the counterfactual coal quantity is 0.16% higher than its actual counterpart. The counterfactual dollar value is 0.72% higher and prices are 0.56% higher. The time-series plots in Figure A.4 show the differences between actual and counterfactual quantities and prices by year. Hence, and contrary to commentary at the time of their peak during the Boom, U.S. coal exports simply displaced other coal exports, with the global coal trade in terms of tons and dollars essentially remaining the same.

More specifically, the counterfactual quantity of non-U.S. coal is 3.76% higher, while that of U.S. coal is 27.15% lower. The prices of U.S. coal increase by 3.58%, while those of non-U.S. coal increase by 1.05%. The pattern of the increase in the exports of countries other than the U.S. is generally consistent with the pattern of the elasticities in Table 3. Exporters with smaller (larger) ω values experience a larger (smaller) increase in their quantities. In the absence of the Boom, most of the increase in Australia's exports in terms of quantity is due to additional imports by its traditional coal trading partners such as Japan and China. The increase in Indonesia's exports, also in terms of quantities, comes from additional imports by China, Japan, and Korea, which have also been long-term trading partners for Indonesia.

In the case of major importers, Brazil, Italy, and the Netherlands, experience the largest percentage decrease in quantities as we move from the actual to the counterfactual outcomes, 4.14%–9.78% (Table 7). Brazil, which experiences the largest decrease in quantities has also the largest import demand elasticity (5.98) in Table 2. None of the remaining importers experiences a change in quantity that exceeds 2% with the change in quantities for Great Britain and Russia being essentially zero. Brazil also experiences that largest percentage change in dollar value, a decrease of 8.34%, while Italy experiences the largest change in prices, an increase of 4.78%.

In terms of U.S. coal exports, we see the largest percentage decrease in quantity for Japan (80.89%), followed by China, Korea, the Netherlands, and Italy, which all experience a decrease of 56.65% or higher in the absence of the boom (Table 9). For this group of countries, we see an increase in prices between 13.26% for Japan and 49.80% for Italy. For Germany, Great Britain, and Russia, the change in prices and quantities of U.S. coal are essentially zero.

As for the mechanism explaining our findings, Japan has a rather diverse set of coal exporters that includes Australia, Indonesia, Russia, Canada, China, and the U.S. Australia and Indonesia are the dominant exporters accounting for 80% of Japan's imports. The U.S. accounts for just 2% of Japan's imports. In the absence of the Boom, 90% of U.S. exports to Japan are captured by Australia and Indonesia, which is not surprising given the geographic proximity to Japan and the long tradition in coal trade between them. As another example, the Netherlands also has a diverse set of coal exporters dominated by Colombia, the U.S., South Africa, and Russia, with the 4 countries accounting for 85% of the country's imports and the U.S. enjoying a share of 18%. Close to 60% of the 16 million metric tons of U.S. coal lost in the absence of the Boom are captured by Russia, South Africa, and Australia with the remainder spread among smaller exporters such as Poland and Ukraine. Interestingly, Colombia does not capture any of lost sales of U.S. coal.

Table 11 provides a breakdown of the change in non-U.S. coal by major importer. In the absence of the Boom, Italy and the Netherlands experience the largest percentage increase in both quantity—7.29% and 10.13%— and price, 2.48% and 2.80%, respectively. The counterfactual outcomes in terms of dollars, quantities, and prices for Great Britain and Russia are essentially identical to the actual ones.

5.3 Environmental Outcomes

Even a small aggregate effect of the Boom in terms of coal consumption may have a significant impact on emissions. This would be the case if, say, Australian or Indonesian coal displaces U.S. coal with different properties that can have material implications for emissions. In what follows, we investigate this issue. In order to identify the carbon dioxide (CO_2) and sulfur dioxide (SO_2) content of the coal trade flows, we need the heat (Btu/lb) and sulfur content (percent)—henceforth, specifications—of the various types of coal traded around the world. Ideally, we would like to know the heat and sulfur content of anthracite, bituminous, and other coal for each of the exporting countries for 2007–2014, which is a rather demanding task.

Section A.3 in the Appendix outlines our approach to collect information from three different sources regarding the heat content (calorific value) and SO_2 content of the coal trade flows in our sample. With the heat content of coal in hand, the calculation of the CO_2 content is straightforward given that there are 211 lbs. of CO_2 per MMBtu of coal. The calculation of SO_2 in lbs per MMBtu of coal is also straightforward once the sulfur content is known. For example, assuming a heat content of 12,000 Btu/lb, and a sulfur content of 3%, the SO_2 content of coal is $(0.03 \times 2)/0.012 = 5.0$ lbs./MMBtu.[31]

We start with a naive approach that assumes a constant heat and SO_2 content of coal, independently of its country of origin: 211 lbs. of CO_2 per MMBtu of coal and 21 MMBtu per metric ton of coal. With this first approach, the implied actual and counterfactual CO_2 content (million metric tons) of all coal trade flows is 15,038 and 15,062, respectively (Table 6). This is an increase of 0.16%, which is equal to the change in quantity due to our assumption that the actual and counterfactual values of heat, CO_2, and SO_2 content are the same. At a social cost of CO_2 (SCC) of \$37 per metric ton, the actual and counterfactual environmental damages from emissions due to combustion of all imported coal are \$556 and \$557 billion, respectively. Hence, the CO_2-related damages are about \$900 million higher in the absence of the Boom. In the same spirit, using an average of 1.3 lbs. of SO_2 per MMBtu of coal and 21 MMBtu per metric ton of coal, the implied actual and counterfactual SO_2 emissions of all imported coal are 92.6 and 92.8 million tons, respectively.

In the case of U.S. coal, the counterfactual (actual) CO_2 emissions are 825 (1,173) million metric tons implying an SCC of \$30.5 (\$43.4) billion. We also see a notable drop in SO_2 emissions for the U.S. as we move from actual to counterfactual outcomes; from 7.2 to 5.1

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[31] Note that 2 is the atomic mass of sulfur dioxide divided by the atomic mass of sulfur. The denominator is due to the fact that there are 10^6 Btu in a MMBtu.

million metric tons. The difference between these actual and counterfactual emissions are useful to calculate the environmental benefits for U.S. consumers associated with U.S. coal shipped elsewhere during the Boom for a rather pessimistic scenario. In a nutshell, the U.S. coal shipped elsewhere would have been used by U.S. electric power plants that substituted away from coal and towards gas on one-to-one MMBtu basis. Moreover, the benefits reported here do not take into account the additional benefits due to the lower gas prices during the Boom (Hausman and Kellogg (2015)), as well as any benefits associated with a net reduction in SO_2, NO_x, and particulate matter emissions. In particular, the Boom eliminated 173 million metric tons of coal with a total heat content of 3,633 million MMBtu. The CO_2 emissions associated with 3,633 million MMBtu of gas are approximately 193 million metric tons. Therefore, the net benefit to U.S. consumers in terms of CO_2 emissions associated with coal exports is equal to 348-193=155 million metric tons or about $5.74 billion.

We also employ an approach that allows for heterogeneity in the heat and sulfur content of coal. In particular, in Figure 4, we refine our calculations of both CO_2 and SO_2 emissions using the heterogeneity in heat and sulfur content in the Appendix Tables A.11 and A.11. Such a refinement entails total actual and counterfactual CO_2 emissions of 15,954 and 15,972 million metric tons, respectively, pointing to an increase of 18 million metric tons, about 0.11%, in the absence of the Boom. In the case of SO_2 emissions, our refinement entail total actual and counterfactual SO_2 emissions of 102.3 and 101.5 million metric tons, respectively, pointing to a decrease of 0.8 million metric tons, about 0.8%, in the absence of the Boom. Hence, although allowing for heterogeneity in the heat and SO_2 content of coal has implications for the level of emissions, it has no material implications for the change in emissions in the absence of the Boom.

5.4 Consumer Welfare

Finally, we measure the welfare effects of the Boom associated with the consumption of imported coal using equivalent and compensating variation in Table 13. We have constructed the table such that positive entries for all three measures of welfare effects imply that consumers in the importing countries are worse off in the absence of the Boom. The rightmost column in the same table pertains to the percentage change in the CES price index, $100 \times \Delta ln(\mathcal{P}^{I}_{gt})$, in the absence of the Boom that is calculated using (25). We report a weighted average of the index for each of the major importers noting that the index, exhibits variation by importer, type of coal, and year.

Across all importers, the EV is $32.1 billion, while the CV, as expected in the case of normal goods, is higher with a value of \$38.6 billion. Among major importers, the largest EV (CV) dollar amount is that for Brazil, \$5.5 (\$7,7) billion, for which the actual dollar value of coal imports is \$21.4 billion. Figure A.5, which provides a time-series plot of our measures of welfare effects along with the percentage change in the CES price index, clearly shows the positive relationship between the two with larger dollar amounts required to restore the actual utility levels during 2011–2013.

6 Discussion, Extensions, and Robustness Checks

6.1 Alternative Elasticity Estimates

Using the same data as for the NLSUR estimator but aggregating across the three types of coal for the top 20 importers, we estimated inverse export elasticities (ωs) for each of the major exporters, by regressing log prices on log quantities using the importing countries' GDP as an instrument and also controlling for importer fixed effects. We did so by estimating one 2SLS regression for each of the exporters and obtained the following ω estimates: Australia (0.55), Indonesia (0.17), USA (0.36), South Africa (0.47), Colombia (0.46). Using the same 2SLS regressions for bituminous coal only, we obtained the following ω estimates: Australia (1.31), Indonesia (0.39), USA (0.58), South Africa (0.64), Colombia (0.44). We also estimated import demand elasticities (σs) for bituminous coal (1.88), anthracite (2.72), and other coal (3.90) using the importing countries' GDP as a demand shifter, as well as importer and year fixed effects. This time, we used the average price in other importing countries and the average distance of other importing countries from their exporters as instruments and estimated one 2SLS regression for each type of coal.

The main message is that our NLSUR elasticity estimates are not only comparable to other elasticity estimates in the literature discussed earlier, they are also comparable to linear 2SLS estimates obtained using the same data. Section A.5 also shows that our counterfactual analysis is robust to elasticity estimates obtained limiting the estimation sample to the pre-Boom period 1990–2006.

6.2 Heterogeneity in Inverse Export Supply Elasticities

For our main results, we use the NLSUR estimator in Soderbery (2017) that delivers export supply elasticities that exhibit variation by importer, exporter, and type of coal, and import demand elasticities that exhibit variation by importer and type of coal. We now provide some additional results for the NLSUR estimator with the export supply elasticities exhibiting variation only by importer and coal type as it would be the case if we were to use the Broda and Weinstein (2006) estimator. The import demand elasticities still exhibit variation by importer and coal type. Due to the ‘system" nature of the estimator, which employs both a demand and a supply equation, altering the heterogeneity of the supply elasticities also has implications for the values of the demand elasticities.

Figure A.7 shows kernel density plots of the inverse export supply (ω) and import demand elasticities (σ) for the Soderbery and Broda-Weinstein (BW) estimators across all three types of coal in our samples avoiding heavy notation to ease the reader. In both cases, we have eliminated estimates in the top and bottom 10% of their distributions. Although eliminating one dimension of heterogeneity in ω implies a distribution with more mass across a smaller range in the case of the BW estimator, the distribution is still skewed. The median is 0.19 and is slightly smaller than the median of 0.275 for the elasticities implied by Soderbery's estimator. In the case of σ, the distribution of the BW estimates is less skewed compared to its counterpart for Soderbery's estimator with a median of 4.0 as opposed to 3.3.

Moving to the implications of the elasticity estimates for our counterfactuals, when employing the BW estimator, there is a 4.77% increase in coal quantities in the absence of the Boom, as opposed to 0.16% in the case of Soderbery's estimator (Table A.13). We also see an increase in the value of trade by 8.4% as opposed to 0.72%, and an increase in in prices by 3.46% as opposed to 0.56%. Moreover, the counterfactual CO_2 emissions are 16,764 as opposed to 15,973 million metric tons when we allow for heterogeneity in the heat content of coal as in Figure 4. Finally, the counterfactual SO_2 emissions are 104.9 as opposed to 101.5 million metric tons also allowing for heterogeneity in the SO_2 content of coal. Importantly, we see a decrease of 47.94%, as opposed to 29.67%, in the quantity of U.S. coal exports, and an increase in U.S. coal prices of 2.75%, as opposed to 3.58%. Therefore, allowing the export supply elasticities to exhibit variation only by coal type and importer has very notable implications for our counterfactual analysis of the trade volume and emissions.

6.3 Domestic Coal

Our main results also do not account for domestic coal. In the set of results that follow, we account for domestic coal subject to some caveats due to data limitations. Before delving into the caveats, we note that our NLSUR estimator can accommodate domestic coal by treating it as a variety for which the importing and exporting countries are identical. We also assume that domestic coal is bituminous, which accounts for more than 70% of the coal trade in COMTRADE data. Given that we treat domestic coal as a bituminous coal variety, accounting for domestic coal has implications for the elasticity estimates associated with bituminous coal alone since we obtain our estimates using a system of import demand and export supply equations for each importer-coal type pair.

In terms of data caveats, we use the difference between production and exports from the EIA International Energy Statistics as a proxy for consumption of domestic coal for the set of countries in Table A.1. We use the export prices from the COMTRADE data as a proxy for the price of domestic coal. Using the difference consumption minus imports as a proxy for the consumption of domestic coal, or import prices as a proxy for the price of domestic coal has not material implications for the qualitative conclusions of our analysis.

