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 the 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. Although a compositional change towards dirtier (lower heat content) 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 CO_2 emissions.

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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—away from coal and towards natural gas—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—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

[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. (2019), among others. Hausman and Kellogg (2015) provide an in-depth analysis of the economic and environmental impacts of the shale revolution.

domestic demand for coal. Second, there is an increase in export supply of U.S. coal because domestic producers are looking for alternative markets to sell their product. 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 (2018), 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 ex-

[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. Between 2002 and 2016, about a third of U.S. exports of steam coal used for electricity generation to major Asian importers (China, India, Korea, Japan) originated from eastern ports, which is consistent with U.S. coal producers having difficulty accessing the Asian market via the Pacific. 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.

porters, in contrast to Feenstra (1994) and Broda and Weinstein (2006) (henceforth, FBW). We do so because, although homogeneous import demand elasticities find empirical support 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 the 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. Later in the paper, we examine the implications for such heterogeneity in export supply elasticities.

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. Panel data allows us to identify and estimate this causal link, and separate this effect from aggregate shocks in the coal international market, which affect all exporters simultaneously.

We calculate counterfactual world coal trade flows by 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 (2018) and UN COMTRADE data between 1990–2014 to estimate import demand and export supply 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. We estimate the relationship between the price of gas in the U.S. and Europe for 1990–2006 and use it to 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 around the world.

We report detailed results regarding our counterfactual analysis for approximately 40 coun-

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

tries 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 0.14% lower than the actual quantity traded. The price (USD/metric ton) and dollar value of coal increase by 0.37% and 0.24%. Moreover, after accounting for heterogeneity in the heat and sulfur content and changes in the equilibrium of the global coal market, we 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. Furthermore, in the absence of the Boom, there is a decrease of 21.3% (18.7%) in the quantity (dollar value) of U.S. coal exports with U.S. coal exporters losing $15.4 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 Western U.S. ports. Wolak' paper and ours are quite different in terms of methodology and focus. While his model is mostly calibrated, ours is fully estimated. 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.[5] According to his findings,

[5]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

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)).[6]

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. 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

for the price of natural gas using the number of heating degree days and the number of cooling degree days as instruments.

[6] 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.[7]

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.[8] 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 U.S. production (tons), while anthracite has accounted for less than 1% (EIA, Annual Coal Review).[9]

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 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]

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

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

[9] To the best of our understanding, sub-bituminous coal and lignite are treated as other coal in the COMTRADE data used in our empirical analysis. According to the documentation of the World Customs Organization for the HS system, anthracite (HS6 270111) means coal having a volatile matter limit not exceeding 14%. Bituminous coal (HS6 270112) means coal having a volatile matter limit exceeding 14% and a calorific value limit (on a moist, mineral matter-free basis) equal to or greater than 5,833 kcal/kg. See https://goo.gl/RPjXgm. Note that 5,833 kcal/kg $\approx$ 21 MMBtu per ton and coals with higher volatile matter contents have lower heating values.

[10] As an example, Andrew Revkin of The New York Times wrote 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

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).[14]

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

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.

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

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 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.[15]

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. Generally, import prices for coal originating from major producing countries, such as the U.S., Australia, Indonesia, Russia, Colombia, Canada, and South Africa, track each other closely (panels (c) and (d)).[16]

3 Model

Our trade model is designed to quantify equilibrium responses to export supply shocks on a market-by-market basis. In what follows, we first describe our international trade model and we then link it to a structural model of the U.S. domestic markets for coal and gas. 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.

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

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

[16] We should note that there are some signs of divergence in prices post 2008.

and the estimation strategy in Soderbery (2018). We assume a representative consumer on the demand side and monopolistic competition (as in Armington (1969)) on the supply side.

In terms of 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, say, 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.[17]

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. 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 the purchases of imported coal.

Although we model preferences similar to Shapiro (2016), our approach generally departs

[17] 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 $G^I_v = 6$.

from his. Shapiro focuses on emissions due to trade of a wide range of goods. We focus on emissions associated with coal trade alone. Hence, we are interested in 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 (2018) 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:

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

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 do not alter our main results in a material way.

3.2 U.S. 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_{dt}^g, 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:

$$p_d^c(q_{dt}^c, p_{dt}^g, w_{dt}^n; \theta) = \theta_0 + \theta_1 q_{dt}^c + \theta_2 p_{dt}^g + \theta_3 w_{dt}, \tag{7}$$

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 coal to sell in the foreign coal market. Although arbitrage is not possible, the two markets are related through production costs:

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

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:

$$\max_{q_{dt}^c, q_{ft}^c} \; p_{dt}^c(q_{dt}^c, p_{dt}^g, w_{dt}; \theta) q_{dt}^c + p_{ft}^c q_{ft}^c - C(q_{dt}^c, q_{ft}^c; \gamma). \tag{9}$$

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

$$p_{ft}^c = \beta_1 \alpha_f (q_{dt}^c)^{\alpha_d} (q_{ft}^c)^{\alpha_f - 1}, \tag{10}$$

$$q_{ft}^c = \left(\frac{p_{ft}^c}{\beta_1 \alpha_f (q_{dt}^c)^{\alpha_d}} \right)^{\frac{1}{\alpha_f - 1}}. \tag{11}$$

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

$$\max_{q_{dt}^c} p_{dt}^c(q_{dt}^c, p_{dt}^g, w_{dt}; \theta) q_{dt}^c + p_{ft}^c q_{ft}^c(q_{dt}^c) - C(q_{dt}^c, q_{ft}^c(q_{dt}^c, p_{ft}^c; z); \gamma), \tag{12}$$

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 as follows

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

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

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

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 (2018). 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 with panel data for different varieties in a given market (importing country), does not accommodate heterogeneity in export supply elasticities. Soderbery's estimator does 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.[18]

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; we focus on the period 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.[19] Following the elimination of observations associated with

[18]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 (2018). Equations (8) and (9) in Soderbery (2018) 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 (2018) to address measurement error in prices since trade data record unit values.

[19]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 very similar.

some clear price 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.[20]

To alleviate the computational burden due to the high-dimension 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 exceptions. In particular, major exporting countries are excluded from the regional aggregation.[21] 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 affected primarily 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 the inverse export elasticity (ω) serves as 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_{gv}^{I}) and import demand (σ_{g}^{I}) elasticities for the three types of coal.[22] 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 0.56.

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

[20] 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.

[21] Table A.6 and the associated note provides information regarding the aggregation of exporters 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). Table A.7 and the associated note provides information regarding the aggregation of importers.

[22] 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. Excluding outliers, as we do in Table 1, is common when reporting summary statistics on trade elasticities given their sheer number; see Broda et al. (2008) and Kee et al. (2008), among others.

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 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 3.87, such that a 1% increase in the price of bituminous coal leads to a 3.87% increase in bituminous coal exports to Japan. The median ω for Korea is 0.30 and it is quite similar to that of Japan implying an export elasticity equal to 3.3.[23] For China, the median ω is much smaller compared to Korea and Japan (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 70% of China's bituminous coal imports, a plausible explanation for the magnitude of our estimates is China's reliance on imports from them.[24]

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).[25] For Australia, Indonesia, Colombia, and South Africa, the median ω values are 0.19–0.27.[26] Both

[23] 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. The ω values for Korea are more dispersed than their counterparts for Japan with a standard deviation of 0.84 compared to 0.15.

[24] 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. In the case of Brazil, the U.S., Austrlia, and Colombia account for 42%, 23%, and 14% of all bituminous imports. In the case of India, Indonesia, South Africa, and Austrlia account for 65%, 18%, and 11% of all bituminous imports. In the case of Russia, Kazhakstan and the U.S. account for 69% and 25% of all bituminous imports. In the case of India and Russia, imports account for less than 10% of consumption according to data from the EIA international statistics.

[25] 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.

[26] 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)

Colombian and South African bituminous coal have multiple European destinations (e.g., the Netherlands, France, Germany) whose individual imports account up to about 1/5 of the two countries' exports.[27]

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 of Russia' imports of bituminous coal are from Kazakhstan and the U.S., 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., Australia, Colombia, and, to a lesser extent, Canada. 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.[28]

4.2 U.S. 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

of Indonesia's total exports.

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

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

following model:

$$\widehat{\eta}^{I}_{gvt} = h(\cdot) + u_{gvt} = \mu_{Igv} + \mu_t + \mu_g p_t \mathbf{1}_{[v=usa]} + u_{gvt} \tag{21}$$

where $\widehat{\eta}^{I}_{gvt} \equiv ln(p^{I}_{gvt}) - \widehat{\omega}^{I}_{gv} ln(q_{gvt})$ 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_{Igv} is an importer-exporter-by-coal-type fixed effect, μ_t is a year fixed effect, p_t 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 $\widehat{\eta}^{I}_{gvt}$. The domestic gas price only affects (directly) the U.S. export supply curves. Furthermore, we expect positive slope coefficients, such that an increase in the U.S. price of gas shifts the U.S. export supply curve to the left.[29]

According to Table 4, the slope coefficients in (21) have the proper signs. The gas price is estimated to have a significant effect of 0.07 on the U.S. coal export shocks, for the case of bituminous coal. Neither the coefficients for anthracite or other coal appear statistically significant, consistent with those types of coal not being used for electricity generation. With these estimates in hand, we now proceed to the counterfactual analysis.[30]

5 Counterfactual Analysis

5.1 Overview

The counterfactual analysis is based on calculating worldwide trade flows for coal in the absence of 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

[29] 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.

[30] 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.