Figure A.8 shows the kernel density plot of the inverse export supply and import demand elasticities for the Soderbery estimator across all three types of coal in our samples with domestic coal. Following previous practice, in both cases, we have eliminated estimates in the top and bottom 10% of their distributions. The distributions of ω with and without domestic coal are essentially identical with a median of 0.29 (0.275). As for the import demand elasticities, the introduction of domestic coal entails moving some of the mass of the distribution from lower values, roughly below 3, to larger values. This result is expected given that a substitute (domestic coal) is added to the consumers' choice set. On one end of the spectrum, in the case of China, for which imports account for about 5% of its total coal consumption during 2007–2014, we see an increase in σ from 3.34 to 4.56. On the other end of the spectrum, in the case of Japan, for which all coal consumed is essentially imported, there is an increase in σ from 4.34 to 4.56.

Additionally, according to Table A.14, there is a 0.65% decrease in coal quantity in the absence of the Boom, as opposed to a 0.16% increase, when we account for domestic coal. We also see a decrease in the value of coal trade by 0.06% as opposed to an increase of 0.72%. The increase in prices is roughly 0.6% and essentially the same as the one when we don't account for domestic coal. The counterfactual (actual) CO_2 emissions are 111,304 (112,129) million metric tons. Finally, the counterfactual (actual) SO_2 emissions are 862 (871) million metric tons. In both cases, we allow for heterogeneity in the heat and SO_2 content of coal. Importantly, we see a very small decrease of 1%, as opposed to 29.7%, in the quantity of U.S. coal and an increase in U.S. coal prices equal to 4.36%, as opposed to 3.58%. Hence, although the introduction of domestic coal has notable implications for our counterfactual analysis of U.S. coal exports, its implications for our counterfactual world trade flows are small.

6.4 Substitution Between Coal and Natural Gas

The final point we discuss is that substitution between coal and natural gas in our trade model is not possible. Such substitution is possible in electricity generation in U.S. and Canada, as well as in Western European countries (Wolak (2016)). The most obvious implication of excluding natural gas from the choice set of our representative consumer is that our import demand elasticity estimates are biased upward (closer to zero). Additionally, given the nature of our NLSUR estimator, we cannot treat the import demand elasticity estimates separately from the inverse export supply elasticity estimates. However, we can argue that such substitution should not affect the qualitative nature of our results keeping in mind that in this case our interest is outside North America.

First, according to the EIA International Energy Statistics, Western Europe (Germany, Great Britain, France, Italy, Spain, Netherlands) accounts for 7% (3.5%) of total coal consumption (production) in MMBtu between 1990 and 2014 using the set of countries in Table A.1. Even if there is substantial substitution between coal and natural gas in Western Europe, this substitution will have small effects in the global coal market. Actually, Wolak estimates a conditional demand equation for coal in Europe. According to his Table 4B, the cross elasticity of coal consumption with respect to the price of gas is 0.18. Meyer and Pac (2015) also estimate conditional demand equations for coal and report cross elasticities of coal consumption with respect to gas prices between 0.40 and 0.51 (see their Table 7). Second, Wolak, who models the substitution between coal and gas in Europe also finds that U.S. coal exports do not significantly contribute to an increase in global CO_2 emissions.

7 Conclusion

The paper analyzes the impact of the U.S. Shale Gas Boom on global carbon emissions associated with international coal trade flows. In particular, we analyze whether the increase in U.S. coal exports following the Boom has contributed to an increase in coal imports around the world such that the reduction in domestic carbon emissions due to coal-to-gas switching is offset by an increase in carbon emissions elsewhere.

We build a structural model that links the domestic to the international coal market employing techniques from industrial organization and international trade. Recently developed techniques in international trade allow us to estimate a large number of heterogeneous inverse export supply and import demand elasticities that play a key role in our analysis. The first-order conditions of a stylized model for the U.S. domestic coal market allows us to link shocks in the U.S. inverse export supply curve to the domestic gas price. We construct counterfactual U.S. gas prices for 2007–2014 using a simple linear regressions that links the gas price in the U.S. to the gas price in Europe using data for 1990–2006.

We use our structural model to simulate counterfactual international coal trade flows in the absence of the Boom. We then convert trade flows into carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions. We present detailed results for counterfactuals for a set of 40 countries accounting for 90% of global coal imports and exports during the period of interest. In the absence of the Boom, the quantity of coal traded 0.16% higher than its actual counterpart. As a result, the CO_2 and SO_2 emissions associated with coal trade flows remain virtually the same. The price and dollar value of coal also increase by less than 0.72%. Hence, and in contrast to commentary around the time of the surge in U.S coal exports, U.S. coal exports simply displaced other coal exports without increasing the total quantity of coal traded and the associated emissions during the Boom. In the absence of the Boom, there is a decrease of 29.7% (27.15%) in the quantity and dollar value of U.S. coal exports with U.S. coal exporters losing \$22.3 billion. The net benefit to U.S. consumers from a reduction in coal-related CO_2 emissions is \$5.7 billion due to coal-to-gas switching in electricity generation in the U.S..

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Tables and Figures

Table 1: Inverse export supply and import demand elasticities: summary statistics

A. Elasticity Statistics						
	Inverse Export Supply (ω)			Import Demand (σ)		
Coal Type	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Anthracite	0.868	0.302	1.829	3.243	3.023	0.881
Bituminous	0.719	0.210	1.779	3.583	3.425	1.001
Other	0.845	0.311	2.067	3.583	3.425	1.049
All	0.802	0.267	1.836	3.504	3.359	0.973
B. Elasticity Statistics						
	Inverse Export Supply (ω)			Import Demand (σ)		
Coal Type	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Anthracite	0.342	0.301	0.215	3.090	3.023	0.522
Bituminous	0.273	0.220	0.191	3.426	3.403	0.682
Other	0.343	0.384	0.166	3.595	3.599	0.562
All	0.313	0.275	0.202	3.324	3.297	0.613

Note: In panel A, we exclude ω values exceeding 20. In panel B, we exclude ω and σ values in the top and bottom 10% of their distribution across all three types of coal.

Table 2: Inverse export supply and import demand elasticities:
Bituminous coal, major importers

			Imports		Inverse Export Supply (ω)			Import Demand (σ)
Importer	Coal	GDP	Value	Quantity	Mean	Median	Std. Dev	Estimate
01-JPN	BIT	4.340	294.588	3559.822	0.294	0.259	0.149	4.355
02-KOR	BIT	0.888	129.183	1672.996	0.539	0.299	0.843	4.217
03-CHN	BIT	2.668	91.282	887.908	0.290	0.049	0.961	3.344
04-GBR	BIT	2.345	39.004	440.822	0.632	0.113	0.789	4.625
05-DEU	BIT	2.907	40.701	438.185	0.206	0.186	0.144	4.678
06-ITA	BIT	1.845	32.338	334.061	0.284	0.252	0.184	3.042
07-NLD	BIT	0.658	19.711	285.105	0.117	0.129	0.056	3.447
08-ESP	BIT	1.224	10.370	151.077	0.093	0.100	0.080	2.822
09-BRA	BIT	1.068	15.817	127.505	0.769	0.450	1.581	5.977
10-RUS	BIT	0.987	2.292	18.221	2.608	0.132	4.681	2.262
11-IND	BIT	0.906	1.196	14.971	0.368	0.445	0.194	2.697

Note: The GDP values for 2006 are in current USD (trillion). The import values are in billion USD and the quantities are in million metric tons for 1990–2014. All statistics are quantity-weighted. The summary statistics for ω are computed excluding values exceeding 20 noting that the 95% percentile of the ω distribution is 4.19.

Table 3: Inverse export supply elasticities:
Bituminous coal, major exporters

			Exports		Inverse Export Supply (ω)		
Exporter	Coal	GDP	Value	Quantity	Mean	Median	Std. Dev
01-AUS	BIT	1.231	339.881	3792.081	0.279	0.259	0.291
02-IDN	BIT	1.295	95.080	1355.568	0.225	0.272	0.166
03-RUS	BIT	0.941	88.663	955.471	1.223	0.910	1.458
04-USA	BIT	0.633	88.035	829.707	0.580	0.132	1.814
05-CAN	BIT	1.644	70.791	702.655	0.347	0.348	0.165
06-COL	BIT	1.133	43.407	607.324	0.331	0.196	0.433
07-CHN	BIT	1.585	32.391	585.872	0.316	0.275	0.094
08-ZAF	BIT	1.130	29.027	461.395	0.796	0.200	1.410
09-POL	BIT	0.707	13.477	216.958	0.150	0.118	0.060
10-KAZ	BIT	0.821	2.167	20.397	0.140	0.132	0.021

Note: The GDP values for 2006 are in current USD (trillion). The export values are in billion USD and the quantities are in million metric tons for 1990–2014. All statistics are quantity-weighted. The summary statistics for ω are computed excluding values exceeding 20 noting that the 95% percentile of the ω distribution is 4.19.

Table 4: Regression of export supply shocks on U.S. natural gas prices

Variable	Coefficient
U.S. gas price × BIT	0.1034^{***}
	(0.0226)
U.S. gas price × OTH	0.2800^{***}
	(0.0956)
U.S. gas price × ANT	0.1165^{***}
	(0.0413)
R-squared	0.7683
Observations	1,380

Note: We report the results from the regression for (21) in the main text. The regression includes importer-by coal type fixed effects. The estimated shocks that serve as dependent variables in (21) are constructed excluding ω values in the top and bottom 10% of their empirical distribution to mitigate the effect of any outliers. The standard errors in parentheses are bootstrapped (1,000 repetitions) to account for the estimation error in the export supply shocks. The asterisks indicate statistical significance as follows: 10%(*), 5%(**), 1%(***).

Table 5: Counterfactual analysis: all coal
economic outcomes, exporters, 2007-2014

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-AUS	289.184	299.568	3.591	2092.253	2148.633	2.695	138.216	139.423	0.873
02-IDN	148.537	152.087	2.390	1825.252	1856.315	1.702	81.379	81.930	0.677
03-USA	82.306	59.961	-27.149	583.748	410.562	-29.668	140.996	146.046	3.582
04-RUS	90.947	95.930	5.480	796.807	832.011	4.418	114.139	115.299	1.017
05-ZAF	39.933	40.989	2.645	392.879	399.767	1.753	101.641	102.532	0.876
06-COL	45.122	48.355	7.164	476.619	502.381	5.405	94.671	96.251	1.669
07-CAN	45.179	47.091	4.230	274.289	282.254	2.904	164.715	166.838	1.289
08-CHN	17.327	17.522	1.128	134.747	135.680	0.693	128.589	129.144	0.432
09-KAZ	4.892	5.053	3.294	160.722	161.465	0.462	30.437	31.295	2.818
10-POL	6.952	7.787	12.019	55.322	60.381	9.145	125.655	128.963	2.633
OTH	64.759	66.769	3.103	689.672	704.779	2.190	93.899	94.737	0.893
Non-USA	752.831	781.152	3.762	6898.561	7083.668	2.683	109.129	110.275	1.050
Total	835.137	841.113	0.716	7482.310	7494.230	0.159	111.615	112.235	0.555

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 6: Counterfactual analysis: all coal
environmental outcomes, exporters, 2007-2014

	CO_2 Emissions		CO_2 Social Cost		SO_2 Emissions	
Country	Actual	CF	Actual	CF	Actual	CF
01-AUS	4205.156	4318.473	155.591	159.784	25.909	26.607
02-IDN	3668.520	3730.952	135.735	138.045	22.602	22.987
03-USA	1173.258	825.177	43.411	30.532	7.229	5.084
04-RUS	1601.478	1672.235	59.255	61.873	9.867	10.303
05-ZAF	789.636	803.480	29.217	29.729	4.865	4.950
06-COL	957.942	1009.721	35.444	37.360	5.902	6.221
07-CAN	551.285	567.295	20.398	20.990	3.397	3.495
08-CHN	270.824	272.700	10.020	10.090	1.669	1.680
09-KAZ	323.030	324.523	11.952	12.007	1.990	1.999
10-POL	111.191	121.359	4.114	4.490	0.685	0.748
OTH	1386.152	1416.515	51.288	52.411	8.540	8.727
Non-USA	13865.213	14237.253	513.013	526.778	85.425	87.718
Total	15038.471	15062.429	556.423	557.310	92.654	92.802

Note: The emissions in million metric tons. The social cost is measured in billion USD assuming \$37 per metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 7: Counterfactual analysis: all coal
economic outcomes, importers, 2007-2014

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-JPN	193.601	193.248	-0.183	1464.870	1464.403	-0.032	132.163	131.963	-0.151
02-KOR	100.455	101.117	0.659	921.594	925.407	0.414	109.001	109.268	0.244
03-CHN	124.406	127.162	2.215	1291.275	1313.514	1.722	96.344	96.811	0.485
04-IND	91.807	91.799	-0.009	818.692	818.469	-0.027	112.139	112.160	0.019
05-DEU	43.022	43.612	1.370	350.616	354.502	1.108	122.704	123.022	0.259
06-GBR	35.465	35.465	0.000	305.789	305.789	-0.000	115.978	115.978	0.000
07-NLD	18.065	17.836	-1.267	159.508	152.908	-4.138	113.256	116.648	2.995
08-ITA	24.395	24.368	-0.111	184.565	175.992	-4.645	132.177	138.462	4.755
09-RUS	4.601	4.601	0.000	151.194	151.194	0.000	30.429	30.429	0.000
10-BRA	21.354	19.572	-8.344	143.864	129.800	-9.776	148.433	150.788	1.587
OTH	177.964	182.332	2.454	1690.342	1702.251	0.705	105.283	107.112	1.737
Total	835.137	841.113	0.716	7482.310	7494.230	0.159	111.615	112.235	0.555

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 8: Counterfactual analysis: all coal
environmental outcomes, importers, 2007-2014

	CO_2 Emissions		CO_2 Social Cost		SO_2 Emissions	
Country	Actual	CF	Actual	CF	Actual	CF
01-JPN	2944.198	2943.259	108.935	108.901	18.140	18.134
02-KOR	1852.284	1859.947	68.535	68.818	11.412	11.459
03-CHN	2595.295	2639.992	96.026	97.680	15.990	16.265
04-IND	1645.465	1645.017	60.882	60.866	10.138	10.135
05-DEU	704.692	712.504	26.074	26.363	4.342	4.390
06-GBR	614.597	614.597	22.740	22.740	3.787	3.787
07-NLD	320.590	307.325	11.862	11.371	1.975	1.893
08-ITA	370.951	353.721	13.725	13.088	2.285	2.179
09-RUS	303.880	303.880	11.244	11.244	1.872	1.872
10-BRA	289.149	260.882	10.699	9.653	1.781	1.607
OTH	3397.369	3421.304	125.703	126.588	20.932	21.079
Total	15038.471	15062.430	556.423	557.310	92.654	92.802

Note: The emissions in million metric tons. The social cost is measured in billion USD assuming \$37 per metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 9: Counterfactual analysis: U.S. coal
economic outcomes, importers, 2007-2014

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-JPN	6.067	1.313	-78.361	30.302	5.790	-80.894	200.232	226.778	13.258
02-KOR	4.840	2.549	-47.331	28.384	12.009	-57.690	170.515	212.261	24.482
03-CHN	4.512	2.480	-45.039	32.173	13.729	-57.328	140.228	180.613	28.800
04-IND	3.902	3.869	-0.858	20.862	20.408	-2.175	187.057	189.576	1.346
05-DEU	7.905	7.905	-0.000	60.440	60.440	-0.000	130.793	130.793	0.000
06-GBR	6.342	6.342	0.000	54.615	54.615	0.000	116.129	116.129	0.000
07-NLD	3.760	2.108	-43.938	28.501	12.355	-56.650	131.932	170.622	29.326
08-ITA	5.557	3.041	-45.278	37.043	13.532	-63.469	150.007	224.706	49.796
09-RUS	1.079	1.079	0.000	4.582	4.582	-0.000	235.424	235.424	0.000
10-BRA	8.930	6.994	-21.680	55.707	41.046	-26.319	160.307	170.400	6.296
OTH	29.411	22.281	-24.243	231.140	172.056	-25.562	127.245	129.500	1.772
Total	82.306	59.961	-27.149	583.748	410.562	-29.668	140.996	146.046	3.582

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 10: Counterfactual analysis: U.S. coal
environmental outcomes, importers, 2007-2014

	CO_2 Emissions		CO_2 Social Cost		SO_2 Emissions	
Country	Actual	CF	Actual	CF	Actual	CF
01-JPN	60.903	11.636	2.253	0.431	0.375	0.072
02-KOR	57.048	24.137	2.111	0.893	0.351	0.149
03-CHN	64.663	27.593	2.393	1.021	0.398	0.170
04-IND	41.930	41.018	1.551	1.518	0.258	0.253
05-DEU	121.477	121.477	4.495	4.495	0.748	0.748
06-GBR	109.768	109.768	4.061	4.061	0.676	0.676
07-NLD	57.283	24.832	2.119	0.919	0.353	0.153
08-ITA	74.451	27.198	2.755	1.006	0.459	0.168
09-RUS	9.210	9.210	0.341	0.341	0.057	0.057
10-BRA	111.964	82.496	4.143	3.052	0.690	0.508
OTH	464.560	345.811	17.189	12.795	2.862	2.131
Total	1173.258	825.177	43.411	30.532	7.229	5.084

Note: The emissions in million metric tons. The social cost is measured in billion USD assuming $37 per metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 11: Counterfactual analysis: non-U.S. coal economic outcomes, importers, 2007-2014

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-JPN	187.534	191.935	2.347	1434.568	1458.613	1.676	130.725	131.587	0.659
02-KOR	95.615	98.568	3.088	893.210	913.397	2.260	107.047	107.913	0.810
03-CHN	119.895	124.683	3.994	1259.102	1299.785	3.231	95.222	95.926	0.739
04-IND	87.905	87.930	0.029	797.830	798.061	0.029	110.180	110.180	0.000
05-DEU	35.117	35.707	1.679	290.176	294.062	1.339	121.020	121.425	0.335
06-GBR	29.123	29.123	-0.000	251.175	251.175	-0.000	115.945	115.945	0.000
07-NLD	14.305	15.728	9.950	131.007	140.553	7.286	109.193	111.904	2.482
08-ITA	18.839	21.328	13.212	147.522	162.460	10.126	127.700	131.279	2.802
09-RUS	3.522	3.522	0.000	146.611	146.612	0.000	24.022	24.022	0.000
10-BRA	12.424	12.578	1.241	88.157	88.755	0.678	140.930	141.719	0.560
OTH	148.553	160.051	7.740	1459.203	1530.195	4.865	101.804	104.595	2.741
Total	752.831	781.152	3.762	6898.561	7083.668	2.683	109.129	110.275	1.050

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 12: Counterfactual analysis: non-U.S. coal environmental outcomes, importers, 2007-2014

	CO_2 Emissions		CO_2 Social Cost		SO_2 Emissions	
Country	Actual	CF	Actual	CF	Actual	CF
01-JPN	2883.295	2931.623	106.682	108.470	17.764	18.062
02-KOR	1795.236	1835.810	66.424	67.925	11.061	11.311
03-CHN	2530.632	2612.399	93.633	96.659	15.592	16.095
04-IND	1603.535	1603.999	59.331	59.348	9.880	9.882
05-DEU	583.216	591.027	21.579	21.868	3.593	3.641
06-GBR	504.829	504.829	18.679	18.679	3.110	3.110
07-NLD	263.307	282.493	9.742	10.452	1.622	1.740
08-ITA	296.500	326.524	10.971	12.081	1.827	2.012
09-RUS	294.670	294.670	10.903	10.903	1.816	1.816
10-BRA	177.185	178.386	6.556	6.600	1.092	1.099
OTH	2932.808	3075.493	108.514	113.793	18.069	18.949
Total	13865.213	14237.253	513.013	526.778	85.425	87.718

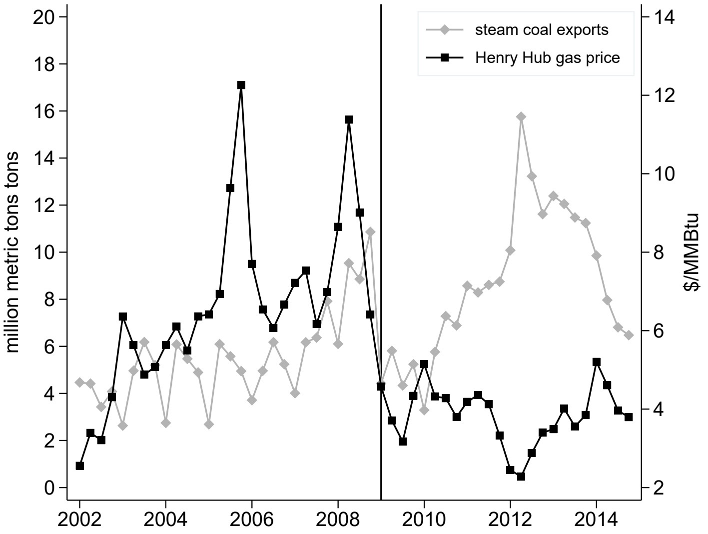
Note: The emissions in million metric tons. The social cost is measured in billion USD assuming $37 per metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 13: Welfare Effects, importers, 2007–2014

Country	EV	ΔW	CV	$100 \times \Delta ln(\mathcal{P}^I_{gt})$
01-JPN	2.428	2.452	2.476	0.463
02-KOR	1.893	1.920	1.948	0.943
03-CHN	2.505	2.539	2.574	1.929
04-IND	0.031	0.031	0.031	1.788
05-DEU	4.800	5.179	5.607	6.202
06-GBR	2.959	3.143	3.345	5.860
07-NLD	1.740	1.854	1.980	5.328
08-ITA	2.613	2.842	3.105	5.313
09-RUS	0.520	0.610	0.736	0.952
10-BRA	5.499	6.470	7.709	13.853
OTH	7.083	7.976	9.099	2.897
Total	32.071	35.018	38.612	2.411

Note: the table shows the equivalent (EV) and compensating (CV) variation to measure the net welfare effects of the Boom for the utility function in (1). We write the the measures of welfare effects such that positive entries imply that consumers are worse off in the absence of the U.S. Shale Gas Boom without taking into account emissions. The percentage change in the CES price index shown in the rightmost column is calculated using (25).

Figure 1: U.S. coal exports and domestic price of natural gas

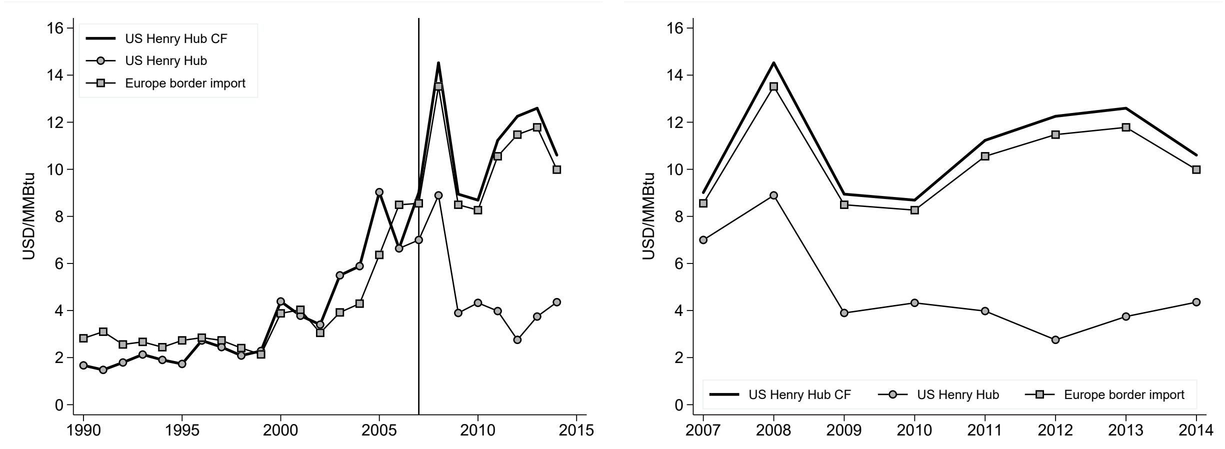


Note: the quarterly gas price is an average of EIA monthly prices for the Henry Hub benchmark. The quarterly exports of coal are from the EIA International Energy Statistics. The vertical line at 2007 indicates the beginning of the U.S. Shale Gas Boom.

Figure 2: U.S. coal production, consumption, and exports

Note: The production and consumption numbers are from the EIA monthly Coal Production and the EIA International Energy Statistics, respectively. The numbers for exports are based on EIA and Census data.

Figure 3: Counterfactual analysis:
U.S. gas prices

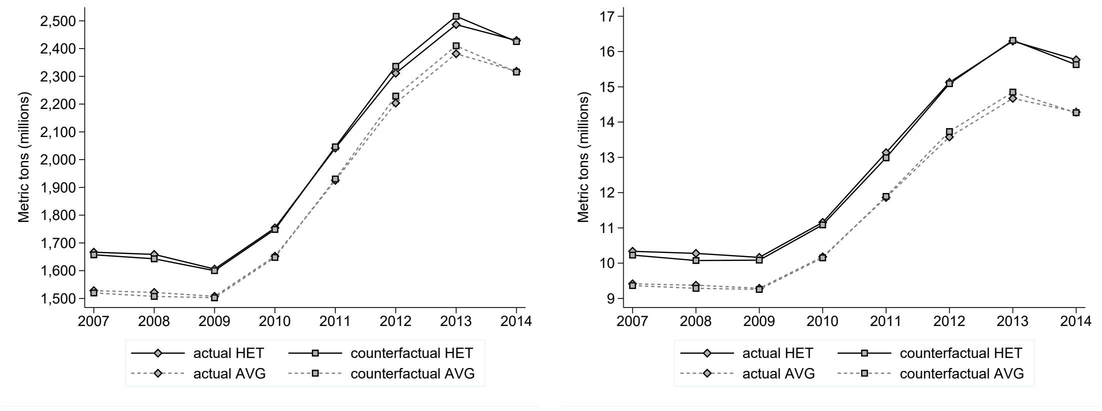


(a) 1990–2014

(b) 2007–2014

Note: The annual average of the U.S. Henry Hub, the Europe border import, and the Japan LNG gas prices are from the World Bank Pink Sheets. The counterfactual Henry Hub gas prices are constructed following the approach in Section 5. Panel (b) shows the three prices during the period that is relevant for our counterfactuals.

Figure 4: Counterfactual analysis:
environmental outcomes, 2007–2014



(a) CO_2 emissions

(b) SO_2 emissions

Panel (a) shows CO_2 emissions using an average heat content of 21 MMBtu per metric ton of coal (AVG) as opposed to the heterogeneous heat content information (HET) in Tables A.11 and A.12. Panel (b) shows SO_2emissions using an average SO_2content of 1.3 lbs per MMBtu of coal and an average heat content of 21 MMBtu per metric ton of coal (AVG), as opposed to the heterogeneous heat and SO_2content information in Tables A.11 and A.12.

A Online Appendix-Not For Publication

A.1 Additional Information on U.S. Coal Exports

Regarding the export split between metallurgical and steam coal, the share of metallurgical coal in annual U.S. exports to China was between 68% and 86% for 2009–2012. Metallurgical coal accounted for around 73% of U.S. exports to Italy and Spain, and close to 50% of U.S. exports to Germany (49%) and the Netherlands (53%) during 2007–2012. The share of metallurgical coal was 38% for the UK. During the same time, metallurgical coal accounted for 84% of U.S. exports to India and 73% of U.S. exports to China. The share of metallurgical coal in U.S. exports to Japan and Korea was 88% and 54%, respectively.