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 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 in the U.S. electric power sector is lower than the actual demand. Due to substitutability between coal and gas, this results in an increased U.S. domestic demand for coal that is served by the domestic supply and plays the role of a negative shock to the U.S. coal export supply curve.[31] Importantly, 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:

$$p^g_{dt,CF} = \begin{cases} p^g_{dt}, & t = 1990, ...2006 \\ \widehat{\lambda}_0 + \widehat{\lambda}_1 p^g_{et}, & t = 2007, ...2014. \end{cases} \tag{22}$$

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

$$p^g_{dt,CF} = \lambda_0 + \lambda_1 p^g_{et} + u_t, \quad t = 1990, ...2006. \tag{23}$$

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

[31] This is the case because coal and gas are closer substitutes for electric power plants when gas prices are lower even after 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. 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.

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 underestimate the difference between actual and counterfactual prices.[32]

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_g^I) and inverse export supply (ω_{gv}^I) elasticities. Given our estimates, prices and quantities of coal are driven by the export supply and import demand shocks η_{gvt}^I and b_{gv}^I, respectively, along with the structure of the import market, which is captured by the price index ($\mathcal{P}_{gt}^I$).[33]

The first economic variable of interest 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:

$$\Delta ln(\mathcal{P}_{gt}^I) = \frac{1}{1+\overline{\omega}_{gt}^I}\Delta\overline{\eta}_{gt}^I, \tag{24}$$

where $\Delta\overline{\eta}_{gt}^I \equiv \overline{\eta}_{gt,CF}^I - \overline{\eta}_{gt}^I$. Furthermore, $\overline{\omega}_{gt}^I$ and $\overline{\eta}_{gt}^I$ are quantity-weighted harmonic means of the inverse export supply elasticities and shocks using the actual quantities. 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:

$$\Delta ln(p_{gvt}^I) = \frac{1}{1+\sigma_g^I\omega_{gv}^I}\Delta\eta_{gvt}^I + \frac{\omega_{gv}^I(\sigma_g^I-1)}{1+\sigma_g^I\omega_{gv}^I}\Delta ln(\mathcal{P}_{gt}^I) \tag{25}$$

$$\Delta ln(q_{gvt}^I) = \frac{-\sigma_g^I}{1+\sigma_g^I\omega_{gv}^I}\Delta\eta_{gvt}^I + \frac{(\sigma_g^I-1)}{1+\sigma_g^I\omega_{gv}^I}\Delta ln(\mathcal{P}_{gt}^I), \tag{26}$$

where $\Delta\eta_{gvt}^I \equiv \eta_{gvt,CF}^I - \eta_{gvt}^I$. Non-U.S. exports are only affected by changes in the price index in each importing country because $\Delta\eta_{gvt}^I = 0$ for non-U.S. coal exports. U.S. exports

[32] 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.

[33] 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.

are affected by both the shifts in the export supply curve and the resulting impact on the price index.

Finally, 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

The main message of our counterfactual analysis is that the increase in U.S. coal exports (because of the Boom) displaced other coal exports, with the global coal trade remaining essentially unchanged. 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.[34] 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.

Our counterfactual results are based upon an export shock in bituminous coal only. This is because anthracite and other coal do not appear to respond to changes in the U.S. price of natural gas (Table 4), which is consistent with bituminous being the type of coal that is a closer substitute to gas. We also note that including anthracite and other coal does not affect the estimated elasticities for bituminous coal, because that model is estimated using importer-coal type pairs.

Overall, the counterfactual coal quantity is 0.14% lower than its actual counterpart. The counterfactual dollar value is 0.24% higher and prices are 0.37% 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

[34] Table A.9 provides a similar breakdown by importer. Table A.19 shows that the results discussed here remain essentially the same if we exclude anthracite, which is not used for electricity generation, from our calculations.

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 1.66% higher, while that of U.S. coal is 21.34% lower. The prices of U.S. coal increase by 3.4%, while those of non-U.S. coal increase by 0.63%. 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, Italy and the Netherlands experience the largest percentage decrease in quantities as we move from the actual to the counterfactual outcomes, 4.38% and 5.09%, respectively (Table A.9). None of the remaining importers experiences an increase or decrease in quantity that exceeds 1%. Italy (1.35%) and the Netherlands (2.01%) also experience the largest percentage change in dollar value.

Restricting the analysis to imports of coal from the U.S., we see the largest percentage decrease in quantity for Japan (70.69%), followed by China, Korea, the Netherlands, and Italy, which all experience a decrease in the 43%–49% range in the absence of the boom (Table A.11). For Germany, Great Britain, Russia and Brazil, 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 the lost sales of U.S. coal.[35]

[35] Table A.13 (Table A.14) provides a breakdown of the change in economic (environmental) outcomes for non-U.S. coal by major importer. In the absence of the Boom, Italy and the Netherlands experience the

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 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.[36]

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 15,018, respectively (Table 6). This is a decrease of 0.135%, 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 \$556.4 and \$555.7 billion, respectively. Hence, the environmental damages related to CO_2 are \$700 million lower 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 92.7 and 92.5 million tons, respectively.

In the case of U.S. coal, the counterfactual (actual) CO_2 emissions are 923 (1,173) million metric tons implying an SCC of \$34.1 (\$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 5.7

largest percentage increase in both quantity—5.84% and 4.56%— and price, 1.92% and 1.56%, respectively. The counterfactual outcomes in terms of dollars, quantities, and prices for Germany, Great Britain, Russia, and Brazil are essentially identical to the actual ones.

[36]For example, assuming a heat content of 12,000 Btu/lb, and a sulfur content of 3%, the SO_2 content of coal is $(0.03s \times 2)/0.012 = 5.0$ lbs./MMBtu. 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 CO_2, NO_x, and particulate matter emissions.

We now employ a more detailed approach in our calculation of the change in emissions, which 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 Tables A.15 and A.16. Such a refinement results in total actual and counterfactual CO_2 emissions of 15,954 and 15,926 million metric tons, respectively, pointing to a decrease of 24 million metric tons, about 0.18%, in the absence of the Boom. In the case of SO_2 emissions, our refinement results in total actual and counterfactual SO_2 emissions of 102.3 and 101.6 million metric tons, respectively, pointing to a decrease of 0.7 million metric tons 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 7. 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 shows 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 (24). 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 \$19.1 billion, while the CV, as expected in the case of normal goods, is higher with a value of \$21.1 billion. Among major importers, the largest EV (CV) dollar amount is that for Germany, \$2.5 (\$2.7) billion, for which the actual dollar value of coal imports is \$43 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 Method to Estimate Elasticities

We now obtain elasticity estimates using 2SLS and compare them to our NLSUR estimates. To do so, we aggregate across the three types of coal for the top 20 importers and we estimate inverse export elasticities (ωs) for each of the major exporters. We regress log prices on log quantities using the importing countries' GDP as an instrument and control for importer fixed effects obtaining the following ω estimates: Australia (0.55), Indonesia (0.17), U.S. (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), U.S. (0.58), South Africa (0.64), Colombia (0.44).

Using the importing countries' GDP as a demand shifter, as well as importer and year fixed effects, we estimate 2SLS import demand elasticities (σs) of 1.88 (bituminous coal), 2.72 (anthracite), and 3.90 (other coal). In this case, we use the average price in other importing countries and the average distance of other importing countries from their exporters as instruments and estimate one 2SLS regression for each type of coal.

The main message is that our NLSUR elasticity estimates in Tables 2 and 3 are not only comparable to other elasticity estimates in the literature discussed earlier but they are also comparable to linear 2SLS estimates obtained using the same data. Moreover, Section A.5 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 (2018) 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 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 1.13% increase in coal quantities in the absence of the Boom, as opposed to a 0.14% decrease in the case of Soderbery's estimator (Table A.17). We also see an increase in the value of trade by 2.3% as opposed to 0.24%, and an increase in prices by 1.17% as opposed to 0.37%. Importantly, there is a decrease of 35.27%, as opposed to 21.34%, in the quantity of U.S. coal exports, and an increase in U.S. coal prices of 2.20%, as opposed to 3.41%. Therefore, a less flexible model that allows the export supply elasticities to exhibit variation only by coal type and importer would over-estimate the impact of the Boom on global coal markets.

6.3 Consumption of Domestic Coal in Importing Countries

Our main results also do not account for domestically produced coal in importing countries. 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, the reader should 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 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 no 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 results in 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.

In terms of the counterfactual analysis, we find a 0.14% decrease in coal quantity in the absence of the Boom when we account for domestic coal, which is essentially identical to the change in coal quantity in our main results (Table A.17). We also see a decrease in the value of coal trade by 0.14% as opposed to an increase of 0.24%. The counterfactual (actual) CO_2 emissions are 96,008 (96,163) million metric tons. Finally, the counterfactual (actual) SO_2 emissions are 685 (686) million metric tons. In both cases, we allow for heterogeneity in the heat and SO_2 content of coal. Finally, we see a decrease of 27.04%, as opposed to 21.34%, in the quantity of U.S. coal and an increase in U.S. coal prices equal to 4.16%, as opposed to 3.41%. Hence, although the introduction of domestic coal has some implications for our counterfactual analysis of U.S. coal exports, the qualitative nature of our main results holds.

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.

6.5 Robustness checks for the effect of U.S. gas prices on bituminous coal

In our counterfactual analysis, we shock the U.S. coal export supply curves using the estimates from Table 4. The relation between the U.S. natural gas price and the U.S. export shocks that we estimate makes economic sense: it has the correct sign and is statistically significant in the case of bituminous coal. Importantly, we see an effect of anthracite, which is not used in electricity generation, that is statistically indistinguishable from zero.

Nevertheless, we also produce alternative counterfactual results based on different degrees of sensitivity of the U.S. coal export supply curves to the U.S. price of natural gas. We do this by scaling the coefficient for bituminous coal (0.07) in Table 4 upwards, or downwards, and repeating the full counterfactual analysis. A summary of the results from this perturbation exercise are reported in Table A.18.[37] As the table shows, the total impact of the Boom on the international coal market is always small for the range of sensitivities we considered.

Therefore, the main message of our paper would continue to hold even if the shock to the U.S. export supply curves were higher or lower than the one that we estimate. In other words, independently of the magnitude of the shift in U.S. coal exports, a large fraction of it would just crowd out coal exports from other countries.

[37] The resulting range is very similar to the one implied by a 95% confidence interval around the point estimate of 0.07.

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 is 0.14% 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 1%. 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 about 20% in the quantity and dollar value of U.S. coal exports with U.S. coal exporters losing $15.4 billion.

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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)			$1/\omega$	Import Demand (σ)		
Coal Type	Mean	Median	Std. Dev.	Median	Mean	Median	Std. Dev.
Anthracite	0.868	0.302	1.829	3.315	3.243	3.023	0.881
Bituminous	0.719	0.210	1.779	4.773	3.583	3.425	1.001
Other	0.845	0.311	2.067	3.213	3.583	3.425	1.049
All	0.802	0.267	1.836	3.741	3.504	3.359	0.973
	B. Elasticity Statistics						
	Inverse Export Supply (ω)			$1/\omega$	Import Demand (σ)		
Coal Type	Mean	Median	Std. Dev.	Median	Mean	Median	Std. Dev.
Anthracite	0.342	0.301	0.215	3.319	3.090	3.023	0.522
Bituminous	0.273	0.220	0.191	4.554	3.426	3.403	0.682
Other	0.343	0.384	0.166	2.623	3.595	3.599	0.562
All	0.313	0.275	0.202	3.631	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)			$1/\omega$	Import Demand (σ)
Importer	Coal	GDP	Value	Quantity	Mean	Median	Std. Dev	Median	Estimate
01-JPN	BIT	4.340	294.588	3559.822	0.294	0.259	0.149	3.867	4.355
02-KOR	BIT	0.888	129.183	1672.996	0.539	0.299	0.843	3.339	4.217
03-CHN	BIT	2.668	91.282	887.908	0.290	0.049	0.961	20.254	3.344
04-GBR	BIT	2.345	39.004	440.822	0.632	0.113	0.789	8.873	4.625
05-DEU	BIT	2.907	40.701	438.185	0.206	0.186	0.144	5.369	4.678
06-ITA	BIT	1.845	32.338	334.061	0.284	0.252	0.184	3.972	3.042
07-NLD	BIT	0.658	19.711	285.105	0.117	0.129	0.056	7.771	3.447
08-ESP	BIT	1.224	10.370	151.077	0.093	0.100	0.080	9.976	2.822
09-BRA	BIT	1.068	15.817	127.505	0.769	0.450	1.581	2.223	5.977
10-RUS	BIT	0.987	2.292	18.221	2.608	0.132	4.681	7.571	2.262
11-IND	BIT	0.906	1.196	14.971	0.368	0.445	0.194	2.247	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)			$1/\omega$
Exporter	Coal	GDP	Value	Quantity	Mean	Median	Std. Dev	Median
01-AUS	BIT	1.231	339.881	3792.081	0.279	0.259	0.291	3.867
02-IDN	BIT	1.295	95.080	1355.568	0.225	0.272	0.166	3.678
03-RUS	BIT	0.941	88.663	955.471	1.223	0.910	1.458	1.099
04-USA	BIT	0.633	88.035	829.707	0.580	0.132	1.814	7.572
05-CAN	BIT	1.644	70.791	702.655	0.347	0.348	0.165	2.870
06-COL	BIT	1.133	43.407	607.324	0.331	0.196	0.433	5.111
07-CHN	BIT	1.585	32.391	585.872	0.316	0.275	0.094	3.634
08-ZAF	BIT	1.130	29.027	461.395	0.796	0.200	1.410	5.009
09-POL	BIT	0.707	13.477	216.958	0.150	0.118	0.060	8.447
10-KAZ	BIT	0.821	2.167	20.397	0.140	0.132	0.021	7.571

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	
U.S. gas price × BIT	0.0695***
	(0.0215)
U.S. gas price × ANT	-0.0701
	(0.2111)
U.S. gas price × OTH	0.0108
	(0.0327)
R-squared	0.9632
Observations	11,966

Note: We report the results from the regression for (21) in the main text. The regression includes importer × exporter × coal type fixed effects and year 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 clustered by exporter and year. 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	% change	actual	CF	% change
01-AUS	289.184	295.972	2.347	2092.253	2129.483	37.231	1.779	138.216	138.988	0.558
02-IDN	148.537	150.756	1.494	1825.252	1844.730	19.478	1.067	81.379	81.722	0.422
03-USA	82.306	66.951	-18.656	583.748	459.204	-124.544	-21.335	140.996	145.798	3.406
04-RUS	90.947	93.929	3.279	796.807	818.495	21.688	2.722	114.139	114.758	0.542
05-ZAF	39.933	40.604	1.682	392.879	397.297	4.418	1.125	101.641	102.201	0.551
06-COL	45.122	47.005	4.173	476.619	492.066	15.447	3.241	94.671	95.526	0.903
07-CAN	45.179	46.425	2.757	274.289	279.546	5.257	1.917	164.715	166.073	0.825
08-CHN	17.327	17.436	0.628	134.747	135.297	0.550	0.408	128.589	128.870	0.219
09-KAZ	4.892	4.996	2.125	160.722	161.204	0.482	0.300	30.437	30.991	1.819
10-POL	6.952	7.274	4.641	55.322	57.233	1.910	3.453	125.655	127.097	1.148
OTH	64.759	65.757	1.540	689.672	697.670	7.998	1.160	93.899	94.252	0.376
Non-USA	752.831	770.153	2.301	6898.561	7013.021	114.460	1.659	109.129	109.818	0.631
Total	835.137	837.104	0.236	7482.310	7472.225	-10.085	-0.135	111.615	112.029	0.371

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	4279.985	155.591	158.359	25.909	26.370
02-IDN	3668.520	3707.667	135.735	137.184	22.602	22.843
03-USA	1173.258	922.940	43.411	34.149	7.229	5.686
04-RUS	1601.478	1645.068	59.255	60.868	9.867	10.135
05-ZAF	789.636	798.516	29.217	29.545	4.865	4.920
06-COL	957.942	988.989	35.444	36.593	5.902	6.093
07-CAN	551.285	561.851	20.398	20.788	3.397	3.462
08-CHN	270.824	271.930	10.020	10.061	1.669	1.675
09-KAZ	323.030	323.999	11.952	11.988	1.990	1.996
10-POL	111.191	115.030	4.114	4.256	0.685	0.709
OTH	1386.152	1402.226	51.288	51.882	8.540	8.639
Non-USA	13865.213	14095.262	513.013	521.525	85.425	86.843
Total	15038.471	15018.202	556.423	555.673	92.654	92.529

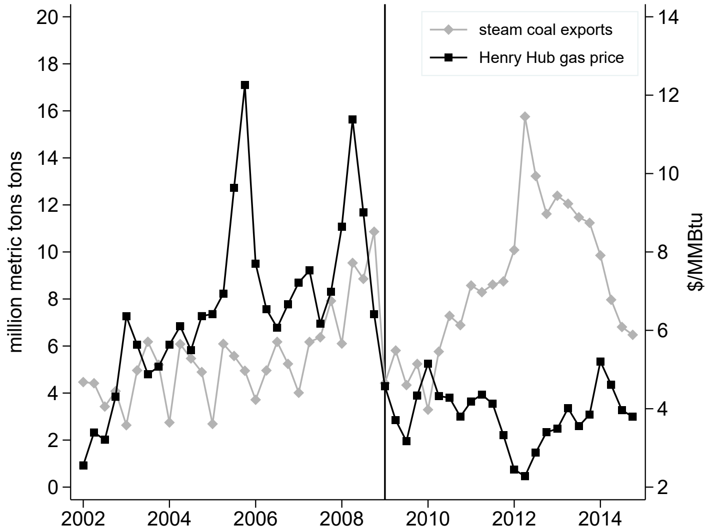
Note: The emissions are in million metric tons. The social cost is measured in billion USD assuming $37 per metric ton. We use CF to refer to counterfactual outcomes in the absence of the U.S. Shale Gas Boom.