The vast majority of metallurgical coal was exported to China from Baltimore and Norfolk during 2007–2012, due to their proximity to the Appalachian region. The same three ports accounted for the vast majority of total (steam plus metallurgical) exports to India and Europe. Most of the steam coal exported to China was shipped from New Orleans, Seattle, or Los Angeles. New Orleans is close to the barges on the Mississippi river moving steam coal and shipping routes to Europe and South America. Seattle and Los Angeles are among the closest ports to the Western region. The largest fraction of (metallurgical plus steam) coal to Europe was shipped from one of the three Eastern ports or Houston. Between 2002 and 2014, Norfolk, Baltimore, and New Orleans accounted for about 86% of total coal exports, 67% of steam coal exports and close to 93% of metallurgical coal exports.

A.2 World trade of Bituminous Coal

To give the reader an idea about the primary destinations of bituminous coal that accounts for most of world coal trade for major exporters, Japan (57%) and Korea (17%) account for about 3/4 of Australia's exports with China being a distant third at 9.6%. Indonesia's export split is similar to Australia's: Japan (32%) and Korea (25%) account for 60% of its exports. Russia's export destinations are rather diverse, which should not be surprising given its geographic spread and the fact that transportation costs are an important factor for coal trade: Japan (17%), Great Britain (13%), Ukraine (13%), Korea (11%), Turkey (9%). Canada (21%) and Japan (12%) account for 1/3 of U.S. exports, with roughly another quarter accounted for by Italy (8%), Great Britain (7%), Germany (6%), and the Netherlands (6%).

As for other major exporters of bituminous coal, About a third of Colombia's exports are to the U.S. (28%), and another 22% is roughly equally split between Germany (12%) and Great Britain (10%). China (15%) and Hong Kong (11)% account for about another 1/4. Seven European countries account for 64% of South Africa' exports, with Japan (9%) and Korea (7%) accounting for another 16%. Close to 80% of Kazakhstan's exports of bituminous coal, which is of primary interest in our empirical analysis, is to Russia (55%) and Ukraine (26%) during 1990–2014. Ten European countries account for 90% of Poland's export with

Germany alone accounting for 41%.

Regarding the primary sources of bituminous coal for major importers, Australia (61%) and Indonesia (12%) together account for almost 3/4 of Japan's imports of bituminous coal. Australia (40%) and Indonesia (20%) also account for most of Korea's imports with China (16%) and Canada (10%) accounting for roughly 25%. Australia (41%), Indonesia (22%) and Mongolia (12%) collectively account for about 3/4 of China's bituminous coal imports (tons). Germany import bituminous coal from a rather diverse set of countries: South Africa (19%), Poland (16.5%), Russia (14%), Colombia (13%), U.S. (13% and Australia (12%). Russia provides more than a quarter of Great Britain's bituminous coal (27%) while Australia (18%), U.S. (17%), and Colombia (13%), accounting collectively account for about half of the country's imports.

A.3 Information on Coal Specifications

We considered three alternative sources of coal specifications. The first is the annual heat content reported for U.S. coal exports by the EIA. The second is the Platts October 2016 Coal Methodology and Specifications Guide. Platts provides the specifications of standardized coal contracts shipped from (delivered to) major exporting (importing) countries. For example, Platts provides specifications for coal shipped (FOB) from Newcastle, Australia, or Richards Bay, South Africa, under standardized contracts. The same information is available for coal delivered (CIF/CFR) to Japan, Korea, or the Amsterdam-Rotterdam-Antwerp (ARA) trading hub, which serves major Western European markets such as France, Belgium, Germany, Spain, and the Netherlands. Note that the heat and sulfur content from Platts does not exhibit time variation.[32] Our third source is annual information for country-specific calorific values in the IEA Coal Information and the Key World Statistics as discussed below.

Panel (a) of Figure A.6 shows the heat content (MMBtu/metric ton) for each year in our sample. The heat content for U.S. coal exports is readily available from the EIA. In the case of Platts, we report a quantity-weighted average of heat content for coal originating in the major producing countries listed in the Platts column of the on-line Appendix Table A.11, as well as for coal imported by the major importing countries in the on-line Appendix Table A.12. Additionally, we calculated a quantity-weighted heat content using average calorific values for bituminous coal reported in the IEA Coal Information for the producing countries in Platts. A problem with this calculation is that we cannot distinguish between

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[32] See `http://www.platts.com/methodology-specifications/coal` noting that multiple contracts may pertain to particular exporting or importing country in which case we use an average of the calorific value and sulfur content. Similar information is available from Argus Coal Daily International at `http://www.argusmedia.com/coal/argus-coal-daily-international/` and globalCoal at `https://www.globalcoal.com/Brochureware/standardtradingcontract/specifications/`.

domestic and imported coal, although the former should dominate the latter given that these countries are major producers. Overall, depending on the source, the heat content is approximately 20–25 MMBtu/metric ton with the lower bound dictated by the exporting countries for which standardized Platts contracts are available.

We also report a quantity-weighted heat content using the calorific values reported in the IEA Key World statistics for the producing countries listed in the IEA column of the same table. The country-specific calorific values between 2002 and 2014 are provided in panel (b). There are two distinct features in this figure. First, there is very little variation in the calorific values for a given country across time. Second, there is tiering in calorific values. For example, Kazakhstan and Indonesia consistently produce coal with lower heat content relative to the remaining countries. South Africa, Poland, and Russia are in the middle of the pack while Australia and U.S. appear in the top, which is not surprising given that both countries are the biggest exporters of metallurgical coal.

In panel (c) of Figure A.6, we report a quantity-weighted SO_2content (lbs./MMBtu) using sulfur-content information from Platts. Panel (d) of the same figure shows that using Platts information for heat and sulfur content for major exporters, we capture more than 90% of all coal flows during this period, while using the same information for major importers, we capture on average 70% of all coal flows.

A.4 Comparisons with Other Elasticity Estimates

The median σ for HS4 2701 in Soderbery (2017), who uses COMTRADE data for 1991–2007, is 2.9, which is highly comparable with our estimates in Table 2. The mean σ is 3.1 and the σ standard deviation is 0.7. His median (mean) ω is 0.05 (0.40) and his ω standard deviation is 0.92. Again, these numbers are comparable to the ones we report in Tables 2 and 3. In Broda et al. (2006) (BGW), the median σ for HS3 270 is 2.9. The mean σ is 9.2 and the σ standard deviation is 22.7. Although their median estimate is comparable to our estimates in Table 2, we have to keep in mind the different levels of aggregation and different time coverage. BGW use COMTRADE data for 1994–2003 and they don't aggregate various countries into regions as we and Soderbery (2017) do. The estimates of ω in Broda et al. (2008) (BLW) for HS4 2701 excluding values above 20 (as in our case) have an average of 0.16. BLW also use COMTRADE data for 1994–2003 and the inverse export supply elasticities exhibit variation only by exporting country. Once again, the level of aggregation and the different time period make a direct comparison between our estimates and theirs difficult.[33]

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[33] The average inverse export elasticity we report here from BLW is based on 5 observations. The summary statistics reported for BGW and BLW are based on publicly available files from David Weinstein's website at: `http://www.columbia.edu/~dew35/TradeElasticities/TradeElasticities.html`.Kee et al. (2008) using the GDP function approach and HS6-level COMTRADE data for about 120 countries during 1998–

Later in the paper, we show that our import demand and inverse export supply elasticity estimates are also consistent with the ones obtained using a 2SLS approach rather than the NLSUR estimator.

A.5 Alternative Estimation Sample

A case can be made to estimate our inverse export supply and import demand elasticities using data for 1990–2006, which is the period that precedes the Boom, such that our estimates are insulated from the effects of the Boom on the world coal trade.

Figure A.9 shows kernel density plots of ω and σ eliminating estimates in the top and bottom 10% of their distributions. The median ω for the shorter sample of 1990–2006 is 0.21, which is slightly smaller than the median ω (0.275) using the longer sample of 1990–2014. In the case of σ, the median is 3.84 for the shorter sample as opposed to 3.30 for the longer sample.

Moving to the counterfactuals for the shorter sample, in the absence of the Boom, there is a 0.12% increase in quantities, a 0.98% increase in the dollar value of trade, and a 0.87% increase in coal prices (Table A.15). The counterfactual CO_2 emissions are 15,968 as opposed to 15.973 million metric tons, and the counterfactual SO_2emissions are 101.8 million metric tons, as opposed to 101.5. In both cases, we allow for heterogeneity in the heat and SO_2content of coal and the comparisons are with the outcomes for the longer estimation sample of 1990–2014. Moreover, there is a decrease of 30.46%, as opposed to 29.67%, in the quantity of U.S. coal exports and an implied increase in U.S. coal prices of 7.32%, as opposed to 3.58%.

2001 report an average import demand elasticity of 3.12 with a standard deviation of 14.05 for a total of 4,900 products. Ghodsi et al. (2016) following the same approach as Kee et al. and using HS6-level COMTRADE data for 1995–2014, report an average import demand elasticity for the mining and quarrying sector of 1.7 in their Table 4.

Table A.1: ISO Alpha-3 country codes

Code	Country
AUS	AUSTRALIA
BEL	BELGIUM
BRA	BRAZIL
CAN	CANADA
CHE	SWITZERLAND
CHL	CHILE
CHN	CHINA
COL	COLOMBIA
CZE	CZECH REPUBLIC
DEU	GERMANY
ESP	SPAIN
FRA	FRANCE
GBR	UNITED KINGDOM
HKG	HONG KONG
HUN	HUNGARY
IDN	INDONESIA
IND	INDIA
ISR	ISRAEL
ITA	ITALY
JPN	JAPAN
KAZ	KAZAKHSTAN
KOR	SOUTH KOREA
MAR	MOROCCO
MEX	MEXICO
MNG	MONGOLIA
MYS	MALAYSIA
NLD	NETHERLANDS
NZL	NEW ZEALAND
POL	POLAND
PRK	NORTH KOREA
PRT	PORTUGAL
RUS	RUSSIAN FEDERATION
THA	THAILAND
TUR	TURKEY
UKR	UKRAINE
USA	UNITED STATES
VEN	VENEZUELA
VNM	VIET NAM
ZAF	SOUTH AFRICA

Table A.2: Major countries

% Coal Quantity			% Coal Value		
exports	imports	imports USA	exports	imports	imports USA
99.13	94.02	94.82	99.19	94.55	94.06

Note: Based on UN COMTRADE data for 1990–2014. The table shows the percentage of total exports, total imports, and imports of U.S. coal that 39 major countries account for. For example, the 39 countries we consider account for 99.13% of total exports. The quantities are in million metric tons and the values are in billion USD.

Table A.3: List of major countries, sorted by total coal exports

	Coal Quantity %			Coal Value %		
Country	Exports	Imports	Imports USA	Exports	Imports	Imports USA
AUS	29.2628	0.0137	0.0014	34.1821	0.0161	0.0006
IDN	17.0009	0.0513	0.0023	14.5965	0.0599	0.0021
USA	9.2216	2.1935	0.0000	10.4653	1.6526	0.0000
RUS	8.4389	2.5252	0.3251	9.6975	0.5790	0.8405
ZAF	7.3667	0.1484	0.1297	5.9783	0.2272	0.2320
COL	5.8012	0.0000	0.0000	5.2709	0.0000	0.0001
CAN	4.8682	2.1947	21.0409	6.0683	1.3418	10.8549
CHN	4.8565	9.2107	2.2726	3.7353	10.5670	3.5128
KAZ	2.7125	0.0284	0.0000	0.6267	0.0170	0.0000
POL	2.2394	0.4643	0.2131	1.7319	0.5467	0.5417
VNM	1.7033	0.0184	0.0000	1.3974	0.0241	0.0000
MNG	0.7521	0.0020		0.5911	0.0007	
VEN	0.7000	0.0235	0.0336	0.5435	0.0266	0.0407
UKR	0.6925	1.2442	1.0864	0.6505	1.6359	2.6955
CZE	0.6484	0.1929	0.0425	0.7195	0.1803	0.1078
PRK	0.5510			0.5258		
NLD	0.2696	2.9286	5.2655	0.2686	2.6191	4.9581
NZL	0.2417	0.0409	0.0000	0.3507	0.0263	0.0001
CHE	0.2192	0.0259	0.0004	0.1997	0.0303	0.0004
BEL	0.1349	0.8504	2.3137	0.1548	0.8489	2.2407
GBR	0.1317	4.4861	6.7321	0.1611	4.7117	6.8975
DEU	0.0823	4.7630	5.7218	0.1352	5.1671	7.2549
ESP	0.0673	1.8958	3.6811	0.1033	1.3960	2.6791
IND	0.0484	7.1773	1.6598	0.0408	9.0444	3.3530
FRA	0.0344	1.8896	3.8489	0.0535	1.9549	3.8468
ISR	0.0196	1.0973	0.1632	0.0133	1.0509	0.0812
MYS	0.0188	1.3450	0.0144	0.0217	1.2823	0.0075
CHL	0.0180	0.7638	0.9771	0.0130	0.4670	0.9655
ITA	0.0114	2.8471	6.9604	0.0142	3.1899	7.4534
JPN	0.0111	25.0692	9.9319	0.0120	25.8932	10.3079
HKG	0.0102	1.4269	0.0000	0.0068	0.9340	0.0001
KOR	0.0084	11.9405	4.7301	0.0121	11.6872	5.5274
BRA	0.0065	2.3996	9.7134	0.0079	2.7742	10.9881
MEX	0.0060	0.3643	1.7338	0.0145	0.3951	1.6553
HUN	0.0057	0.1970	0.4317	0.0047	0.2663	0.9309
THA	0.0024	1.4299	0.0044	0.0030	0.9741	0.0056
TUR	0.0021	1.7785	3.1748	0.0038	2.1810	3.9791
PRT	0.0015	0.7219	1.4970	0.0014	0.5438	1.0161
MAR	0.0001	0.2666	1.1152	0.0001	0.2343	1.0834

Note: based on UN COMTRADE data for HS6 codes 270111, 270112, 270119 for 1990–2014. The table reads as follows: Japan (JPN) accounts for 25.1% of total imports in terms of quantities and for 25.9% in terms of value (USD). Australia (AUS) accounts for 29.3% of all exports in terms tons and for 34.2% in terms of value (USD).