Table 7: Welfare Effects, importers, 2007–2014

Country	EV	ΔW	CV	$100 \times \Delta ln(\mathcal{P}^I_{gt})$
01-JPN	1.630	1.641	1.652	0.309
02-KOR	1.249	1.261	1.273	0.622
03-CHN	1.691	1.706	1.722	1.288
04-IND	0.021	0.021	0.021	1.194
05-DEU	2.461	2.557	2.659	2.890
06-GBR	2.026	2.111	2.200	3.818
07-NLD	1.190	1.242	1.297	3.431
08-ITA	1.738	1.835	1.942	3.290
09-RUS	0.367	0.410	0.464	0.589
10-BRA	1.888	2.009	2.142	3.716
OTH	4.861	5.255	5.712	1.810
Total	19.123	20.049	21.084	1.395

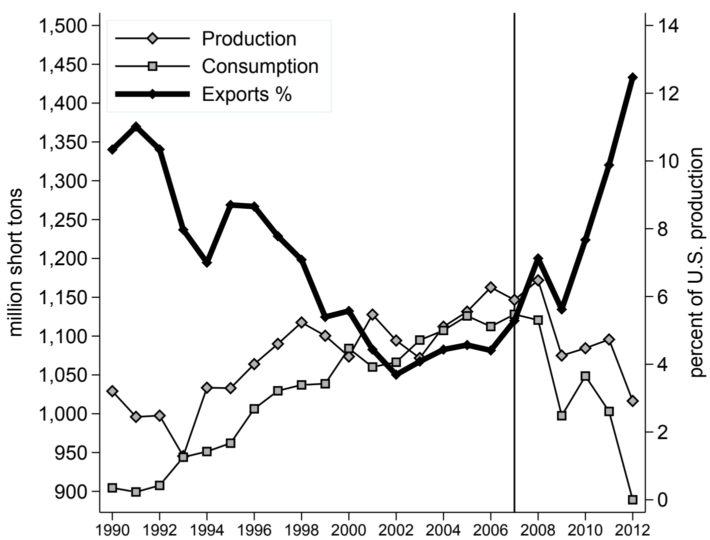
Note: the table shows the equivalent (EV) and compensating (CV) variation to measure the net welfare effects of the Boom for the utility function in (1). We write the measures of welfare effects such that positive entries imply that consumers are worse off in the absence of the U.S. Shale Gas Boom without taking into account emissions. The percentage change in the CES price index shown in the rightmost column is calculated using (24).

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



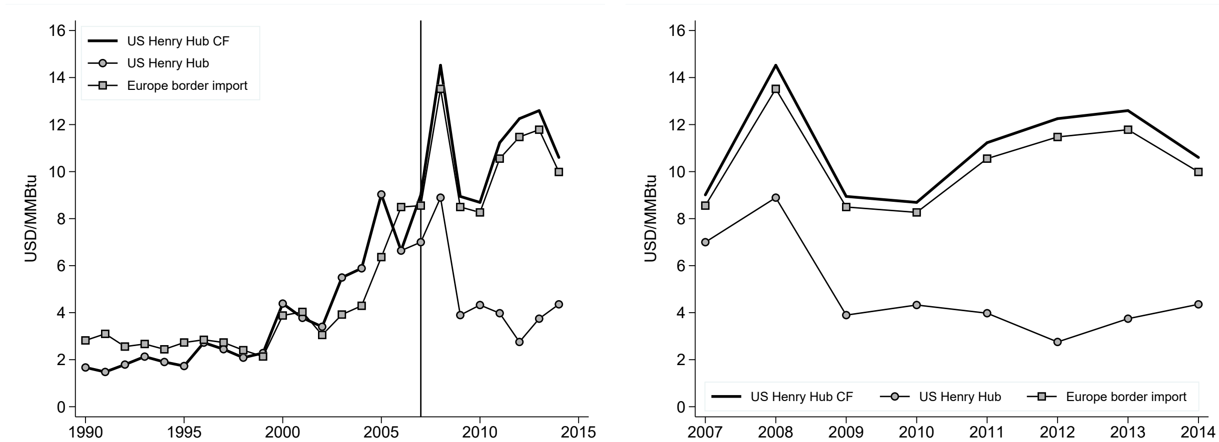
Note: the quarterly gas price is an average of EIA monthly prices for the Henry Hub benchmark. The quarterly exports of coal are from the EIA International Energy Statistics. The vertical line at 2007 indicates the beginning of the U.S. Shale Gas Boom.

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.

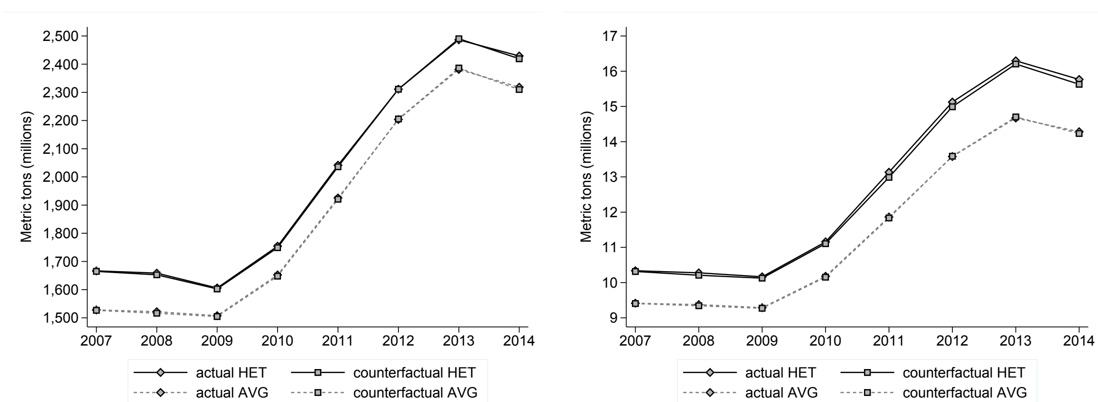
Figure 3: Counterfactual analysis:
U.S. gas prices



(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 counterfactual analysis (2007–2014).

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



(a) CO_2 emissions (b) SO_2 emissions

Note: 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.15 and A.16. Panel (b) shows SO_2 emissions using an average SO_2 content 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_2 content information in Tables A.15 and A.16.

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.[38] 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.15, as well as for coal imported by the major importing countries in the on-line Appendix Table A.16. 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

[38] 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_2 content (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 (2018), 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 (2018) 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.[39]

[39]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 0.31% decrease in quantities, a 0.12% increase in the dollar value of trade, and a 0.43% increase in coal prices (Table A.17). The counterfactual CO_2 emissions are 15,968 as opposed to 15,972 million metric tons, and the counterfactual SO_2 emissions are 101.8 million metric tons, as opposed to 101.5. In both cases, we allow for heterogeneity in the heat and SO_2 content of coal and the comparisons are with the outcomes for the longer estimation sample of 1990–2014. Moreover, there is a decrease of 16.74%, as opposed to 21.34%, in the quantity of U.S. coal exports and an implied increase in U.S. coal prices of 4.72%, as opposed to 3.41%.

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

		BIT		ANT		OTH	
Country/Region	Count	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 (2018) 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

		BIT		ANT		OTH	
Country/Region	Count	Quantity	Value	Quantity	Value	Quantity	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 (2018) 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	0.156	0.051	0.701
02-JPN	ALL	140.636	0.261	0.180	0.246	0.339	0.180	0.381
03-BRA	ALL	137.542	3.469	1.798	5.058	3.470	1.798	5.057
04-ITA	ALL	98.559	0.279	0.119	1.557	0.331	0.137	1.557
05-GBR	ALL	95.327	1.207	0.772	1.107	1.653	1.246	1.512
06-DEU	ALL	81.020	0.976	0.894	0.743	1.377	0.964	1.015
07-NLD	ALL	74.560	4.057	2.679	2.521	5.477	2.679	4.458
08-KOR	ALL	66.978	0.200	0.092	1.430	0.246	0.141	1.430
09-FRA	ALL	54.501	8.773	9.628	2.308	10.240	10.042	2.663
10-ESP	ALL	52.125	6.167	3.284	6.789	8.764	3.284	13.020
OTH	ALL	243.443	13.147	5.702	15.012	21.049	6.227	25.055

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

Country	Coal Value			Coal Quantity			Coal Price		
	actual	CF	% change	actual	CF	% change	actual	CF	% change
01-JPN	193.601	192.545	-0.546	1464.870	1459.499	-0.367	132.163	131.925	-0.180
02-KOR	100.455	100.721	0.264	921.594	922.553	0.104	109.001	109.176	0.160
03-CHN	124.406	126.075	1.341	1291.275	1304.021	0.987	96.344	96.681	0.351
04-IND	91.807	91.800	-0.008	818.692	818.504	-0.023	112.139	112.156	0.015
05-DEU	43.022	43.022	0.000	350.616	350.616	0.000	122.704	122.704	0.000
06-GBR	35.465	35.465	0.000	305.789	305.789	0.000	115.978	115.978	0.000
07-NLD	18.065	17.702	-2.012	159.508	152.525	-4.378	113.256	116.058	2.474
08-ITA	24.395	24.065	-1.354	184.565	175.172	-5.089	132.177	137.379	3.935
09-RUS	4.601	4.601	0.000	151.194	151.194	0.000	30.429	30.429	0.000
10-BRA	21.354	21.354	0.000	143.864	143.864	0.000	148.433	148.433	0.000
OTH	177.964	179.756	1.007	1690.342	1688.487	-0.110	105.283	106.460	1.118
Total	835.137	837.104	0.236	7482.310	7472.225	-0.135	111.615	112.029	0.371

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.10: Counterfactual analysis: all coal environmental outcomes, importers, 2007-2014

Country	CO_2 Emissions		CO_2 Social Cost		SO_2 Emissions	
	Actual	CF	Actual	CF	Actual	CF
01-JPN	2944.198	2933.404	108.935	108.536	18.140	18.073
02-KOR	1852.284	1854.212	68.535	68.606	11.412	11.424
03-CHN	2595.295	2620.913	96.026	96.974	15.990	16.148
04-IND	1645.465	1645.087	60.882	60.868	10.138	10.136
05-DEU	704.692	704.692	26.074	26.074	4.342	4.342
06-GBR	614.597	614.597	22.740	22.740	3.787	3.787
07-NLD	320.590	306.556	11.862	11.343	1.975	1.889
08-ITA	370.951	352.073	13.725	13.027	2.285	2.169
09-RUS	303.880	303.880	11.244	11.244	1.872	1.872
10-BRA	289.149	289.149	10.699	10.699	1.781	1.781
OTH	3397.369	3393.639	125.703	125.565	20.932	20.909
Total	15038.471	15018.202	556.423	555.673	92.654	92.529

Note: The emissions are 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 A.11: 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	2.079	-65.743	30.302	8.882	-70.689	200.232	234.022	16.875
02-KOR	4.840	3.168	-34.545	28.384	16.014	-43.582	170.515	197.828	16.018
03-CHN	4.512	3.004	-33.411	32.173	17.912	-44.325	140.228	167.715	19.602
04-IND	3.902	3.878	-0.619	20.862	20.520	-1.641	187.057	189.001	1.039
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	2.517	-33.062	28.501	15.538	-45.481	131.932	161.986	22.780
08-ITA	5.557	3.742	-32.657	37.043	19.025	-48.642	150.007	196.696	31.124
09-RUS	1.079	1.079	0.000	4.582	4.582	0.000	235.424	235.424	0.000
10-BRA	8.930	8.930	0.000	55.707	55.707	0.000	160.307	160.307	0.000
OTH	29.411	24.307	-17.357	231.140	185.969	-19.542	127.245	130.702	2.717
Total	82.306	66.951	-18.656	583.748	459.204	-21.335	140.996	145.798	3.406

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.12: 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	17.851	2.253	0.661	0.375	0.110
02-KOR	57.048	32.185	2.111	1.191	0.351	0.198
03-CHN	64.663	36.001	2.393	1.332	0.398	0.222
04-IND	41.930	41.242	1.551	1.526	0.258	0.254
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	31.230	2.119	1.156	0.353	0.192
08-ITA	74.451	38.237	2.755	1.415	0.459	0.236
09-RUS	9.210	9.210	0.341	0.341	0.057	0.057
10-BRA	111.964	111.964	4.143	4.143	0.690	0.690
OTH	464.560	373.774	17.189	13.830	2.862	2.303
Total	1173.258	922.940	43.411	34.149	7.229	5.686

Note: The emissions are 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 A.13: 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	190.466	1.564	1434.568	1450.617	1.119	130.725	131.300	0.440
02-KOR	95.615	97.553	2.026	893.210	906.539	1.492	107.047	107.610	0.526
03-CHN	119.895	123.070	2.649	1259.102	1286.109	2.145	95.222	95.692	0.493
04-IND	87.905	87.922	0.019	797.830	797.984	0.019	110.180	110.180	-0.000
05-DEU	35.117	35.117	0.000	290.176	290.176	0.000	121.020	121.020	0.000
06-GBR	29.123	29.123	0.000	251.175	251.175	0.000	115.945	115.945	0.000
07-NLD	14.305	15.185	6.150	131.007	136.987	4.564	109.193	110.849	1.516
08-ITA	18.839	20.323	7.879	147.522	156.147	5.847	127.700	130.152	1.920
09-RUS	3.522	3.522	0.000	146.611	146.611	0.000	24.022	24.022	0.000
10-BRA	12.424	12.424	0.000	88.157	88.157	0.000	140.930	140.930	0.000
OTH	148.553	155.449	4.642	1459.203	1502.517	2.968	101.804	103.459	1.626
Total	752.831	770.153	2.301	6898.561	7013.021	1.659	109.129	109.818	0.631

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: 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	2915.552	106.682	107.875	17.764	17.963
02-KOR	1795.236	1822.026	66.424	67.415	11.061	11.226
03-CHN	2530.632	2584.912	93.633	95.642	15.592	15.926
04-IND	1603.535	1603.845	59.331	59.342	9.880	9.882
05-DEU	583.216	583.216	21.579	21.579	3.593	3.593
06-GBR	504.829	504.829	18.679	18.679	3.110	3.110
07-NLD	263.307	275.326	9.742	10.187	1.622	1.696
08-ITA	296.500	313.836	10.971	11.612	1.827	1.934
09-RUS	294.670	294.670	10.903	10.903	1.816	1.816
10-BRA	177.185	177.185	6.556	6.556	1.092	1.092
OTH	2932.808	3019.865	108.514	111.735	18.069	18.606
Total	13865.213	14095.262	513.013	521.525	85.425	86.843

Note: The emissions are 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 A.15: 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_2 content is an average of the sulfur content for Platts FOB contracts.

Table A.16: 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_2 content 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.17: Counterfactual analysis: all coal economic outcomes, exporters, 2007-2014, accounting for domestic coal

a. Broda and Weinstein (2006) elasticities

	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	82.306	54.449	-33.846	583.748	377.844	-205.904	-35.273	140.996	144.103	2.204
Non-USA	752.831	799.990	6.264	6898.561	7188.794	290.232	4.207	109.129	111.283	1.974
Total	835.137	854.438	2.311	7482.310	7566.638	84.328	1.127	111.615	112.922	1.171

b. accounting for domestic coal

	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	82.306	62.546	-24.007	583.748	425.904	-157.844	-27.040	140.996	146.856	4.156
Non-USA	4496.159	4509.520	0.297	48610.276	48699.169	88.894	0.183	92.494	92.600	0.114
Total	4578.465	4572.067	-0.140	49194.024	49125.073	-68.951	-0.140	93.070	93.070	0.000

c. based on estimates for 1990–2016

	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	82.306	71.764	-12.808	583.748	486.032	-97.716	-16.739	140.996	147.654	4.722
Non-USA	752.831	764.384	1.535	6898.561	6973.102	74.540	1.081	109.129	109.619	0.449
Total	835.137	836.148	0.121	7482.310	7459.134	-23.176	-0.310	111.615	112.097	0.432

d. main results

	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	82.306	66.951	-18.656	583.748	459.204	-124.544	-21.335	140.996	145.798	3.406
Non-USA	752.831	770.153	2.301	6898.561	7013.021	114.460	1.659	109.129	109.818	0.631
Total	835.137	837.104	0.236	7482.310	7472.225	-10.085	-0.135	111.615	112.029	0.371

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. In panel (d), we replicate the results from Table 5.

Table A.18: Robustness checks for the effect of U.S. gas prices on bituminous coal

a. U.S.

		Coal Value			Coal Quantity				Coal Price		
Country	α	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	0.50	82.306	78.597	-4.506	583.748	552.179	-31.569	-5.408	140.996	142.340	0.953
USA	0.75	82.306	72.054	-12.456	583.748	498.453	-85.296	-14.612	140.996	144.555	2.524
USA	0.90	82.306	68.865	-16.331	583.748	474.143	-109.605	-18.776	140.996	145.240	3.010
USA	1.00	82.306	66.951	-18.656	583.748	459.204	-124.544	-21.335	140.996	145.798	3.406
USA	1.10	82.306	65.278	-20.688	583.748	448.451	-135.297	-23.177	140.996	145.564	3.240
USA	1.25	82.306	62.998	-23.459	583.748	433.097	-150.652	-25.808	140.996	145.458	3.165
USA	1.50	82.306	59.815	-27.326	583.748	413.088	-170.660	-29.235	140.996	144.800	2.698

b. non-U.S. exporters

		Coal Value			Coal Quantity				Coal Price		
Country	α	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
Non-USA	0.50	752.831	756.587	0.499	6898.561	6923.150	24.589	0.356	109.129	109.284	0.142
Non-USA	0.75	752.831	763.234	1.382	6898.561	6967.228	68.667	0.995	109.129	109.546	0.383
Non-USA	0.90	752.831	767.403	1.936	6898.561	6994.717	96.155	1.394	109.129	109.712	0.534
Non-USA	1.00	752.831	770.153	2.301	6898.561	7013.021	114.460	1.659	109.129	109.818	0.631
Non-USA	1.10	752.831	773.196	2.705	6898.561	7032.721	134.159	1.945	109.129	109.943	0.746
Non-USA	1.25	752.831	777.733	3.308	6898.561	7062.342	163.781	2.374	109.129	110.124	0.912
Non-USA	1.50	752.831	785.712	4.368	6898.561	7114.136	215.575	3.125	109.129	110.444	1.205

c. all exporters

		Coal Value			Coal Quantity				Coal Price		
Country	α	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
Total	0.50	835.137	835.184	0.006	7482.310	7475.329	-6.981	-0.093	111.615	111.725	0.099
Total	0.75	835.137	835.288	0.018	7482.310	7465.681	-16.629	-0.222	111.615	111.884	0.241
Total	0.90	835.137	836.267	0.135	7482.310	7468.860	-13.450	-0.180	111.615	111.967	0.316
Total	1.00	835.137	837.104	0.236	7482.310	7472.225	-10.085	-0.135	111.615	112.029	0.371
Total	1.10	835.137	838.474	0.400	7482.310	7481.172	-1.138	-0.015	111.615	112.078	0.415
Total	1.25	835.137	840.731	0.670	7482.310	7495.439	13.129	0.175	111.615	112.166	0.494
Total	1.50	835.137	845.527	1.244	7482.310	7527.224	44.914	0.600	111.615	112.329	0.640

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. We report results associated with perturbations of the bituminous coal coefficient in Table 4 of the form $\alpha \times \widehat{\beta}_{BIT}$ for the values of α indicated in the second column. In the case of $\alpha = 1$, we replicate the results from Table 5.