Table A.4: List of major countries, sorted by total coal imports

	Coal Quantity %			Coal Value %		
Country	Exports	Imports	Imports USA	Exports	Imports	Imports USA
JPN	0.0111	25.0692	9.9319	0.0120	25.8932	10.3079
KOR	0.0084	11.9405	4.7301	0.0121	11.6872	5.5274
CHN	4.8565	9.2107	2.2726	3.7353	10.5670	3.5128
IND	0.0484	7.1773	1.6598	0.0408	9.0444	3.3530
DEU	0.0823	4.7630	5.7218	0.1352	5.1671	7.2549
GBR	0.1317	4.4861	6.7321	0.1611	4.7117	6.8975
NLD	0.2696	2.9286	5.2655	0.2686	2.6191	4.9581
ITA	0.0114	2.8471	6.9604	0.0142	3.1899	7.4534
RUS	8.4389	2.5252	0.3251	9.6975	0.5790	0.8405
BRA	0.0065	2.3996	9.7134	0.0079	2.7742	10.9881
CAN	4.8682	2.1947	21.0409	6.0683	1.3418	10.8549
USA	9.2216	2.1935	0.0000	10.4653	1.6526	0.0000
ESP	0.0673	1.8958	3.6811	0.1033	1.3960	2.6791
FRA	0.0344	1.8896	3.8489	0.0535	1.9549	3.8468
TUR	0.0021	1.7785	3.1748	0.0038	2.1810	3.9791
THA	0.0024	1.4299	0.0044	0.0030	0.9741	0.0056
HKG	0.0102	1.4269	0.0000	0.0068	0.9340	0.0001
MYS	0.0188	1.3450	0.0144	0.0217	1.2823	0.0075
UKR	0.6925	1.2442	1.0864	0.6505	1.6359	2.6955
ISR	0.0196	1.0973	0.1632	0.0133	1.0509	0.0812
BEL	0.1349	0.8504	2.3137	0.1548	0.8489	2.2407
CHL	0.0180	0.7638	0.9771	0.0130	0.4670	0.9655
PRT	0.0015	0.7219	1.4970	0.0014	0.5438	1.0161
POL	2.2394	0.4643	0.2131	1.7319	0.5467	0.5417
MEX	0.0060	0.3643	1.7338	0.0145	0.3951	1.6553
MAR	0.0001	0.2666	1.1152	0.0001	0.2343	1.0834
HUN	0.0057	0.1970	0.4317	0.0047	0.2663	0.9309
CZE	0.6484	0.1929	0.0425	0.7195	0.1803	0.1078
ZAF	7.3667	0.1484	0.1297	5.9783	0.2272	0.2320
IDN	17.0009	0.0513	0.0023	14.5965	0.0599	0.0021
NZL	0.2417	0.0409	0.0000	0.3507	0.0263	0.0001
KAZ	2.7125	0.0284	0.0000	0.6267	0.0170	0.0000
CHE	0.2192	0.0259	0.0004	0.1997	0.0303	0.0004
VEN	0.7000	0.0235	0.0336	0.5435	0.0266	0.0407
VNM	1.7033	0.0184	0.0000	1.3974	0.0241	0.0000
AUS	29.2628	0.0137	0.0014	34.1821	0.0161	0.0006
MNG	0.7521	0.0020		0.5911	0.0007	
COL	5.8012	0.0000	0.0000	5.2709	0.0000	0.0001
PRK	0.5510			0.5258		

Note: based on UN COMTRADE data for HS6 codes 270111, 270112, 270119 for 1990–2014. The table reads as follows: Japan (JPN) accounts for 25.1% of total imports in terms of quantities and for 25.9% in terms of value (USD). Australia (AUS) accounts for 29.3% of all exports in terms tons and for 34.2% in terms of value (USD).

Table A.5: List of major countries, sorted by imports of U.S. coal

	Coal Quantity %			Coal Value %		
Country	Exports	Imports	Imports USA	Exports	Imports	Imports USA
CAN	4.8682	2.1947	21.0409	6.0683	1.3418	10.8549
JPN	0.0111	25.0692	9.9319	0.0120	25.8932	10.3079
BRA	0.0065	2.3996	9.7134	0.0079	2.7742	10.9881
ITA	0.0114	2.8471	6.9604	0.0142	3.1899	7.4534
GBR	0.1317	4.4861	6.7321	0.1611	4.7117	6.8975
DEU	0.0823	4.7630	5.7218	0.1352	5.1671	7.2549
NLD	0.2696	2.9286	5.2655	0.2686	2.6191	4.9581
KOR	0.0084	11.9405	4.7301	0.0121	11.6872	5.5274
FRA	0.0344	1.8896	3.8489	0.0535	1.9549	3.8468
ESP	0.0673	1.8958	3.6811	0.1033	1.3960	2.6791
TUR	0.0021	1.7785	3.1748	0.0038	2.1810	3.9791
BEL	0.1349	0.8504	2.3137	0.1548	0.8489	2.2407
CHN	4.8565	9.2107	2.2726	3.7353	10.5670	3.5128
MEX	0.0060	0.3643	1.7338	0.0145	0.3951	1.6553
IND	0.0484	7.1773	1.6598	0.0408	9.0444	3.3530
PRT	0.0015	0.7219	1.4970	0.0014	0.5438	1.0161
MAR	0.0001	0.2666	1.1152	0.0001	0.2343	1.0834
UKR	0.6925	1.2442	1.0864	0.6505	1.6359	2.6955
CHL	0.0180	0.7638	0.9771	0.0130	0.4670	0.9655
HUN	0.0057	0.1970	0.4317	0.0047	0.2663	0.9309
RUS	8.4389	2.5252	0.3251	9.6975	0.5790	0.8405
POL	2.2394	0.4643	0.2131	1.7319	0.5467	0.5417
ISR	0.0196	1.0973	0.1632	0.0133	1.0509	0.0812
ZAF	7.3667	0.1484	0.1297	5.9783	0.2272	0.2320
CZE	0.6484	0.1929	0.0425	0.7195	0.1803	0.1078
VEN	0.7000	0.0235	0.0336	0.5435	0.0266	0.0407
MYS	0.0188	1.3450	0.0144	0.0217	1.2823	0.0075
THA	0.0024	1.4299	0.0044	0.0030	0.9741	0.0056
IDN	17.0009	0.0513	0.0023	14.5965	0.0599	0.0021
AUS	29.2628	0.0137	0.0014	34.1821	0.0161	0.0006
CHE	0.2192	0.0259	0.0004	0.1997	0.0303	0.0004
HKG	0.0102	1.4269	0.0000	0.0068	0.9340	0.0001
NZL	0.2417	0.0409	0.0000	0.3507	0.0263	0.0001
COL	5.8012	0.0000	0.0000	5.2709	0.0000	0.0001
KAZ	2.7125	0.0284	0.0000	0.6267	0.0170	0.0000
VNM	1.7033	0.0184	0.0000	1.3974	0.0241	0.0000
PRK	0.5510			0.5258		
USA	9.2216	2.1935	0.0000	10.4653	1.6526	0.0000
MNG	0.7521	0.0020		0.5911	0.0007	

Note: based on UN COMTRADE data for HS6 codes 270111, 270112, 270119 for 1990–2014. The table reads as follows: Japan (JPN) accounts for 25.1% of total imports in terms of quantities and for 25.9% in terms of value (USD). Australia (AUS) accounts for 29.3% of all exports in terms tons and for 34.2% in terms of value (USD).

Table A.6: Regions and trade: coal exports 1990–2014

Country/ Region	County Count	BIT		ANT		OTH	
		Quantity	Value	Quantity	Value	Quantity	Value
AUS	1	3805.131	340.952	75.147	8.916	613.061	69.706
IDN	1	1356.382	95.149	3.524	0.236	1250.602	83.782
USA	1	1128.803	105.692	18.003	1.921	269.192	20.845
RUS	1	968.856	89.453	101.618	11.067	225.328	18.514
CAN	1	704.946	71.007	1.530	0.158	41.045	3.321
ZAF	1	624.107	38.398	44.244	3.136	462.819	31.848
COL	1	610.333	43.751	13.198	0.892	267.245	20.056
CHN	1	587.684	32.550	101.790	9.276	62.835	4.211
POL	1	222.721	14.174	7.645	0.609	113.501	6.476
KAZ	1	23.102	2.359	18.179	0.149	375.231	5.184
GBR	1	8.885	0.841	5.536	0.549	5.800	0.588
DEU	1	3.782	0.321	5.374	0.970	3.477	0.367
IND	1	1.218	0.057	0.143	0.009	6.073	0.436
FRA	1	0.794	0.095	0.774	0.092	3.721	0.470
MEX	1	0.753	0.153	0.028	0.009	0.139	0.015
BRA	1	0.748	0.069	0.063	0.007	0.184	0.021
ITA	1	0.704	0.070	0.569	0.053	0.480	0.051
JPN	1	0.394	0.034	0.312	0.024	1.000	0.090
ASA	39	125.175	8.138	343.663	23.630	33.397	1.727
SEU	23	88.633	8.763	71.955	5.418	61.504	4.311
SAM	20	88.350	5.510	3.182	0.221	20.970	1.296
NWU	16	55.794	4.402	16.013	1.755	67.339	5.263
OCE	9	22.202	2.186	0.014	0.001	15.103	2.144
AFR	45	9.196	1.016	0.818	0.152	9.912	0.945
CAR	12	1.024	0.075	0.061	0.007	0.424	0.025

Note: Trade volume for bituminous coal (BIT), anthracite (ANT), and other coal (OTH). The quantities in million metric tons and values in billion USD. The lower part of the table contains information for the following regions: Asia (ASA), Southern/Eastern Europe (SEU), Northern/Western Europe (NWU), South America (SAM), Africa (AFR), Oceania (OCE), and the Caribbean (CAR). See Table A2 in Soderbery (2017) for the assignment of countries to regions subject to the following changes: SAM excludes COL, ASA excludes IDN and KAZ, SEU excludes POL, AFR excludes ZAF.

Table A.7: Regions and trade: coal imports 1990–2014

Country/ Region	County Count	BIT Quantity	BIT Value	ANT Quantity	ANT Value	OTH Quantity	OTH Value
JPN	1	3576.286	295.541	107.062	10.203	166.068	12.088
KOR	1	1686.981	130.139	95.539	10.342	50.955	2.975
CHN	1	1109.503	103.000	302.404	21.186	221.514	16.985
DEU	1	556.147	47.682	37.365	3.813	137.861	11.929
GBR	1	473.020	40.677	17.553	1.451	198.275	15.706
ITA	1	335.594	32.462	6.641	0.653	94.940	6.040
NLD	1	290.584	20.187	8.949	0.666	150.157	11.296
USA	1	264.489	15.647	4.958	0.398	67.361	4.240
CAN	1	254.576	13.144	9.836	0.932	72.589	2.394
FRA	1	251.957	20.484	32.806	3.051	5.383	0.461
ESP	1	153.489	10.600	13.085	0.960	124.534	5.575
BRA	1	130.485	16.057	26.494	2.003	211.485	15.993
MEX	1	55.047	4.762	0.625	0.078	0.271	0.010
RUS	1	18.461	2.329	20.528	0.354	348.753	4.424
IND	1	15.006	1.200	7.304	1.310	1079.769	108.508
AUS	1	0.097	0.008	0.941	0.121	1.064	0.068
SEU	19	452.839	44.237	60.227	4.619	130.208	7.905
ASA	32	418.793	34.889	27.456	2.833	642.845	45.360
NWU	14	292.389	21.341	29.080	3.674	127.222	7.291
SAM	15	119.844	10.442	1.073	0.137	53.430	0.807
AFR	29	7.321	0.826	24.847	0.486	100.820	7.588
OCE	3	6.219	0.544	0.553	0.084	5.473	0.250
CAR	11	5.670	0.619	0.228	0.032	0.043	0.005

Note: Trade volume for bituminous coal (BIT), anthracite (ANT), and other coal (OTH). The quantities in million metric tons and values in billion USD. The lower part of the table contains information for the following regions: Asia (ASA), Southern/Eastern Europe (SEU), Northern/Western Europe (NWU), South America (SAM), Africa (AFR), Oceania (OCE), and the Caribbean (CAR). See Table A2 in Soderbery (2017) for the assignment of countries to regions subject to the following changes: SAM excludes COL, ASA excludes IDN and KAZ, SEU excludes POL, AFR excludes ZAF.