Table A.19: Counterfactual analysis: all coal economic outcomes, exporters, 2007-2014, excluding anthracite

a. excluding anthracite

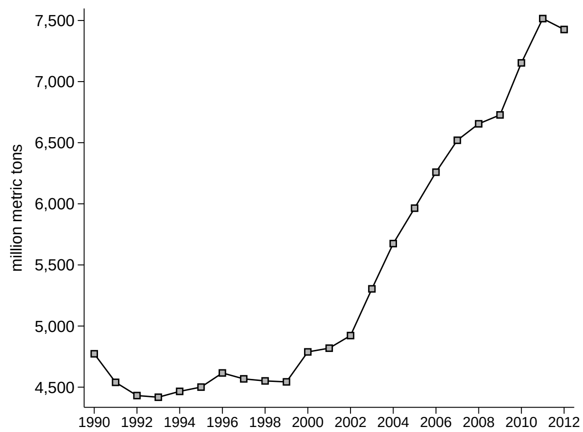
	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	81.197	65.842	-18.911	576.788	452.244	-124.544	-21.593	140.775	145.590	3.421
Non-USA	702.491	719.814	2.466	6415.413	6529.872	114.459	1.784	109.501	110.234	0.670
Total	783.688	785.656	0.251	6992.201	6982.116	-10.085	-0.144	112.080	112.524	0.396

b. including anthracite

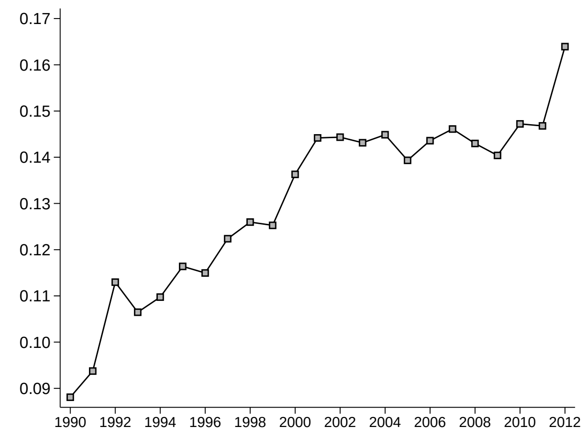
	Coal Value			Coal Quantity				Coal Price		
Country	actual	CF	% change	actual	CF	change	% change	actual	CF	% change
USA	82.306	66.951	-18.656	583.748	459.204	-124.544	-21.335	140.996	145.798	3.406
Non-USA	752.831	770.153	2.301	6898.561	7013.021	114.460	1.659	109.129	109.818	0.631
Total	835.137	837.104	0.236	7482.310	7472.225	-10.085	-0.135	111.615	112.029	0.371

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. In panel b, we replicate the results from Table 5.

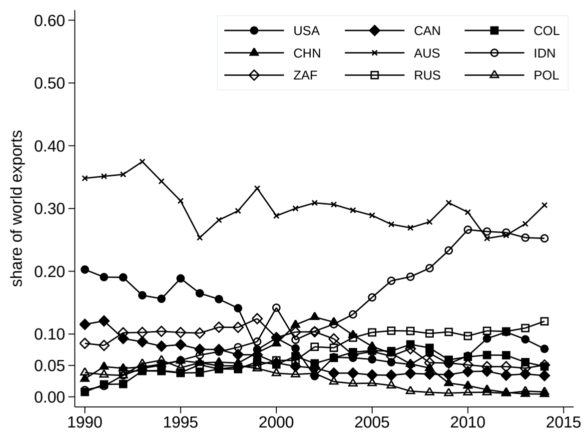
Figure A.1: Coal markets overview



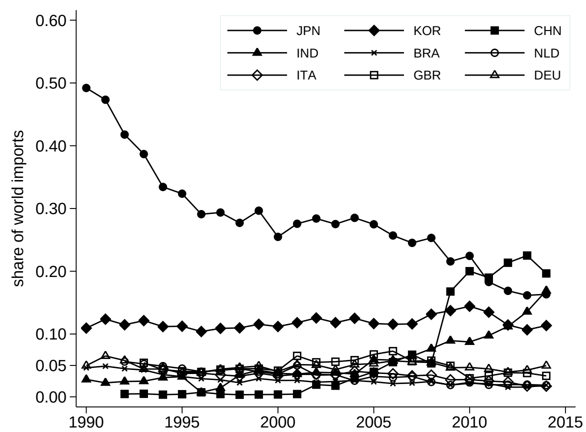
(a) Consumption



(b) Trade/Consumption Ratio



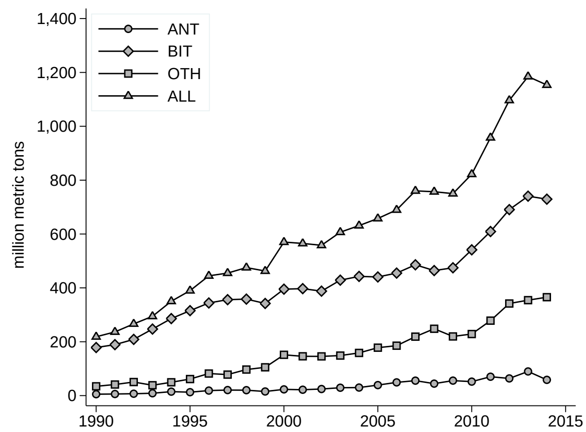
(c) Major exporters



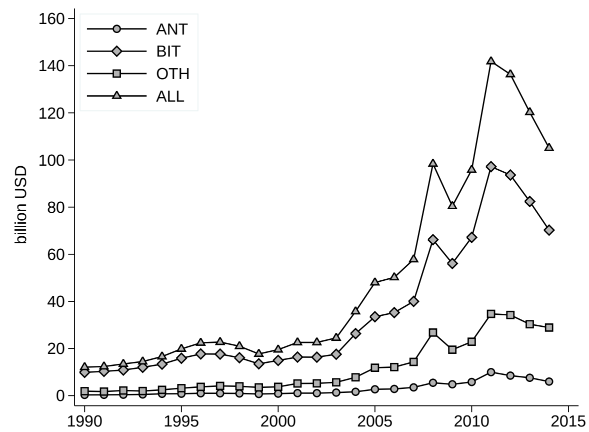
(d) Major importers

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.

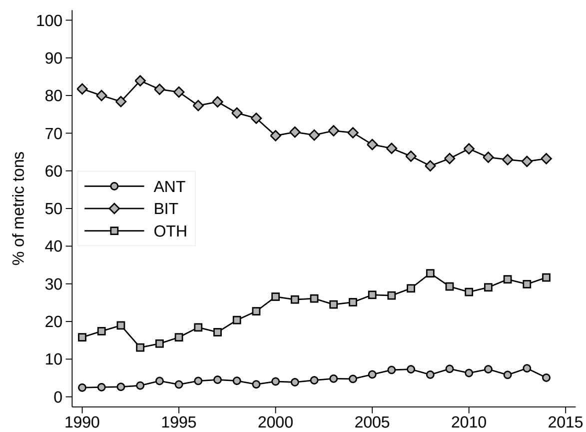
Figure A.2: World trade by type of coal



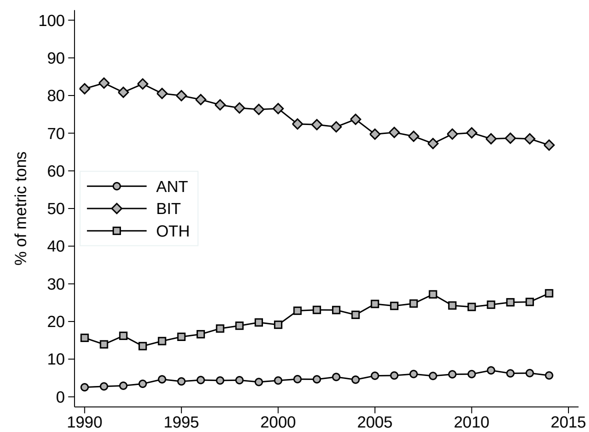
(a) quantity



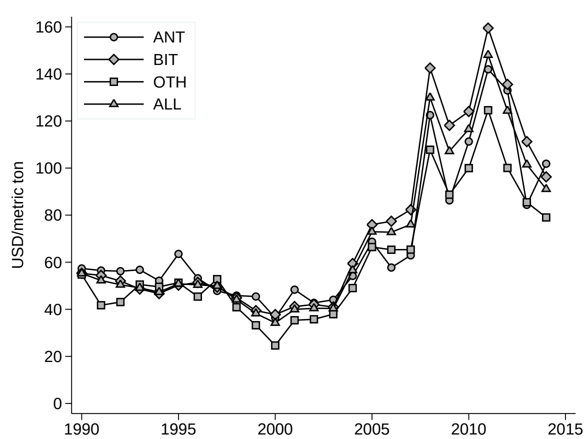
(b) value



(c) quantity, %



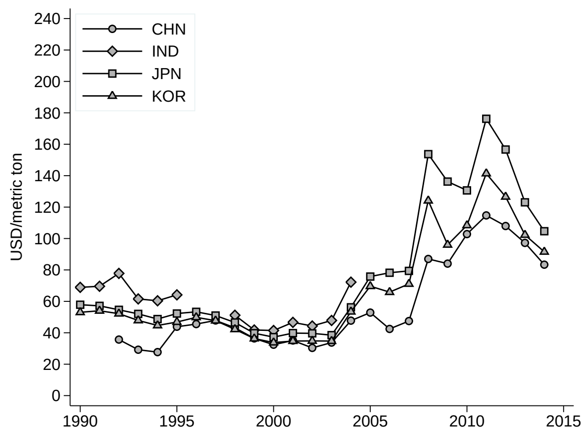
(d) value, %



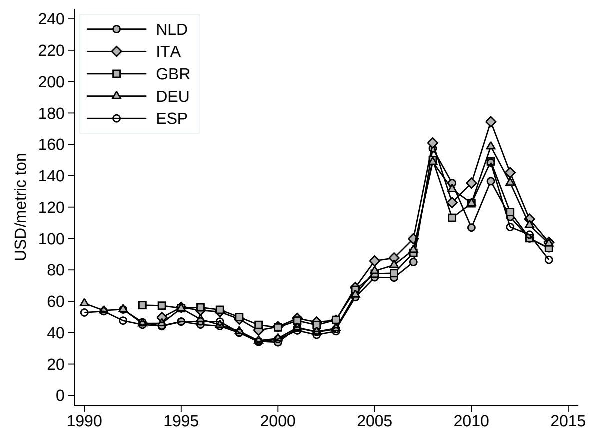
(e) price

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

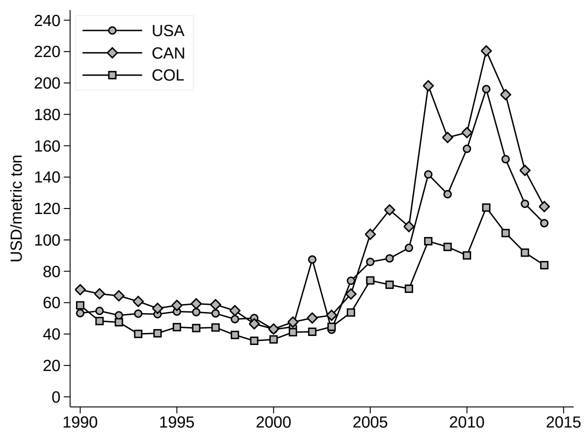
Figure A.3: Coal prices per metric ton



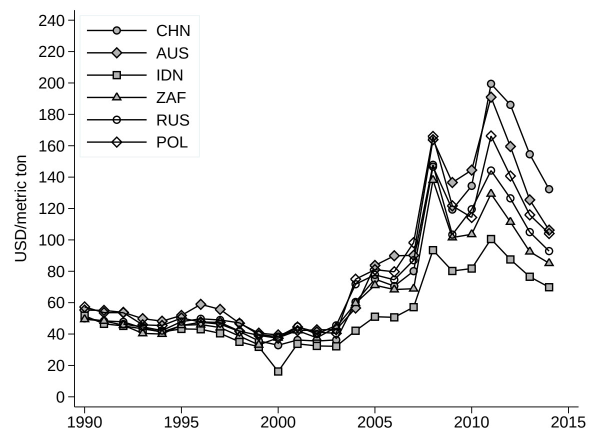
(a) coal prices for importers: Asia



(b) coal prices for importers: Europe



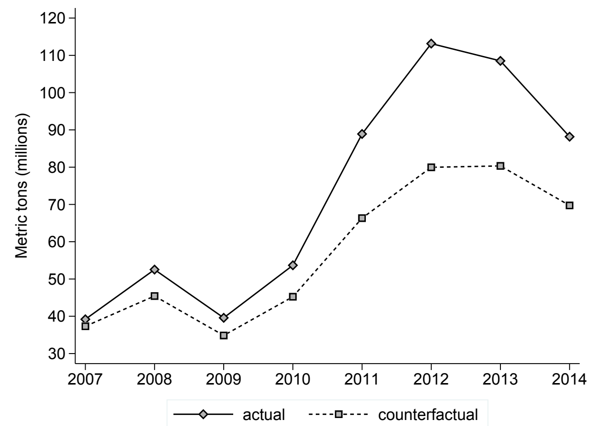
(c) coal prices for exporters: Americas



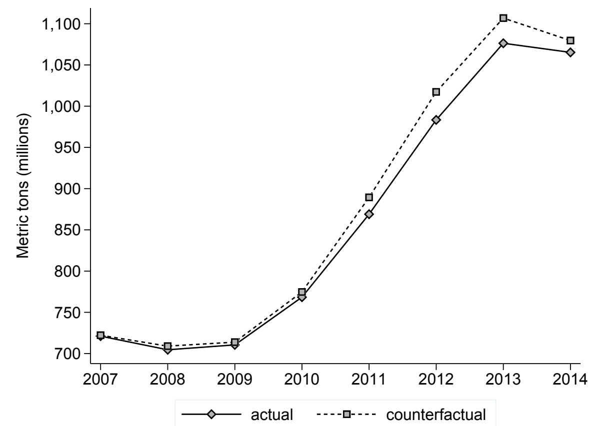
(d) coal prices exporters: Other

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.

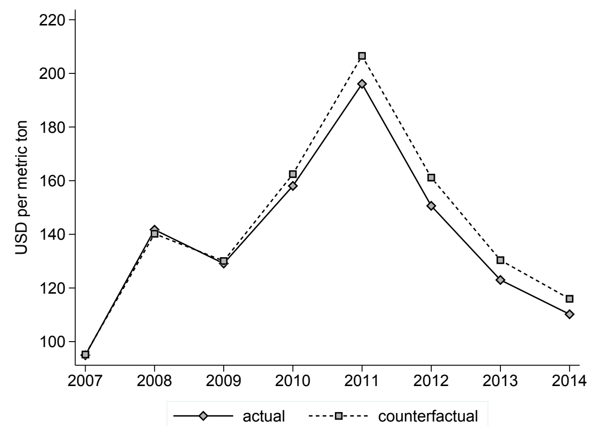
Figure A.4: Counterfactual analysis:
economic outcomes, 2007–2014