Table A.8: Supply shocks for major importers: all coal

			Actual			Counterfactual		
Country	Coal	Imports	Mean	Median	Std.Dev.	Mean	Median	Std.Dev.
01-CAN	ALL	297.939	0.136	0.051	0.699	0.242	0.051	1.693
02-JPN	ALL	140.636	0.261	0.180	0.246	0.396	0.180	0.499
03-BRA	ALL	137.542	3.469	1.798	5.058	12.285	1.798	43.389
04-ITA	ALL	98.559	0.279	0.119	1.557	1.177	0.146	13.289
05-GBR	ALL	95.327	1.207	0.772	1.107	1.967	1.509	1.857
06-DEU	ALL	81.020	0.976	0.894	0.743	1.704	1.209	1.193
07-NLD	ALL	74.560	4.057	2.679	2.521	6.503	2.679	6.032
08-KOR	ALL	66.978	0.200	0.092	1.430	0.414	0.141	3.409
09-FRA	ALL	54.501	8.773	9.628	2.308	11.329	10.594	4.062
10-ESP	ALL	52.125	6.167	3.284	6.789	10.707	3.284	17.752
OTH	ALL	243.443	13.147	5.702	15.012	26.905	11.023	32.666

Note: We report statistics across the three types of coal. All statistics are quantity-weighted using actual quantities for 1990–2014. The coal imports are in million metric tons. We use OTH to refer to all other importers.

Table A.9: Asia Pacific and Atlantic thermal coal assessments I

Contract	Cal.Value I	Cal. Value II	Sulfur %	Ash %	Moisture %	Vol. Matter %
CFR Guangzhou	3,600-4,000	NAR	Max 1	Max 10	Max 40	N/A
CFR Guangzhou	4,500-5,900	NAR	Max 1	Max 12	Max 30	N/A
CFR Guangzhou	5,300-5,700	NAR	Max 1	Max 23	Max 18	Max 40
CFR India East	3,600-4,000	GAR	Max 0.6	Max 8	Max 41	N/A
CFR India East	4,000-4,400	GAR	Max 1	Max 8	Max 41	N/A
CFR India East	4,800-5,200	GAR	Max 1	Max 8	Max 41	N/A
CFR India East	5,300-5,700	NAR	Max 1	Max 8	Max 41	N/A
CFR India East	N/A	N/A	Max 1	Max 8	Max 41	N/A
CFR India West	3,600-4,000	GAR	Max 0.6	Max 8	Max 41	N/A
CFR India West	4,000-4,400	GAR	Max 1	Max 8	Max 41	N/A
CFR India West	4,800-5,200	GAR	Max 1	Max 8	Max 41	N/A
CFR India West	5,300-5,700	NAR	Max 1	Max 8	Max 41	N/A
CFR India West	N/A	N/A	Max 1	Max 8	Max 41	N/A
CFR South China	5,300-5,700	NAR	Max 1	Max 23	Max 18	Max 40
CIF ARA	5,800-6,100	NAR	Max 1	Max 16	Max 14	N/A
CIF Japan	5,850-6,250	NAR	Max 1	Max 14	Max 15	Max 30
CIF Korea	5,850-6,250	NAR	Max 1	Max 17	Max 15	Max 30
CIF Turkey	5,850-6,300	NAR	0.5-1	6-15	15-Oct	N/A

Note: The assessments are from the Platts Coal Methodology and Specifications Guide for October 2016. The difference between net- and gross-as-received energy values is the latent heat of the water vapor, which lowers the effective calorific value of the coal. Mositure and Ash reduces net calorific value.

Table A.10: Asia Pacific and Atlantic thermal coal assessments II

Contract	Cal.Value I	Cal. Value II	Sulfur %	Ash %	Moisture %	Vol. Matter %
FOB ARA Barge	5,800-6,100	NAR	Max 1	Max 16	Max 14	N/A
FOB Colombia	5,750-6,100	NAR	Max 0.9	Max 12	Max 15	N/A
FOB Gladstone	6,300-6,700	GAR	Max 0.6	Max 12	Max 10	Max 30
FOB Kalimantan	3,600-4,000	GAR	Max 0.6	Max 9	Max 41	N/A
FOB Kalimantan	4,000-4,400	GAR	Max 1	Max 10	Max 40	N/A
FOB Kalimantan	4,800-5,200	GAR	Max 1	Max 12	Max 30	N/A
FOB Kalimantan	5,700-6,100	GAR	Max 1	Max 15	Max 20	N/A
FOB Kalimantan	5,700-6,100	GAR	Max 1	Max 15	Max 20	N/A
FOB Newcastle	5,300-5,700	NAR	Max 0.75	17-23	Max 15	N/A
FOB Newcastle	6,100-6,500	GAR	Max 0.75	Max 14	Max 15	27-35
FOB Newcastle	6,100-6,500	GAR	Max 0.75	Max 15	Max 15	27-35
FOB Newcastle	6,100-6,500	GAR	Max 0.75	Max 16	Max 15	27-35
FOB Newcastle	6,100-6,500	GAR	Max 0.75	Max 17	Max 15	27-35
FOB Poland	5,800-6,100	NAR	Max 0.8	Max 16	Max 14	N/A
FOB Qinhuangdao	4,800-5,200	NAR	Max 1	Max 25	Max 18	Max 40
FOB Qinhuangdao	5,300-5,700	NAR	Max 1	Max 20	Max 18	Max 40
FOB Qinhuangdao	5,300-5,700	NAR	Max 1	Max 14	Max 12	Max 30
FOB Qinhuangdao	6,100-6,300	GAR	Max 0.8	Max 10	Max 12	Max 30
FOB Richards Bay	5,300-5,700	NAR	Max 1	17-23	Max 13	N/A
FOB Richards Bay	5,800-6,100	NAR	Max 1	Max 16	Max 12	N/A
FOB Russia Baltic	5,800-6,100	NAR	Max 1	Max 16	Max 14	N/A
FOB Russia Pacific	6,200-6,400	GAR	Max 0.4	Max 15	Max 14	Max 30

Note: The assessments are from the Platts Coal Methodology and Specifications Guide for October 2016. The difference between net- and gross-as-received energy values is the latent heat of the water vapor, which lowers the effective calorific value of the coal. Mositure and Ash reduces net calorific value.

Table A.11: coal heat and sulfur dioxide content: major exporters

Country	Heat MMBtu/metric ton	SO_2 lbs./MMBtu
AUS	24.12	1.18
CAN	19.84	1.11
CHN	22.02	1.52
COL	23.81	1.39
IDN	19.27	1.52
IND	15.08	0.88
POL	23.81	1.30
RUS	24.41	0.73
USA	23.44	2.44
ZAF	22.82	1.55

Note: The heat content is an average of the heat content from Platts FOB contracts for coal originating in the countries listed in the leftmost column with the exception of the U.S. for which we report an average of the annual heat rates for coal exports reported by the EIA. The SO_2content is an average of the sulfur content for Platts FOB contracts.

Table A.12: coal heat and sulfur dioxide content: major importers

Country	Heat MMBtu/metric ton	SO_2 lbs./MMBtu
ARA	23.81	1.30
CHN	19.12	1.64
IND	20.17	1.59
JPN	24.13	1.10
KOR	24.13	1.10
TUR	23.81	1.48

Note: The heat content is an average of the heat content for coal in Platts CFR/CIF contracts for coal delivered in the countries listed in the leftmost column with the exception The SO_2content is an average sulfur content for Platts CFR/CIF contracts. ARA refers to the Platts contracts for the Amsterdam-Roterdam-Antwerp (ARA) hub, which we use for Western European Countries (NLD, DEU, GBR, ITA).

Table A.13: Counterfactual analysis: all coal economic outcomes, exporters, 2007-2014, Broda and Weinstein (2006) approach

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-AUS	289.184	322.879	11.652	2092.253	2246.423	7.369	138.216	143.730	3.989
02-IDN	148.537	152.228	2.485	1825.252	1853.589	1.552	81.379	82.126	0.918
03-USA	82.306	44.024	-46.511	583.748	303.889	-47.942	140.996	144.870	2.748
04-RUS	90.947	114.935	26.377	796.807	957.195	20.129	114.139	120.075	5.201
05-ZAF	39.933	46.845	17.311	392.879	447.402	13.878	101.641	104.705	3.015
06-COL	45.122	63.341	40.378	476.619	616.725	29.396	94.671	102.706	8.487
07-CAN	45.179	54.258	20.096	274.289	309.745	12.927	164.715	175.171	6.348
08-CHN	17.327	17.469	0.823	134.747	135.478	0.543	128.589	128.947	0.279
09-KAZ	4.892	5.686	16.226	160.722	164.176	2.149	30.437	34.632	13.780
10-POL	6.952	11.241	61.702	55.322	77.066	39.304	125.655	145.858	16.078
OTH	64.759	72.346	11.715	689.672	727.506	5.486	93.899	99.443	5.905
Non-USA	752.831	861.229	14.399	6898.561	7535.306	9.230	109.129	114.292	4.732
Total	835.137	905.253	8.396	7482.310	7839.196	4.770	111.615	115.478	3.461

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table A.14: Counterfactual analysis: all coal economic outcomes, exporters, 2007-2014, accounting for domestic coal

	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-AUS	360.778	361.209	0.119	3011.427	3013.245	0.060	119.803	119.874	0.059
02-IDN	202.968	203.241	0.134	2300.669	2303.081	0.105	88.221	88.247	0.030
03-USA	743.292	735.813	-1.006	7700.891	7305.194	-5.138	96.520	100.725	4.356
04-RUS	230.291	230.941	0.282	1965.479	1969.174	0.188	117.168	117.278	0.094
05-ZAF	207.199	207.384	0.090	1855.602	1857.049	0.078	111.661	111.674	0.012
06-COL	47.427	48.224	1.682	497.069	503.276	1.249	95.413	95.821	0.427
07-CAN	72.411	72.541	0.179	549.393	549.920	0.096	131.802	131.912	0.083
08-CHN	2373.669	2373.715	0.002	27722.180	27722.338	0.001	85.623	85.625	0.001
09-KAZ	50.464	50.468	0.006	624.641	624.656	0.002	80.790	80.793	0.004
10-POL	93.393	93.780	0.415	1098.017	1100.585	0.234	85.056	85.209	0.181
OTH	857.559	858.919	0.159	8985.799	8994.959	0.102	95.435	95.489	0.057
Non-USA	4496.159	4500.423	0.095	48610.276	48638.284	0.058	92.494	92.528	0.037
Total	5239.451	5236.236	-0.061	56311.166	55943.478	-0.653	93.045	93.599	0.595

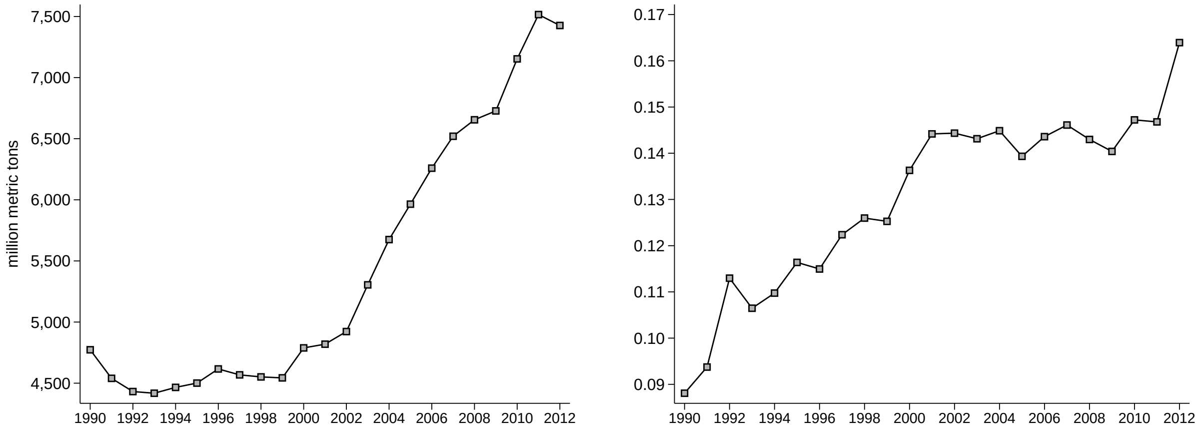
Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table A.15: Counterfactual analysis: all coal economic outcomes, exporters 2007-2014, based on estimates for 1990–2016

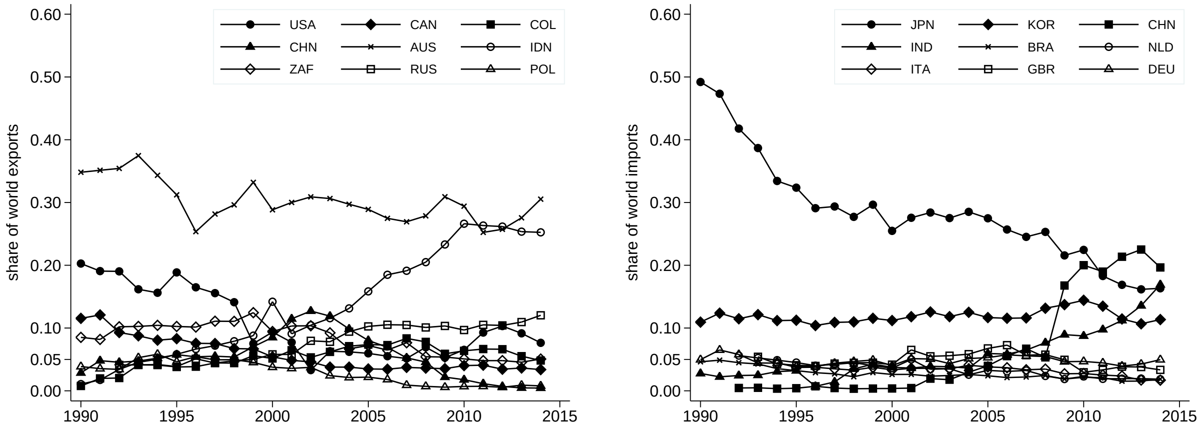
	Coal Value			Coal Quantity			Coal Price		
Country	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-AUS	289.184	300.509	3.916	2092.253	2151.706	2.842	138.216	139.661	1.045
02-IDN	148.537	150.656	1.427	1825.252	1844.118	1.034	81.379	81.695	0.389
03-USA	82.306	61.425	-25.370	583.748	405.948	-30.458	140.996	151.313	7.318
04-RUS	90.947	96.370	5.963	796.807	835.230	4.822	114.139	115.381	1.088
05-ZAF	39.933	40.724	1.981	392.879	397.897	1.277	101.641	102.348	0.695
06-COL	45.122	49.301	9.261	476.619	513.868	7.815	94.671	95.940	1.341
07-CAN	45.179	47.436	4.995	274.289	283.897	3.503	164.715	167.088	1.441
08-CHN	17.327	17.396	0.398	134.747	135.089	0.254	128.589	128.773	0.143
09-KAZ	4.892	5.025	2.714	160.722	161.311	0.367	30.437	31.149	2.339
10-POL	6.952	8.129	16.940	55.322	62.509	12.991	125.655	130.047	3.495
OTH	64.759	66.385	2.510	689.672	699.514	1.427	93.899	94.901	1.067
Non-USA	752.831	781.929	3.865	6898.561	7085.141	2.705	109.129	110.362	1.130
Total	835.137	843.354	0.984	7482.310	7491.089	0.117	111.615	112.581	0.866