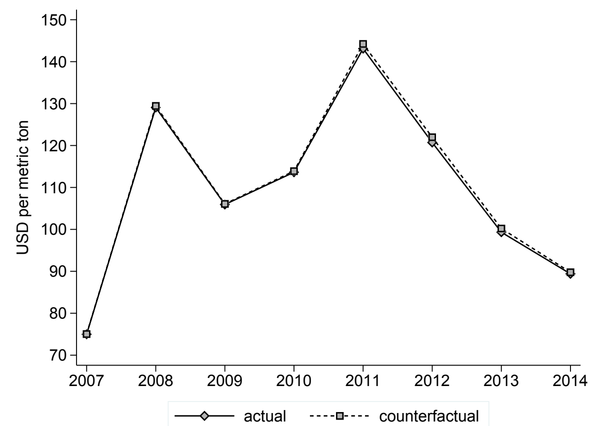
(a) quantity, U.S. coal



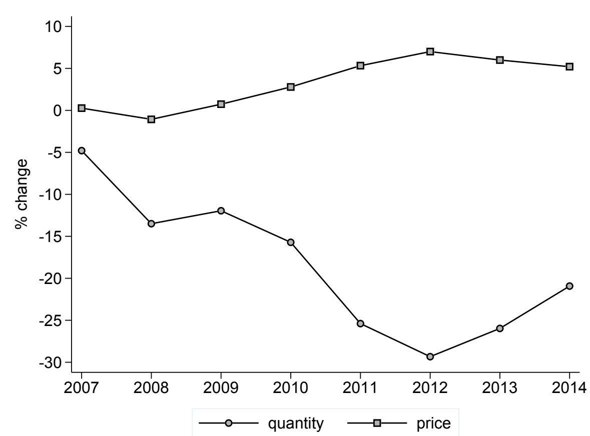
(b) quantity, non-U.S. coal



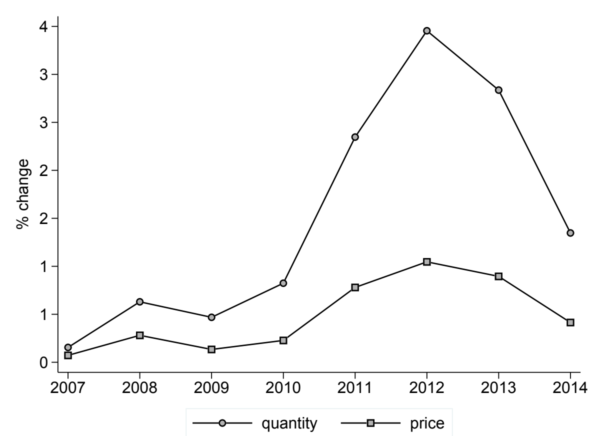
(c) price, U.S. coal



(d) price, U.S. coal



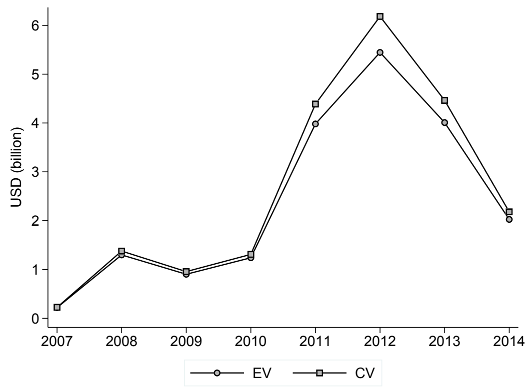
(e) % change, U.S. coal



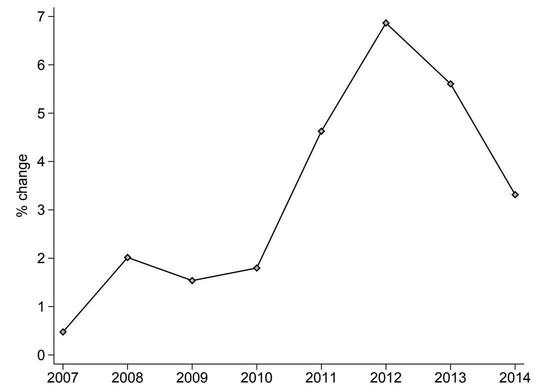
(f) % change, non-U.S.coal

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



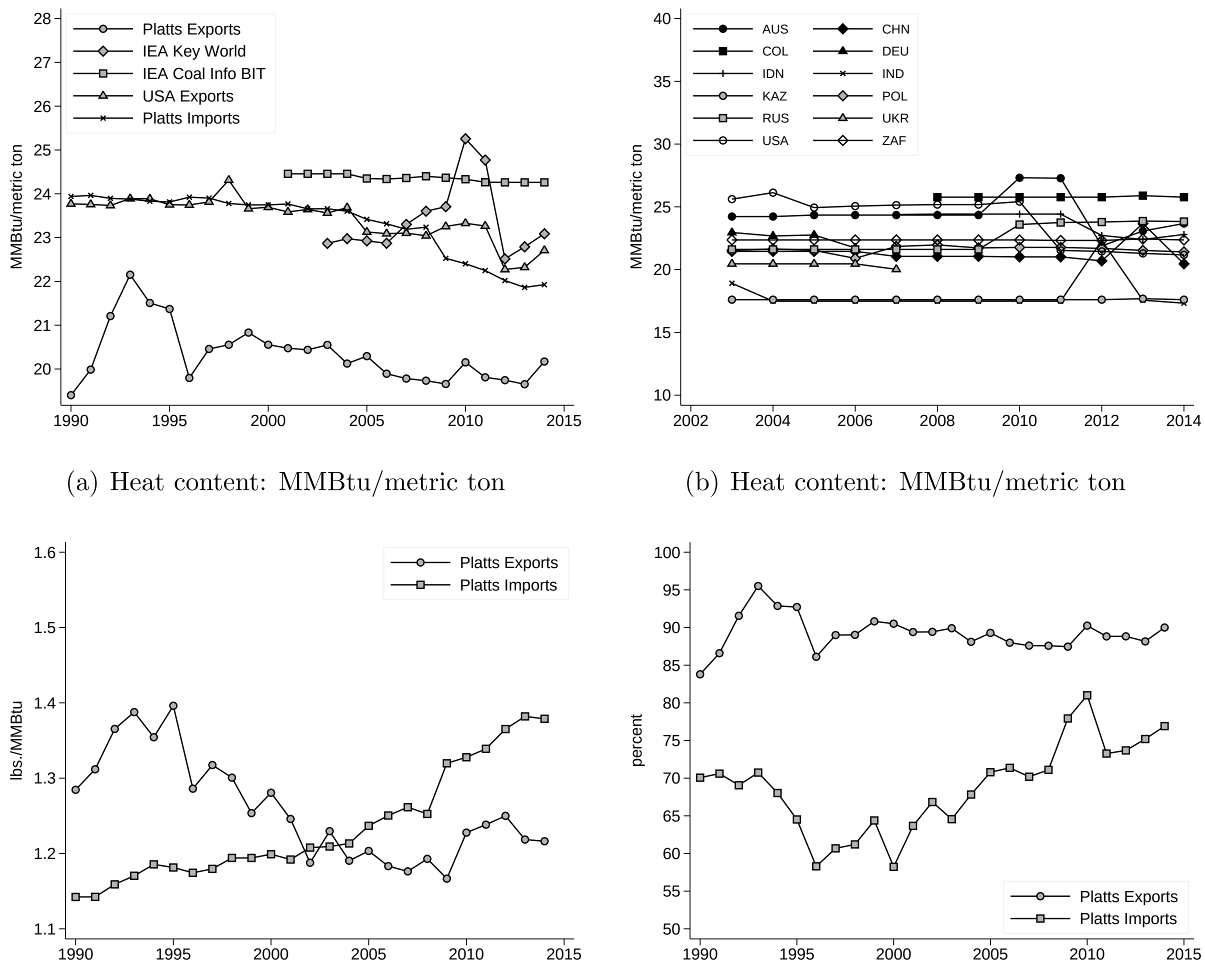
(a) welfare



(b) CES price index

Note: Panel (a) shows 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

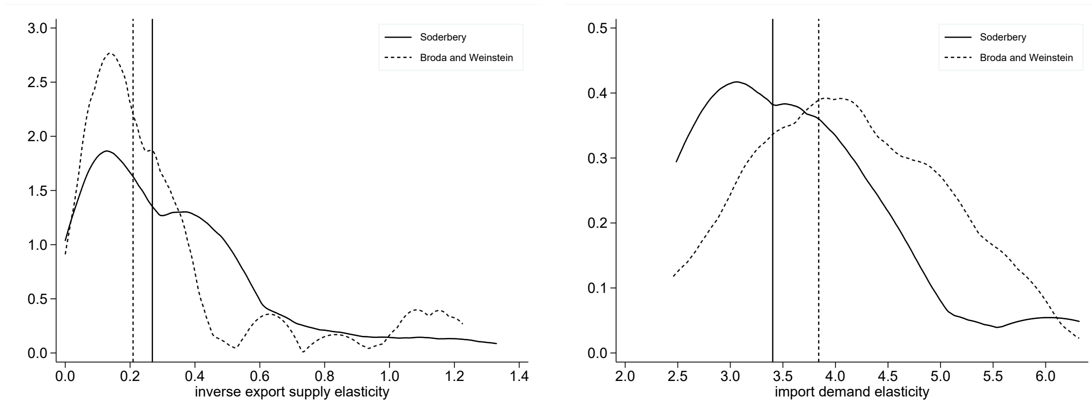
(b) Heat content: MMBtu/metric ton

(c) SO_2 content: lbs./MMbtu

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

Note: See Section 5.4 for additional details.

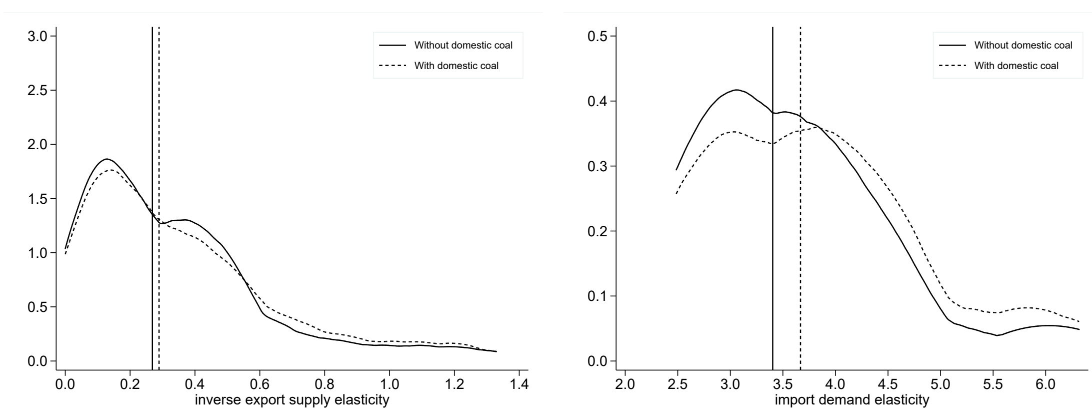
Figure A.7: Export and import elasticities:
Soderbery (2018) vs. Broda and Weinstein (2006)



(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.

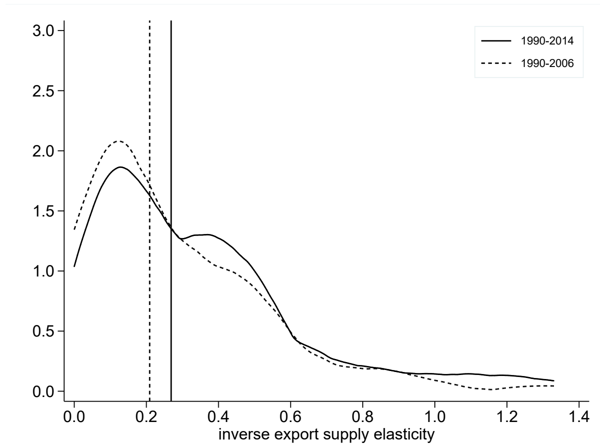
Figure A.8: Export and import elasticities:
Accounting for domestic coal



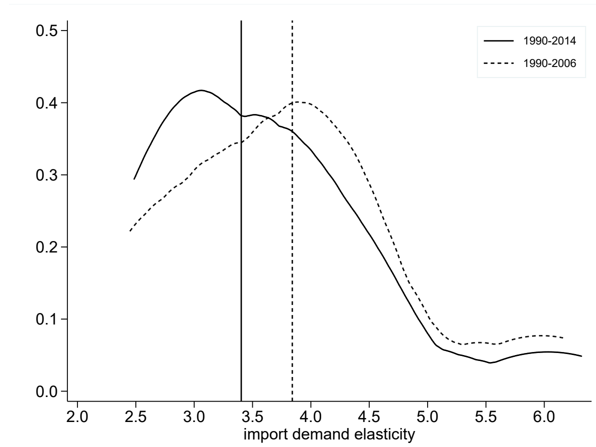
(a) inverse export supply elasticities (ω) (b) import demand elasticities (σ)

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 (2018) 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.