Note: The values are in billion USD, the quantities are in million metric tons, and the prices are in USD/metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Figure A.1: Coal markets overview



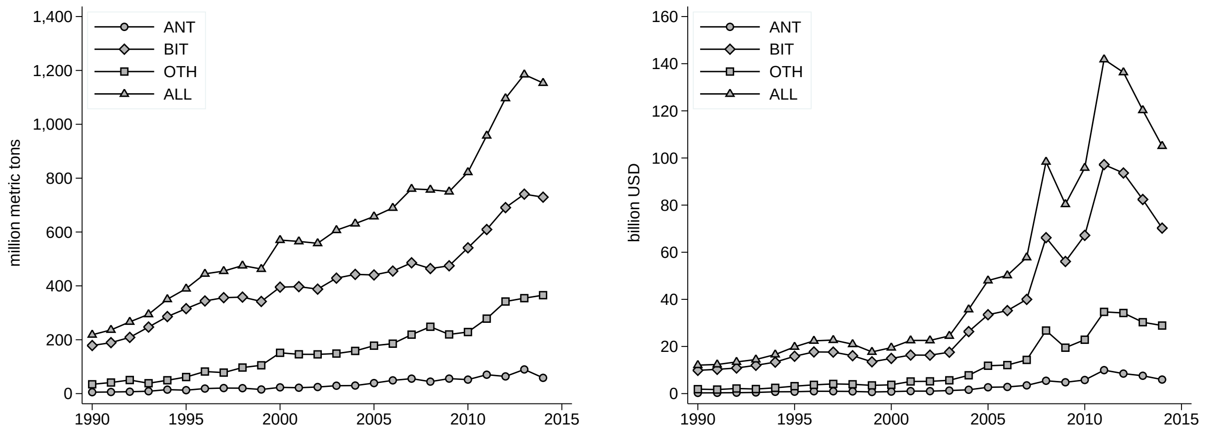
(a) Consumption (b) Trade/Consumption Ratio



(c) Major exporters (d) Major importers

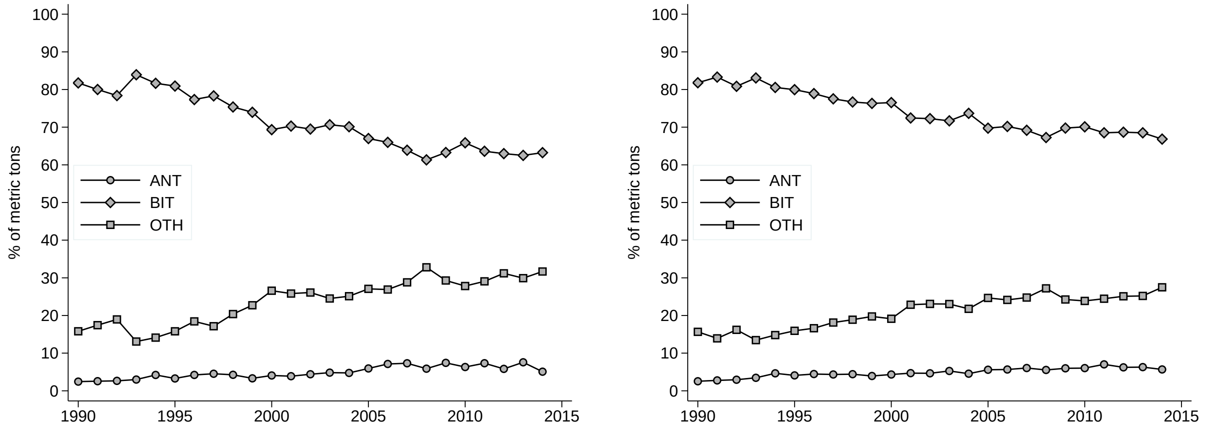
Note: panels (a) and (b) are based on data from the EIA International Energy Statistics. Panels (c) and (d) are based on UN COMTRADE import data.

Figure A.2: World trade by type of coal



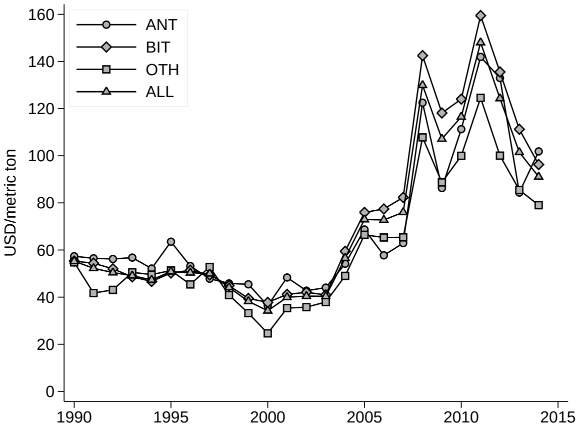
(a) quantity

(b) value



(c) quantity, %

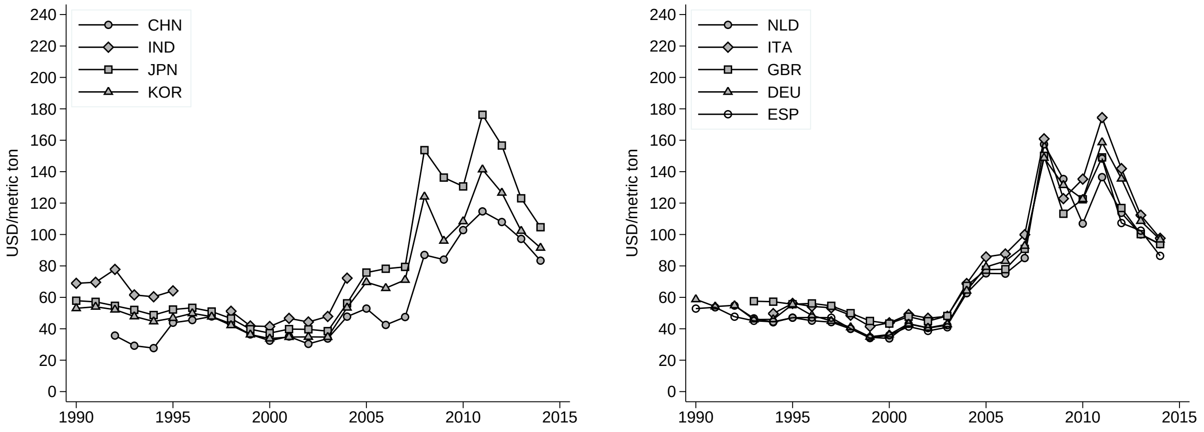
(d) value, %



(e) price

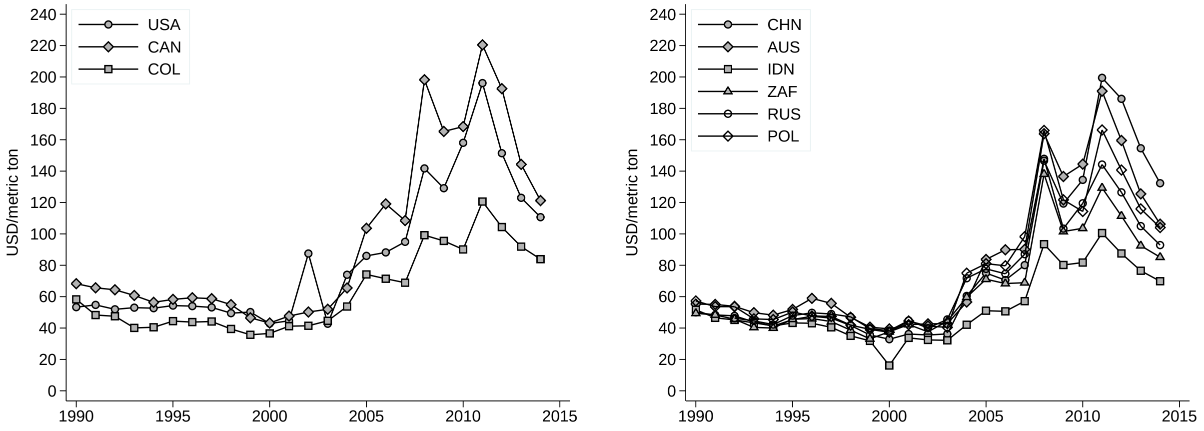
Note: based on import file for HS6 codes: 270111 (anthracite (ANT)), 270112 (bituminous (BIT)), 270119 (other (OTH)).

Figure A.3: Coal prices per metric ton



(a) coal prices for importers: Asia

(b) coal prices for importers: Europe

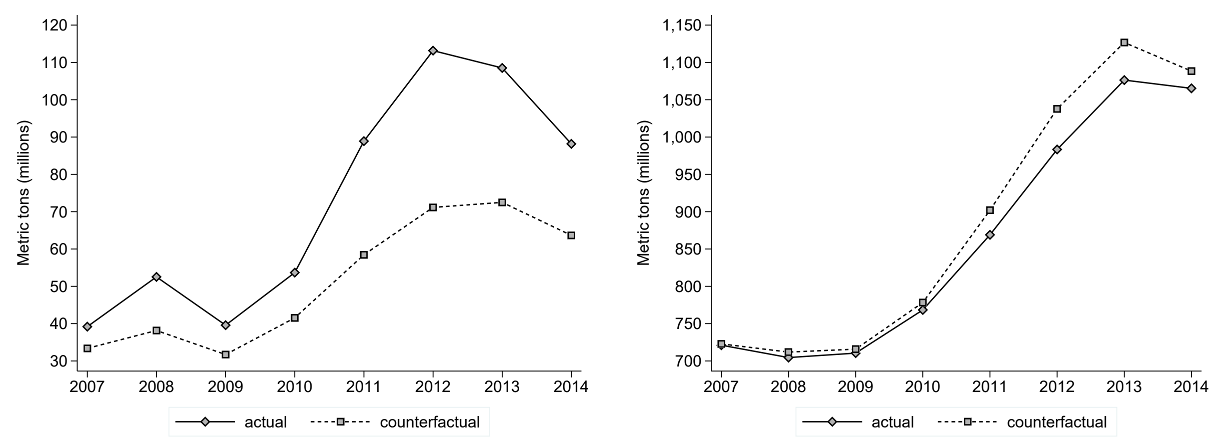


(c) coal prices for exporters: Americas

(d) coal prices exporters: Other

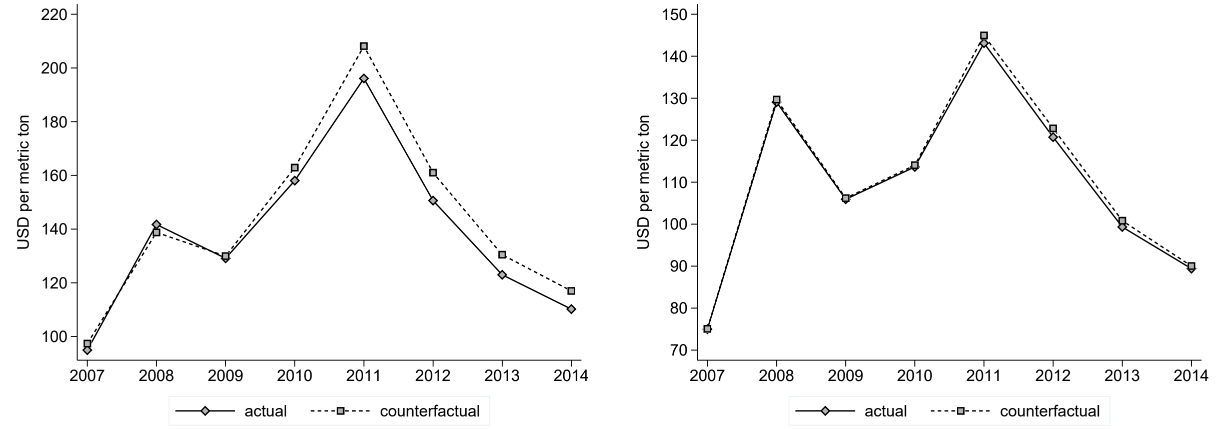
Note: Based on UN COMTRADE import prices. Panel (a) shows the import price for coal paid by various Asian countries. Panel (b) shows the import price for coal paid by various European countries. Panel (c) shows the import price for coal originating in the Americas. Panel (d) shows the import price for coal originating in other parts of the world.

Figure A.4: Counterfactual analysis:
economic outcomes, 2007–2014



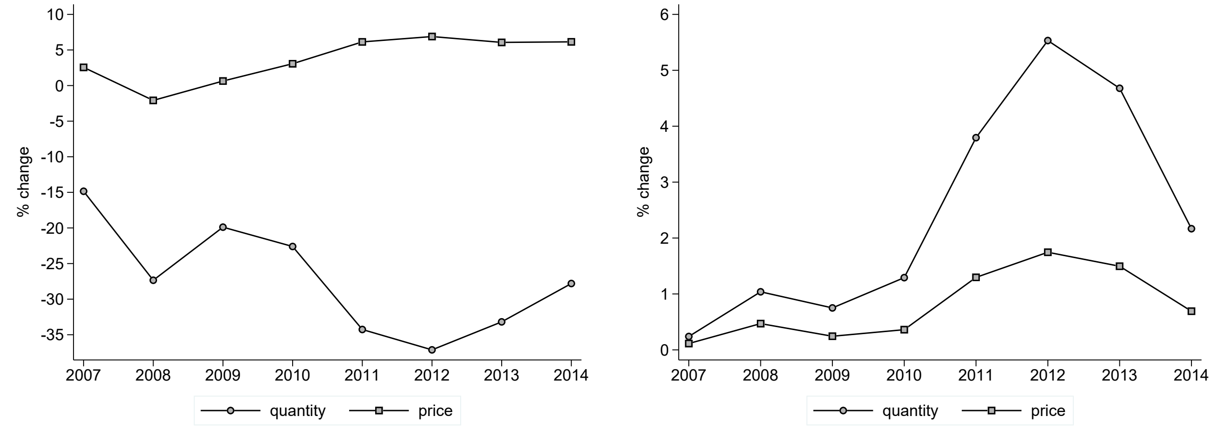
(a) quantity, U.S. coal

(b) quantity, non-U.S. coal



(c) price, U.S. coal

(d) price, U.S. coal

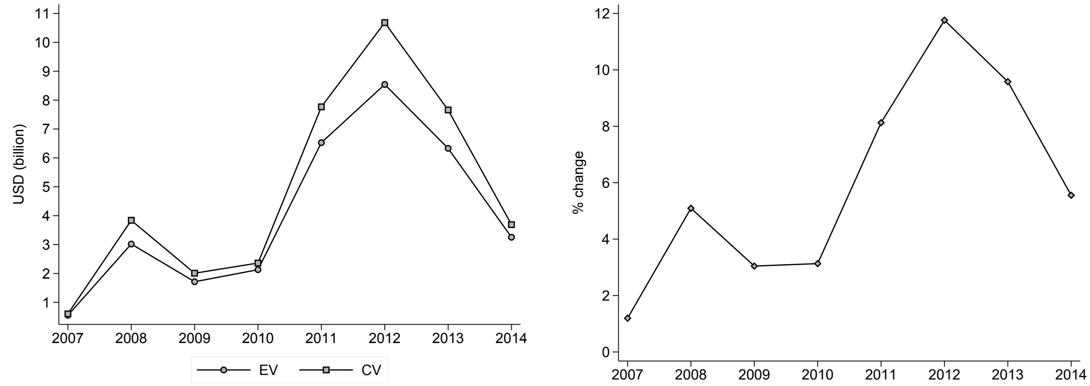


(e) % change, U.S. coal

(f) % change, non-U.S.coal

Note: We provide time series plots of actual and counterfactual quantities and prices for U.S. and non-U.S. coal for the period that is relevant for our counteractuals.

Figure A.5: Counterfactual analysis:
economic outcomes, 2007–2014

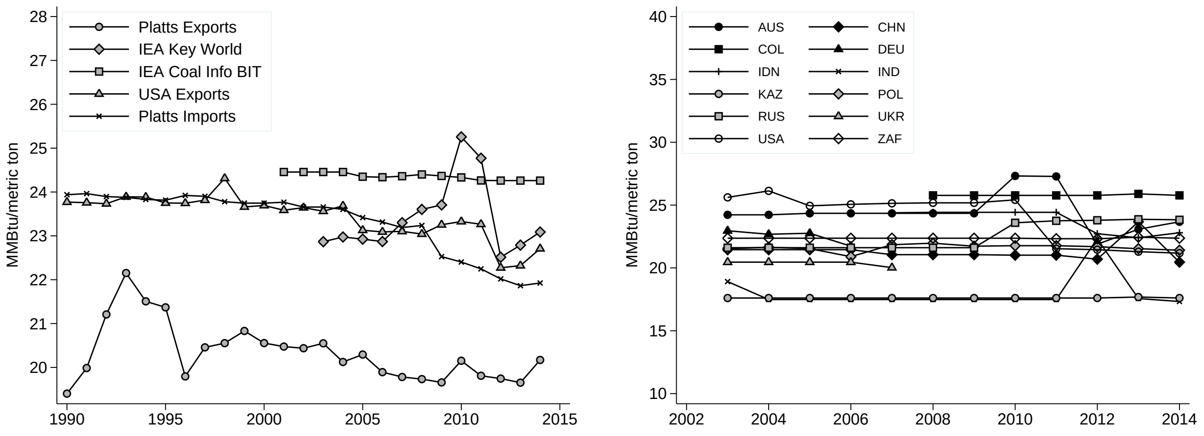


(a) welfare

(b) CES price index

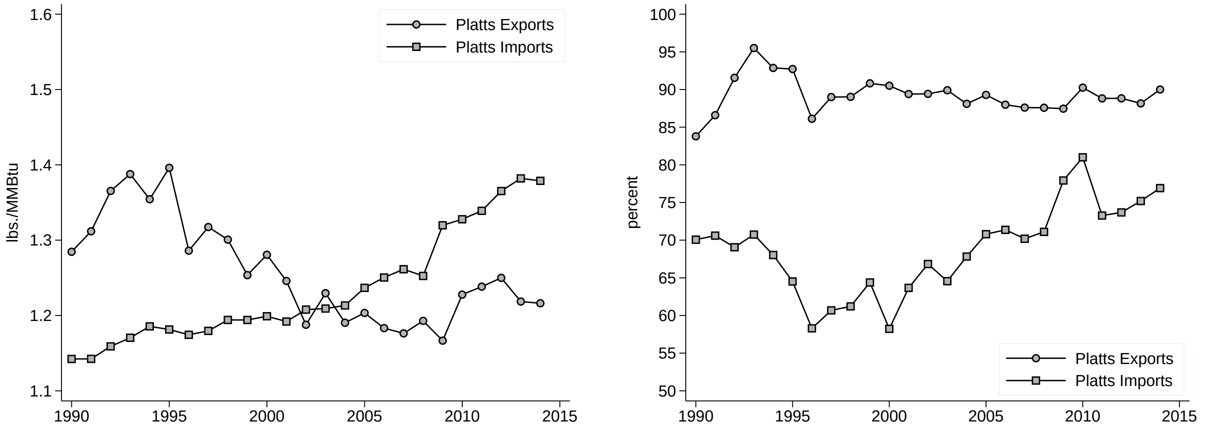
Note: Panel (a) the equivalent (EV) and compensating (CV) variation associated with the consumption of imported coal and discarding environmental damages. Positive values for the two measures of welfare effects imply that consumers in importing countries are worse off in the absence of the Boom. Panel (b) shows a quantity-weighted average change in the CES price index in the absence of the Boom.

Figure A.6: Coal specifications



(a) Heat content: MMBtu/metric ton

(b) Heat content: MMBtu/metric ton

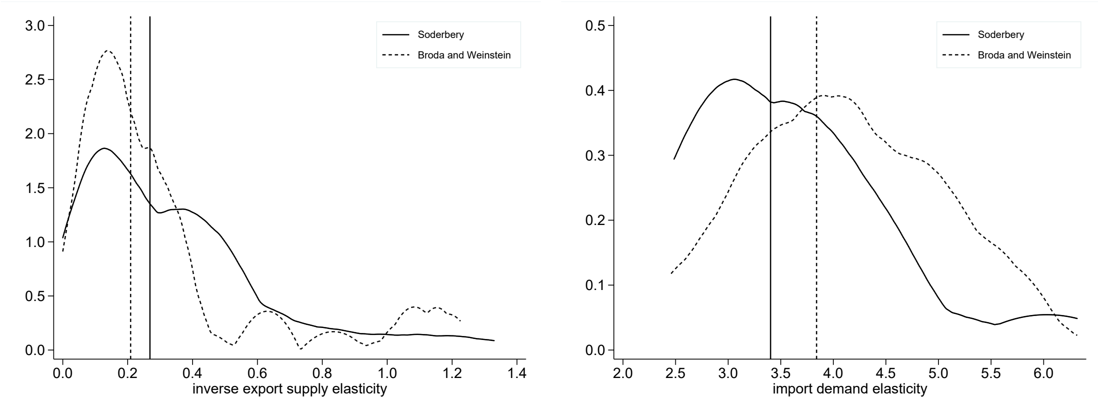


(c) SO_2content: lbs./MMbtu

(d) Share of coal flows with heat and sulfur content information

Note: See Section 5.4 for additional details.

Figure A.7: Export and import elasticities:
Soderbery (2017) vs. Broda and Weinstein (2006)

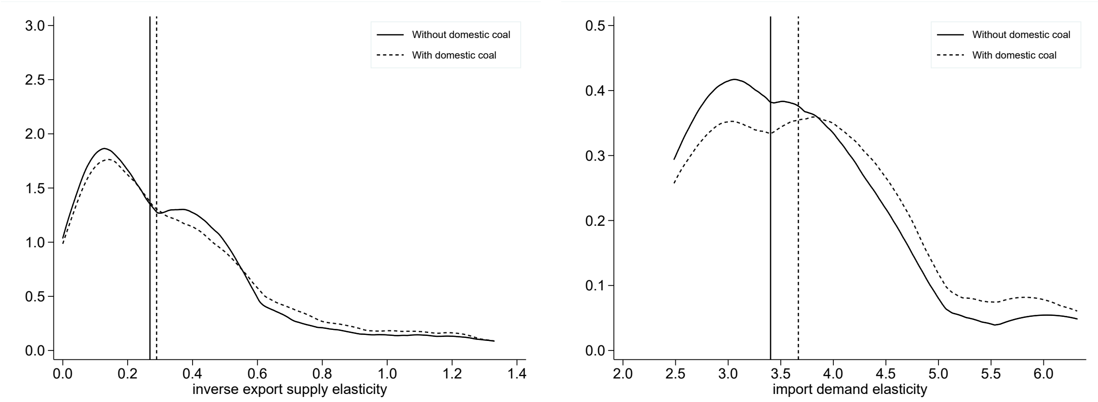


(a) inverse export supply elasticities (ω)

(b) import demand elasticities (σ)

Note: Panel (a) shows a kernel density plot of the inverse export supply elasticities for the Sodebery and Broda-Weinstein (BW) estimators for all three types of coal. The vertical lines indicate the median of the corresponding distributions. Panel (b) shows a kernel density plot of the import demand elasticities for the two estimatos. The supply elasticity estimates exhibit variation by importer, coal type, and exporter (importer and coal type) in the case of Soderbery's (BW's) estimator. For both estimators, the import demand elasticities exhibit variation by importer and coal type.

Figure A.8: Export and import elasticities:
Accounting for domestic coal

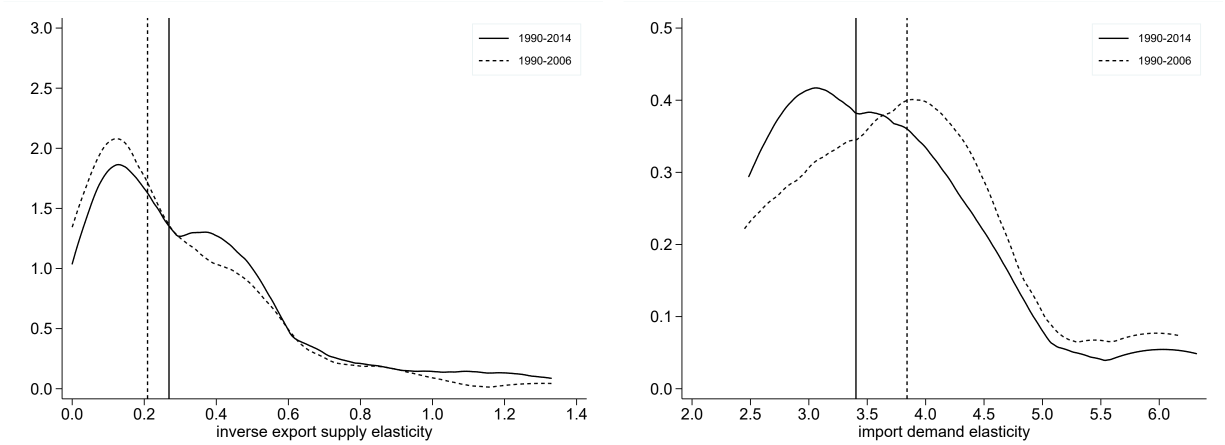


(a) inverse export supply elasticities (ω)

(b) import demand elasticities (σ)

Note: Panel (a) shows a kernel density plot of the inverse export supply elasticities for the Sodebery estimator with and without domestic coal. Panel (b) shows a kernel density plot of the import demand elasticities with and without domestic coal. The vertical lines indicate the medians of the corresponding distributions in both panels.

Figure A.9: Export and import elasticities:
Alternative estimation sample



(a) inverse export supply elasticities (ω) (b) import demand elasticities (σ)

Note: Panel (a) shows a kernel density plot of the inverse export supply elasticities for the Soderbery (2017) estimator for two alternative estimation samples noting that 2007–2014 is the period relevant for our counterfactuals. Panel (b) shows a kernel density plot of the import demand elasticities for the two alternative estimation samples. The vertical lines indicate the medians of the corresponding distributions in both panels.

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